British Columbia Geological Survey mineral deposit profiles, 1995 to 2012; updated with new profiles for VMS, porphyry, and mafic-ultramafic deposits

Compiled by D.V. Lefebure and L.D. Jones

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Front cover: Folded bands of massive sulphides interlayered with fine-grained siliciclastic deposits from the Sullivan mine, southeastern British Columbia; sedimentary exhalative Zn-Pb-Ag (Sedex, sediment-hosted massive sulphide); mineral deposit profile E14. **Photo by Fiona Katay.**

Back cover: Coarse-grained magnesite crystals from the Baymag mine, southeastern British Columbia; sparry magnesite (Veitsch-type, carbonate-hosted magnesite); mineral deposit profile E09. **Photo by David Lefebure.**

BRITISH COLUMBIA

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1. Introduction

The mineral deposit profiles compiled herein were initially prepared by the British Columbia Geological Survey (BCGS) between 1995 and 2012. Most of the profiles were initially published in BCGS Open File reports or in Geological Fieldwork volumes and were made available to the public on the BCGS website. The profiles are concise but comprehensive descriptions of metallic mineral, industrial mineral, gemstone, and coal deposits. These descriptions include geological characteristics, mineral exploration techniques, resource data, age of mineralization, tectonic setting, and concepts about deposit origins. Although the profiles have a global scope, many provide information specific to British Columbia.

The purpose of the present report is to re-release all 120 profiles in one collection, with the original profiles virtually unchanged. In addition, the BCGS has initiated a multi-year mineral potential mapping project to identify areas of high prospectivity for key mineral systems across the province, and this release includes ten profiles for VMS, porphyry, and mafic-ultramafic deposits, which include mineral systems information and are included as an Addendum. The next generation of mineral deposit profiles will further support completing modern resource assessments, likely enabled by artificial intelligence applications.

2. Starting point: A provincial mineral potential assessment

In 1992, the BCGS initiated a mineral potential assessment of British Columbia. Completed by 1997 (Grunsky et al., 1994; Kilby, 1995; Kilby, 1996; Grunsky, 1997; Bobrowsky et al., 1998), this assessment was the first detailed mineral potential evaluation completed by any country for an entire province or state. It was also the first assessment to evaluate the potential for finding a broad spectrum of industrial mineral deposits (Kilby et al., 1998).

The BCGS recognized that province-scale estimates of mineral potential needed a common base that included well-defined and standardized mineral deposit models (Lefebure et al., 1995; Lefebure and Ray, 1995; Lefebure and Höy, 1996; Simandl et al., 1999). The mineral deposit profiles were used to classify known deposits and to compile representative grade and tonnage data (Grunsky, 1995). Most importantly, the profiles provided criteria that enable people to estimate the number of possible undiscovered mineral deposits. The inspiration for the mineral deposit profiles was from collections of model descriptions by the Geological Survey of Canada (Eckstrand,1984) and the United States Geological Survey (Cox and Singer, 1986). Both these collections used standardized approaches and limited descriptions to key information. The BCGS used Eckstrand (1984) to establish a template for the mineral deposit profiles and to develop author guidelines. Cox and Singer (1986) demonstrated the importance of including a wide variety of deposit models with grade and tonnage data, and identified numerous metallic ore deposit types that helped guide the BCGS select profile types.

Other organizations have published similar collections of mineral deposit models. For example, the Ontario Geological Survey published 27 metallic and 21 industrial mineral deposit models (Rogers et al., 1995), with an emphasis on metallic deposits in the Canadian Shield. The Geological Association of Canada published two collections of model descriptions (Sheahan et al., 1988; Sheahan and Cherry, 1993). Twenty-four of the British Columbia mineral deposit profiles were upgraded by the Yukon Geological Survey to include more Yukon information and references (Fonseca and Bradshaw, 2005). Descriptions of mineral deposit models that describe styles of mineralization that are best represented in Australia were published by Hodgson (1998), Solomon and Groves (2000), and Phillips (2017). In addition, the Australians have taken the lead in developing a mineral systems approach to better understand the origin of mineral deposits and applying this approach to both mineral exploration and resource assessments (Pirajno, 2009; McCuaig and Hronsky, 2014; Pirajno, 2015; Kreuzer et al., 2015; Huston et al., 2016).

3. Mineral deposit models

Hodgson (1993, p.1) defined an ore deposit model as “a conceptual and/or empirical standard, embodying both the descriptive features of the deposit type, and an explanation of these features in terms of geological processes.” Deposit model descriptions span the spectrum from detailed treatments of very similar mines and occurrences to more generalized descriptions of less well-known, and commonly more diverse, deposits. The latter may be more difficult to incorporate properly into a resource assessment or classification system as their geological characteristics may not be defined sufficiently. Commonly, geoscientists disagree about which depositional model is the most appropriate for a specific deposit, which underscores the need for accurate and standardized descriptions. Furthermore, as details about a specific model emerge, it may be recognized that what was previously considered a single model represents a family of two or more deposit types. For example, the iron oxide copper gold (IOCG) deposit model may encompass four related, but distinguishable types (Fraser et al., 2007).

Industry, government and academic scientists and engineers use deposit models in different ways. Exploration geologists and prospectors use them to help decide what regions to explore and which mineral occurrences present the best economic targets. Mine geologists and metallurgical engineers find them helpful as a starting point to decide how best to exploit ore bodies and mitigate environmental harm. However, there has been discussion about the importance and dangers of deposit models (Cox, 1993; Hodgson, 1993) and their relevance to exploration (Thompson, 1993; Etheridge and Henley, 1996). One of the key points underscored by this debate is that although models are useful for organizing data and understanding processes, they may lead to oversimplifications of complex natural phenomena and to important data being ignored because they do not fit the model.

4. Selection of mineral deposit profiles

The initial step in developing the mineral deposit profiles was to identify the general types of mineral deposits. Given the diversity of deposits in British Columbia, it was important to consider metallic mineral, coal, industrial mineral and gemstone deposits. No consideration was given to anthropogenic deposits with economic potential, such as tailings, because they lacked significant resources to include in a mineral potential assessment. However, tailings impoundments and other earth material deposits produced by human activity are now included in British Columbia's mineral database (MINFILE) and might be considered in modern mineral deposit classifications. Although the selection of profiles was initially guided by the needs of the BCGS province-wide mineral potential assessment, it was quickly realized that a more global outlook was warranted to ensure that all mineral resources would be included, and an extensive list of candidates was developed (Lefebure et al., 1995). Although the list was global in scope, some deposit types that are unlikely to occur in British Columbia were excluded (e.g., Bushveld Fe-Ti-V or komatiitic nickel). The following general criteria were used to choose the deposit types as profiles and how best to establish the boundaries between them.

1. The deposit models should have their own distinct characteristics that relate to a particular style of mineralization and/or related geological characteristics that are important to guide mineral exploration and to carry out mineral potential assessments.
2. All profiles should include examples of mineral deposits that are being mined or have been mined. Some profiles were created for deposit types, such as Shale-hosted Ni-Zn-Mo-PGE and Alaskan-type PGEs (Pt±Os±Rh±Ir), that had only been mined on a small scale. These were included as they were judged to have the potential to become more economically important mineral deposits in the future.
3. An individual mineral deposit could only be included in a single deposit profile.
4. The knowledge of the deposit type should be adequate to produce a coherent deposit model and ensure that it is truly distinct.

In addition, the BCGS approach was to split rather than group deposit types. If a deposit model includes two distinct mineral deposit types it will homogenize the characteristics and provide less utility for mineral exploration and resource assessments. Therefore, every effort was made to separate distinct deposit types. An example of this choice was to maintain separate deposit profiles for three types of gold veins (Au-quartz veins, Intrusion-related Au pyrrhotite veins, Turbidite-hosted Au veins) even though they might all be grouped as mesothermal gold-quartz veins by some geologists or orogenic gold deposits by others.

The selection of mineral deposit profiles was an iterative process. As the mineral deposit profiles were being written in the 1990s and early 2000s, adjustments were made to the master listing of deposit profiles and decisions were made to drop some models and add others. For example, a profile titled Carbonate-hosted, nonsulphide Zn (hypogene) was added to acknowledge the emerging understanding of the importance and genesis of these deposits (Paradis and Simandl, 2012). Similarly, a new style of gold mineralization best exemplified by the Fort Knox gold mine in Alaska was attracting considerable attention. Now commonly referred to as reduced intrusion-related gold deposits (Hart and Goldfarb, 2005), this required a new deposit profile: Plutonic-related Au quartz veins and veinlets. In addition, new styles of mineralization were being found in British Columbia or being recognized elsewhere and needed to be considered. For example, the Subaqueous hot spring Au-Ag profile was based largely on the Eskay Creek deposit in northwest British Columbia (Alldrick, 1996; Alldrick, 1999). Research results from the southeast Pacific at the time had documented shallow, precious metal-rich, exhalative sulphide deposits (Hannington, 1993) which underlined the requirement for a totally new deposit model.

Some profiles were included because of the potential for discoveries in British Columbia. For example, the classical Carlin-type gold model is based on deposits found only in the United States (mainly Nevada). Nonetheless, Poulsen (1996) identified favourable terranes in the Canadian Cordillera and a profile titled Carbonate-hosted disseminated Au-Ag was created (Schroeter and Poulsen, 1996). Although a number of deposits outside of the United States are Carlin-like, including the Golden Bear mine in British Columbia, it was not until 2009 that exploration drilling in the Keno Hill mining district in Yukon discovered a classical Carlin-type mineralized zone on the Rau property. Similarly, the discovery of a nickel-bearing, shale-hosted occurrence named the Nick in Yukon in the early 1990s led to developing a profile called Shale-hosted Ni-Zn-Mo-PGE with an eye to their future potential (Lefebure, 1995; Lefebure and Coveney Jr., 1995). The Talvivaara mine in Finland is this deposit type and opened in 2008. It is the world's first biological heap leach project for nickel and also produces zinc with the potential to recover other metals (Jowitt and Keays, 2011).

It was essential to include profiles describing deposits that seemed unique to British Columbia and that were excluded from lists such as Cox and Singer (1986). For example, the distinctive characteristics of a group of porphyry copper-gold deposits associated with alkalic intrusive and volcanic rocks (Porphyry Cu-Au: Alkalic) have guided mineral exploration in the province for more than 50 years (Barr et al., 1976). In the last couple of decades, similar copper-gold deposits have been widely recognized in New South Wales.

5. BCGS classification of mineral deposit profiles

In ancient times, deposits were classified on the basis of mining product. As a better understanding of ore deposits emerged, early miners learned how important knowing the shape or form of different types of deposits was to their discovery and extraction. Late in the nineteenth century and well into the twentieth, the emphasis in North America and Europe shifted largely to origins, particularly for metallic ores. More sophisticated classifications using genesis, host environment, plate tectonics and/or mineral systems have emerged over the last century and a half and they continue to evolve. Nonetheless, as noted by Jensen and Bateman (1979), "ever since Agricola first classified ore deposits, successive writers have attempted classification of mineral deposits, none of which has obtained unanimous endorsement". Despite progress in understanding the different types of mineral deposits and how they form, geologists have been frustrated that specific mineral deposit classification systems do not work well for all types of mineral occurrences and deposits (e.g., Guilbert and Park, 1986; Evans, 1993), likely reflecting the complexity of some mineral deposits and their ore-forming processes.

Based on work by Laznicka (1985) and the USGS (Cox and Singer, 1986), the BCGS adopted three indices to organize and list the mineral deposit profiles: deposit group, commodity, and earth material affinities. The deposit group index is a single-entry system using terms well known by economic geologists. The commodity index lists profiles by products and is a multiple entry index for deposits producing more than one commodity. The earth material affinity index uses lithology, surficial materials, and other terms and is also a multiple entry index.

5.1 Deposit group index

Deposit group index is used as the primary index for organizing the BCGS mineral deposit profiles. Profiles are grouped into broad families of deposit types using a letter designation (Table 1) using terms common to economic geologists, such as porphyry, industrial rocks, organic, placer and manto. The different group names reflect a variety of characteristics derived from associated Earth materials, environment, style of mineralization, orebody form, or use. The main groupings in Table 1 are further subdivided by number, creating an alphanumeric reference code for each deposit profile (Table 2). For example, C01 is the code for the surficial placers profile and C03 is the code for the marine placers profile in the same group. Where possible, individual profiles are placed adjacent to similar ones within deposit groups and between deposit groups. If the BCGS does not yet have a published profile for a deposit type, this is indicated by an asterisk after the code (e.g. B01*). The BCGS alphanumeric reference code for the deposit profiles is recorded in all tables and used to order the individual deposit profiles. Minor updates to some of the deposit profile codes and names originally presented by Lefebure et al. (1995) are recorded in Table 2, which also includes alternative deposit model names and example deposits.

For the convenience of readers familiar with the USGS deposit models from the 1980s and 1990s (e.g., Cox and Singer, 1986; Orris and Bliss, 1991; Orris, 1992; Orris and Bliss, 1992), the USGS model codes are also listed. As with the BCGS profiles, these codes are marked by an asterisk (39f*) to show that they were not published as of

1999. In a few cases Orris and Bliss (1991) have created a USGS model code (13g*, 27e, 25ka*) that also has been used by other USGS authors for a metallic mineral deposit; therefore, references to these three industrial mineral models are prefixed with IM (IM13g*, IM27e, IM25ka*).

Table 1. Mineral deposit group names used for the principal index for the profiles.

A – Organic	K – Skarn
B – Residual/surficial	L – Porphyry
C – Placer	M – Ultramafic/mafic association
D – Continental sedimentary and volcanic rocks	N – Carbonatites, kimberlites and lamproites
E – Sediment-hosted	O – Pegmatite
F – Chemical sediment	P – Metamorphic-hosted
G – Marine volcanic association	Q – Gems and semi-precious stones
H – Epithermal	R – Industrial rocks
I – Vein, breccia and stockwork	S – Other
J – Manto	

5.2 Commodity Index

The commodity index for the mineral deposit profiles provides another easy method for finding a particular deposit type or identifying which profiles relate to a specific commodity (Lefebure and Höy, 1996). This multiple entry index (Table 2) and has been updated to be consistent with all the deposit profiles presented herein. The mineral deposit profiles span a broad spectrum of commodities and mines that could potentially produce metals, coal, industrial minerals, gemstones and/or semi-precious stones. The profiles commonly list two or more commodities that can be primary products or by-products. Minor commodities that are produced by only one or two mines associated with a particular deposit profile are commonly not included. Similarly, by-products that have been produced by old mines related to a specific deposit profile may not be included if they are no longer considered to be economically attractive to extract.

5.3 Earth material affinities index

A third index characterizes the mineral deposit profiles according to the most commonly associated host materials, primarily rocks, but also unconsolidated surficial materials (Appendix 2). The earth materials affinities index can be particularly useful for mineral potential assessments where the bedrock geology is a key criterion for estimating the number of undiscovered deposits. This index only provides one to three associated types of earth materials per mineral deposit profile. For many profiles this does not capture all the associated earth materials, particularly those hosted by rocks. It is anticipated that as mineral deposit classifications start incorporating multi-hierarchical classifications that it will be more practical to capture all the associated earth materials relevant to a particular mineral deposit model.

6. Grade and tonnage data

As part of the mineral potential assessment of British Columbia, grade and tonnage data were compiled from the provincial MINFILE database for all mines and significant deposits in the province (Grunsky, 1995); data for 21 mineral deposit profiles were published by Lefebure and Höy (1996). Initially, these data were used to complement those by Singer et al. (1993). As the assessment progressed, British Columbia data were used where possible. Current resource data can be retrieved by deposit type in digital form from MINFILE, the BCGS mineral occurrence database.

7. Conclusions

This contribution compiles 120 mineral deposit profiles prepared between 1995 and 2012 that were previously only available in different publications. The profiles, which include metallic mineral, coal, industrial mineral and gemstone deposits, are categorized by deposit group, commodity, and earth material affinities. Standardized and concise descriptions provide details about geological characteristics, mineral exploration techniques, resource information, and concepts about deposit origin(s). Except for minor typographic corrections, the information in the profiles remains unchanged from the time of original publication. Although the content of some profiles is dated, all contain factual information that remains current; some of the profiles are as current today as when they were first published.

8. Acknowledgements

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The BCGS collaborated with geoscientists from the Geological Survey of Canada, the United States Geological Survey, universities, and the mineral exploration industry. These collaborations contributed greatly to quality and breadth of the profiles. In particular we thank Ken Dawson and Rod Kirkham (GSC), Dennis Cox, Paul Barton, and Ted Theodore (USGS), John Thompson (University of British Columbia), Felix Mutschler (Eastern Washington University), and James MacDougall (J.J. MacDougall and Associates Ltd).

For use in the provincial mineral potential assessment, Robert Brown, Nick Carter, Robert Helgason, and Ron McMillan classified about 10,000 of the better described mineral occurrences using the mineral deposit profiles, which provided a check on the effectiveness of the profiles for describing the complete array of mineral deposit types in British Columbia. The original group of profile editors at BCGS were: Z.D. Hora, T. Höy, D.V. Lefebure, G.E. Ray, and G.J. Simandl; Brian Grant and John Newell provided final editorial comments.

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Table 2. Mineral deposit profiles listed by deposit group.

Profile Code	Deposit Profile Name	Alternate Names	USGS. Model #
	A - Organic		
A01	Peat		- -
A02	Lignite	"Brown coal"	- -
A03	Sub-bituminous coal	Thermal coal, Black lignite	- -
A04	Bituminous coal	Coking coal, Thermal coal	- -
A05	Anthracite	Stone coal	- -
	B – Residual/Surficial/Supergene		
B01*	Laterite Fe	Gossan Fe	- -
B02*	Laterite Ni		38a
B03*	Laterite-Saprolite Au	Eluvial placers	38g
B04*	Bauxite Al	Lateritic bauxite	38b
B05	Residual kaolin	Primary kaolin	38h*
B06*	dropped - Fireclay		38i
B07*	Bog Fe, Mn, U, Cu, Au		- -
B08*	Surficial U	"Calcrete U"	- -
B09	Carbonate-hosted, nonsulphide Zn-Pb (supergene)	Karst-hosted Fe, Al, Pb-Zn	- -
B10*	Gossan Au-Ag	Residual Au; Precious metal gossans	- -
B11*	Marl		
B12	Sand and Gravel		
	C - Placer		
C01	Surficial placers	Placer Au-PGE-Sn-diamond-mag-gar-gems	39a to e
C02	Buried-channel placers	Paleochannel placers	39a to e
C03	Marine placers	Off-shore heavy mineral sediments	39f*?
C04*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	Quartz pebble conglomerate Au-U	29a
	D- Continental Sedimentary and Volcanic Rocks		
D01	Open-system zeolites		25oa
D02	Closed-basin zeolites		25ob
D03	Volcanic redbed Cu	Basaltic Cu	23
D04*	included in D05 as a subtype - basal uranium		- -
D05	Sandstone U±V	Roll front U, Tabular U, Basal U	30c
D06*	Volcanic-hosted U	"Epithermal" U, Volcanogenic U	25f
D07	Iron Oxide Cu±Au±P±REE	Olympic Dam type, Kiruna type	29b,25i

‘* An asterisk after the mineral deposit profile or the USGS model number indicates that there is no published description using the standardized format as shown in this document or by Cox and Singer (1986).

Profile Code	Global Examples Deposit (Province, State or Country)	British Columbia Examples
	A- Organic	Version 2.3
A01	Ireland, Ontario, New Brunswick	Fraser Delta, North Coast
A02	Estevan (Saskatchewan)	Skonun Point (Graham Island)
A03	Highvale (Alberta), Powder River Basin (Wyoming)	Hat Creek, Princeton
A04	Gregg River (Alberta), Sydney Coalfield (Nova Scotia)	Quintette, Bullmoose, Greenhills, Fording
A05	Pennsylvannia Coalfields, Canmore (Alberta)	Mt Klappan
	B - Residual/Surficial/Supergene	
B01*	Glenravel (Ireland)	
B02*	Riddle (Oregon), Mt. Vernon (Washington)	
B03*	Mt. Gibson (Australia), Akaiwang (Guyana)	
B04*	Pocos de Caldas (Brazil), Salem Hills (Oregon)	Florence (Sooke)
B05	Germany, North Carolina, Idaho	Lang Bay, Sumas Mountain
B06*		
B07*	Trois Riviéres (Québec)	Whipsaw Creek, Limonite Creek, Iron King
B08*	Flodelle Creek (Washington)	Prairie Flats
B09	Balmat (New York), Leadville (Colorado), Silesia-Cracow district (Poland)	Redbird, Reeves MacDonald, Annex
B10*	Rio Tinto (Spain)	Villalta
B11*		Cheam Lake (Chiliwack)
B12		
	C- Placer	
C01	North Saskatchewan River (Saskatchewan), Nome (Alaska)	Fraser River, Quesnel River, Graham Island
C02	Livingstone Creek (Yukon), Valdez Creek (Alaska)	Williams Creek, Otter Creek, Bullion mine
C03	New South Wales & Queensland (Australia)	Middlebank (north Vancouver Island)
C04*	Elliot Lake (Ontario), Witwatersrand (S. Africa)	Mulvehill
	D - Continental Sedimentary and Volcanic Rocks	
D01	Ash Meadows (California), John Day Formation (Oregon)	Princeton Basin, Cache Creek area
D02	Bowie (Arizona), Lake Magadi (Kenya)	
D03	Keewenaw (Michigan), Coppermine (Northwest Territories)	Sustut Copper, Shamrock, NH
D04*	not assigned	
D05	Colorado Plateau, Grants (New Mexico)	Blizzard, Tyee
D06*	Marysvale (Utah), Aurora (Oregon)	Rexspar, Bullion (Birch Island)
D07	El Romeral (Chile), Sue-Dianne (Northwest Territories)	Iron Range

Table 2. Mineral deposit profiles listed by deposit group.

Profile Code	Deposit Profile Name	Alternate Names	USGS. Model #
	E - Sediment-Hosted		
E01*	Almaden Hg		27b
E02	Carbonate-hosted Cu±Pb±Zn	Kipushi Cu-Pb-Zn	32c
E03	Carbonate-hosted disseminated Au-Ag	Carlin-type Au	26a,19c
E04	Sediment-hosted Cu-Ag-Co	Sediment-hosted stratiform Cu	30b
E05	Sandstone Pb		30a
E06	Bentonite	Volcanic clay, Soap clay	28e?*
E07	Sedimentary kaolin	"Secondary" kaolin	31k*
E08	Carbonate-hosted talc	Dolomite-hosted talc	18?i*
E09	Sparry magnesite	Veitsch-type, carbonate-hosted magnesite	18i*
E10*	Mississippi Valley-type barite±fluorite	Mississippi Valley-type barite	- -
E11*	Mississippi Valley-type fluorite±barite	Carbonate-hosted fluorite±barite	32d*
E12	Mississippi Valley-type Pb-Zn	Carbonate-hosted Pb-Zn, Appalachian Zn	32a/32b
E13	Irish-type carbonate-hosted Zn-Pb	Kootenay Arc-type Zn-Pb, Remac-type	- -
E14	Sedimentary exhalative Zn-Pb-Ag	Sedex, Sediment-hosted massive sulphide	31a
E15	Blackbird sediment-hosted Cu-Co	Sediment-hosted Cu-Co massive sulphide	24d
E16	Shale-hosted Ni-Zn-Mo-PGE	Sediment-hosted Ni	- -
E17	Sediment-hosted barite	Bedded barite	31b
E18	Carbonate-hosted, nonsulphide Zn (hypogene)	Willemite-dominant deposits, Zinc-oxides	- -
	F - Chemical Sediment		
F01	Sedimentary manganese		34b
F02	Bedded gypsum	Marine evaporite gypsum	35ae
F03	Gypsum-hosted sulphur	Frasch sulphur	- -
F04*	Bedded celestite		35aa*
F05*	Palygorskite	Attapulgite	34e*
F06*	Lacustrine diatomite	Diatomaceous earth, Kieselguhr	31s
F07	Sedimentary Phosphate	Upwelling-type phosphate	34c
F08*	Warm current-type phosphate		34d
F09*	Playa and Alkaline Lake Evaporites	Hydromagnesite	35ba,bmT
F10	Lake Superior & Rapitan types iron-formation		34a
F11	Ironstone	Minette ores	34f
	G - Marine Volcanic Association		
G01	Algoma-type iron-formation		28b
G02*	Volcanogenic Mn		24c
G03*	Volcanogenic anhydrite / gypsum		- -
G04	Besshi massive sulphide Cu-Zn	Kieslager	24b
G05	Cyprus massive sulphide Cu (Zn)		24a
G06	Noranda/Kuroko massive sulphide Cu-Pb-Zn		28a
G07	Subaqueous hot spring Ag-Au		- -

Profile Code	Global Examples Deposit (Province, State or Country)	British Columbia Examples

	E - Sediment-Hosted	Version 2.3
E01*	Almaden (Spain), Santa Barbara (Peru)	
E02	Tsumeb (Namibia), Kipushi (Zaire), Ruby Creek (Alaska)	
E03	Rau (Yukon), Carlin, Getchell & Cortez (Nevada)	Golden Bear
E04	Kupferschiefer (Germany), White Pine (Michigan)	Roo, Commerce, Chal 4
E05	Laisvall (Sweden), George Lake (Saskatchewan)	
E06	Black Hills (Wyoming), Rodalquilar (Spain)	Parton River, Princeton, Quilchena
E07	Cordova District (Alabama), Ozark Region (Missouri)	Sumas Mountain, Quinsam
E08	Treasure Mtn (Montana), Trimouns (France)	Red Mountain, Silver Dollar
E09	Eugui (Spain), Veitsch (Austria)	Mt. Brussilof, Driftwood Creek
E10*	Illinois - Kentucky, Italian Alps	Muncho Lake
E11*	Illinois - Kentucky, Italian Alps	Liard Fluorite
E12	Viburnum Trend (Missouri), Pine Point (Northwest Terr.)	Robb Lake, Monarch
E13	Navin, Lisheen & Tynagh (Ireland), Troya (Spain)	Reeves MacDonald, HB, Jersey, Duncan
E14	Mount Isa (Australia), Faro & Grum (Yukon)	Sullivan, Cirque, Driftpile
E15	Blackbird & Sheep Creek (Montana), Boleo (Mexico)	
E16	Nick (Yukon), Tianeshan & Zunyi (China)	
E17	Tea (Yukon), Magcobar (Ireland)	Kwadacha
E18	Abenab West (Namibia), Abu Samar (Sudan)	

	F - Chemical Sediment	
F01	Molongo (Mexico), Atasu (Kazakhstan)	
F02	Paris Basin (France), Appalachian Basins (New York)	Lussier River, Windermere
F03	Texas, Louisiana, Poland, Coronation (Alberta)	Trutch area
F04*	Lake Enon (Nova Scotia), Mexico, Germany	Kitsault Lake
F05*	Metalline Falls (Washington)	
F06	Juntura and Trout Ck Formations (Oregon)	Crownite Formation (Quesnel)
F07	Phosphoria Formation (Idaho), Meskala (Morocco)	Fernie synclinorium
F08*	Athabaska Basin (Saskatchewan), Florida	
F09*		Milk River
F10	Mesabi Ranges (Minnesota), Mackenzie Mountains (Yukon)	
F11	Clinton Formation (Alabama), France, Germany	Peace River region

	G - Marine Volcanic Association	
G01	Vermillion iron formation (Minnesota), Helen (Ontario)	Falcon, Lady A
G02*	Olympic Mountains (Washington), Nicoya (Costa Rica)	
G03*		Britannia, Falkland
G04	Besshi (Japan), Greens Creek (Alaska)	Goldstream, Windy Craggy, Standard
G05	Mavrovouni (Cyprus), Lasail (Oman)	Anyox camp, Chu Chua, Lang Creek?
G06	Horne & Millenbach (Québec), Kuroko District (Japan)	Britannia, Kutcho Creek, Myra Falls
G07	Osorezan (Japan)	Eskay Creek

Table 2. Mineral deposit profiles listed by deposit group.

Profile Code	Deposit Profile Name	Alternate Names	USGS. Model #
	H - Epithermal		
H01	Travertine	Tufa	35d*
H02	Hot spring Hg		27a
H03	Hot spring Au-Ag		25a
H04	Epithermal Au-Ag-Cu; high sulphidation	Acid-sulphate, qtz-alunite Au	25d
H05	Epithermal Au-Ag; low sulphidation	Adularia-sericite epithermal	25c
H06*	Epithermal Mn		25g
H07	Sn-Ag veins	Polymetallic Sn veins	25h, 20b
H08	Alkalic intrusion-associated Au-Ag	Alkalic intrusion-related Au, Au-Ag-Te	22b
H09	Hydrothermal clays	Kaolin, Alunite, Siliceous cap, Pyrophyllite	25lb*
	I - Vein, Breccia and Stockwork		
I01	Au-quartz veins	Mesothermal, Motherlode, saddle reefs	36a
I02	Intrusion-related Au pyrrhotite veins	Subvolcanic shear-hosted gold	- -
I03	Turbidite-hosted Au veins	Meguma type	36a
I04	Iron formation-hosted Au	Iron formation-hosted gold	36b
I05	Polymetallic veins Ag-Pb-Zn±Au	Felsic intrusion associated Ag-Pb-Zb veins	22c, 25b
I06	Cu±Ag quartz veins	Churchill-type vein Cu	?
I07*	Silica veins		- -
I08	Silica-Hg carbonate		27c
I09	Stibnite veins and disseminations	Simple and disseminated Sb deposits	27d,27e
I10	Vein barite		IM27e
I11	Barite-fluorite veins		26c*
I12*	W veins	Quartz-wolframite veins	15a
I13*	Sn veins and greisens		15b, 15c
I14	Five-element veins Ni-Co-As-Ag±(Bi,U)	Ni-Co-native Ag veins, cobalt-type veins	- -
I15	"Classical" U veins	Pitchblende veins, vein uranium	
I16	Unconformity-associated U	Unconformity-veins, Unconformity U	37a
I17	Cryptocrystalline ultramafic-hosted magnesite veins	Bone magnesite, Kraubath-type magnesite	- -
	J - Manto		
J01	Polymetallic manto Ag-Pb-Zn	Polymetallic replacement deposits	19a
J02	Manto and stockwork Sn	"Replacement Sn", Renison-type	14c
J03*	dropped - Mn veins and replacements	covered by I05 and J01	19b
J04*	Sulphide manto Au	Au-Ag sulphide mantos	- -

Profile Code	Global Examples Deposit (Province, State or Country)	British Columbia Examples
	H - Epithermal	Version 2.3
H01	Gardiner (Montana), Salida (Colorado), Lazio (Italy)	Clinton, Slocan, Deep River
H02	Sulphur Bank (California), Steamboat Springs (Nevada)	Ucluelet
H03	McLaughlin (California), Round Mountain (Nevada)	Brucejack, Cinola, Clisbako, Trout?
H04	El Indio (Chile), Nansatsu (Japan)	Westpine, Taylor-Windfall, Mt. McIntosh
H05	Comstock (Nevada), Sado (Japan)	Lawyers, Blackdome, Silbak Premier
H06*	Talamantes (Mexico), Gloryana (New Mexico)	
H07	Black Range (New Mexico), Potosi (Bolivia), Ashio (Japan)	D Zone and Lang Creek (Cassiar)
H08	Emperor (Fiji), Cripple Creek (Colorado), Zortman (Montana)	Flathead, Howell, Howe
H09	Cornwall (England)	Monteith Bay, Pemberton Hills
	I - Vein, Breccia and Stockwork	
I01	Alaska-Juneau (Alaska), Campbell, Dome (Ontario)	Bralorne, Erickson, Polaris-Taku
I02		Scottie, Snip, Johnny Mountain, Iron Colt
I03	Ballarat (Australia), Meguma (Nova Scotia)	Frasergold, Reno, Queen, Island Mountain
I04	Homestake (South Dakota)	
I05	Elsa (Yukon), Coeur d'Alene (Idaho), Creede (Colorado)	Silver Queen, Beaverdell, Silvana
I06	Nikolai (Alaska), Butte (Montana)	Davis-Keays, Churchill Copper, Bull River
I07*		Granby Point
I08	Red Devil? (Alaska), New Almaden (California)	Pinchi, Bralorne Takla, Silverquick
I09	Becker-Cochran (Yukon), Lake George (New Brunswick)	Minto, Congress, Snowbird
I10	Matchewan (Ontario), Jbel Ighoud (Morocco)	Parson. Brisco, Fireside
I11	St. Lawrence (Newfoundland), Mongolian fluorite belt	Rock Candy, Eaglet
I12*	Pasto Bueno (Peru), Carrock Fell (England)	
I13*	Cornwall (England), Lost River (Alaska)	Duncan Lake
I14	Cobalt camp (Ontario), Erzgebirge district (Germany)	
I15	Beaverlodge (Saskatchewan), Schwartzwalder (Colorado)	Purple Rose, Fisher, Dixie
I16	Rabbit Lake, Key Lake (Saskatchewan), Jabiluka (Australia)	
I17	Chalkidiky area (Greece), Kraubath (Austria)	Sunny, Pinchi Lake
	J - Manto	
J01	East Tintic district (Utah), Naica (Mexico)	Bluebell, Midway
J02	Renison Bell (Australia), Dachang district (China)	
J03*	Dropped	
J04*	Ketza River (Yukon)	Mosquito Creek, Island Mountain

Table 2. Mineral deposit profiles listed by deposit group.

Profile Code	Deposit Profile Name	Alternate Names	USGS Model #
	K - Skarn		
K01	Cu skarns		18a,b
K02	Pb-Zn skarns		18c
K03	Fe skarns		18d
K04	Au skarns		18f*
K05	W skarns		14a
K06	Sn skarns		14b
K07	Mo skarns		- -
K08	Garnet skarns		- -
K09	Wollastonite skarns		18g
	L - Porphyry		
L01	Subvolcanic Cu-Ag-Au (As-Sb)	Enargite Au, Transitional Au-Ag	22a/25e
L02*	Porphyry-related Au	Granitoid Au, Porphyry Au	20d
L03	Alkalic porphyry Cu-Au	Diorite porphyry copper	- -
L04	Porphyry Cu ± Mo ± Au	Calcalkaline porphyry	17,20,21a
L05	Porphyry Mo (Low F- type)	Calcalkaline Mo stockwork	21b
L06	Porphyry Sn	"Subvolcanic tin"	20a
L07	Porphyry W	Stockwork W-Mo	21c*
L08	Porphyry Mo (Climax-type)	Granite molybdenite	16
L09	Plutonic-related Au quartz veins & veinlets	Reduced intrusion-related gold deposits	- -
	M - Ultramafic / Mafic		
M01*	Flood Basalt-Associated Ni-Cu	Basaltic subvolcanic Cu-Ni-PGE	5a/5b
M02*	Gabbroid Stocks Ni-Cu	Tholeiitic intrusion-hosted Ni-Cu	7a
M03	Podiform chromite		8a/8b
M04	Magmatic Fe-Ti±V oxide deposits	Mafic intrusion-hosted Ti-Fe deposits	7b
M05	Alaskan-type Pt±Os±Rh±Ir	Zoned ultramafic, Uralian-type	9
M06	Ultramafic-hosted chrysotile asbestos	Serpentinite-hosted asbestos	8d
M07	Ultramafic-hosted talc-magnesite		8f*
M08	Vermiculite deposits		- -
	N – Carbonatites, Kimberlites and Lamproites		
N01	Carbonatite-associated deposits		10
N02	Kimberlite-hosted diamonds	Diamond pipes	12
N03	Lamproite-hosted diamonds		12
	O - Pegmatite		
O01*	Rare element pegmatite - LCT family	Zoned pegmatite (Li-Ce-Ta)	13a*,b*
O02*	Rare element pegmatite - NYF family	Niobium-Yttrium-Fluorine pegmatite	- -
O03*	Muscovite pegmatite	Mica-bearing pegmatite	13f*
O04*	Feldspar-quartz pegmatite	Barren pegmatite	IM13g,e*

Profile Code	Global Examples Deposit (Province, State or Country)	British Columbia Examples
	K - Skarn	Version 2.3
K01	Mines Gaspé (Québec), Carr Fork (Yukon)	Craigmont, Phoenix
K02	San Antonio (Mexico), Ban Ban (Australia)	Piedmont, Contact
K03	Shinyama (Japan), Cornwall (Pennsylvannia)	Tasu, Jessie, Merry Widow, HPH
K04	Fortitude (Nevada), Buckhorn Mountain (Washington)	Nickel Plate
K05	Cantung & Mactung (Yukon), Pine Creek (California)	Emerald Tungsten, Dimac
K06	Lost River (Alaska), JC (Yukon)	Daybreak
K07	Little Boulder Creek (Idaho), Mt. Tennyson (Australia)	Coxey, Novelty
K08		Crystal Peak
K09	Fox Knoll & Lewis (New York)	Mineral Hill, Rossland
	L - Porphyry	
L01	Lepanto (Philippines), Kori Kollo (Bolivia)	Equity Silver, Thorn
L02*	Marte & Lobo (Chile), Lihir (Papua New Guinea)	Snowfields
L03	Tai Parit (Philippines)	Afton, Copper Mountain, Galore Creek
L04	Chuquicamata & La Escondida (Chile)	Highland Valley, Gibraltar
L05	Quartz Hill (Alaska)	Endako, Kitsault, Glacier Gulch
L06	Llallagua (Bolivia), Potato Hills (Yukon)	
L07	Logtung (Yukon), Xingluokeng (China)	Boya
L08	Climax & Henderson (Colorado)	
L09	Dublin Gulch (Yukon), Fort Knox (Alaska),	
	M - Ultramafic / Mafic	
M01*	Noril'sk (Russia), Duluth (Minnesota)	
M02*	Lynn Lake (Manitoba), Kluane (Yukon)	Giant Mascot, Nickel Mountain
M03	Josephine ophiolite (Oregon), Coto (Philippines),	Castle Mountain, Scottie Creek
M04	Lac Tio & Magpie (Quebec), Tellnes (Norway)	Lodestone Mountain?, Tanglewood Hill?
M05	Red Mountain (Alaska), Tin Cup Peak (Oregon)	Tulameen Complex
M06	Thetford (Québec)	Cassiar, Kutcho
M07	Thetford & Magog (Québec), Deloro (Ontario)	
M08	Enoree (USA)	Fort Fraser area
	N – Carbonatites, Kimberlites and Lamproites	
N01	Palabora (South Africa), Mountain Pass (California)	Aley, Mount Grace tuff
N02	Kimberley & Premier (South Africa)	Cross
N03	Argyle (Australia)	
	O - Pegmatite	
O01*	Bikita Field (Zimbabwe), Blackhills (South Dakota)	
O02*	South Platte district (Colorado), Bancroft (Ontario)	
O03*	Rajahstan (India), Appalachian Province (USA)	
O04*	Buckingham (Québec)	

Table 2. Mineral deposit profiles listed by deposit group.

Profile Code	Deposit Profile Name	Alternate Names	USGS Model #
	P - Metamorphic-Hosted		
P01	Andalusite hornfels		- -
P02	Kyanite, muscovite, garnet in metasediments		- -
P03	Microcrystalline graphite	"Amorphous" graphite	18k
P04	Crystalline flake graphite		37f
P05	Vein graphite in metamorphic terrains	"Lump and chip" graphite	37g
P06	Corundum in aluminous metasediments		- -
	Q – Gems and Semi-Precious Stones (diamonds Under N)		
Q01	Jade		- -
Q02	Rhodonite		- -
Q03*	Agate		- -
Q04*	Amethyst		- -
Q05*	Jasper		- -
Q06	Columbia-type emeralds		31c
Q07	Schist-hosted emeralds	Exometamorphic emerald deposit	- -
Q08	Sediment-hosted precious opal	Australian-type opal	- -
Q09	Ultramafic-related corundum		- -
Q10	Alkali basalt/lamprophyre-hosted sapphire and ruby		- -
Q11	Volcanic-hosted precious opal		- -
	R - Industrial Rocks		
R01	Cement shale		- -
R02	Expanding shale		- -
R03	Dimension stone – granite		- -
R04	Dimension stone – marble		- -
R05*	Dropped (Dimension stone – andesite)	See R03	- -
R06	Dimension stone - sandstone		30d*
R07	Silica-rich rocks	High-silica quartzite	30e*
R08	Flagstone		- -
R09	Limestone		- -
R10	Dolomite		- -
R11	Volcanic ash/cinder and pumice		- -
R12	Perlite		IM25ka*
R13	Nepheline syenite		- -
R14	Alaskite		- -
R15*	Crushed rock	Road metal, Riprap, Railroad ballast	- -
	S - Other		
S01	Broken Hill type Pb-Zn-Ag±Cu	Shuswap-type, Ammeburg-type Pb-Zn	- -

Profile Code	Global Examples Deposit (Province, State or Country)	British Columbia Examples
	P - Metamorphic-Hosted	Version 2.3
P01	Bushveld (South Africa), Brittany (France)	Leech River
P02	Willis Mountain (Virginia), NARCO (Québec)	
P03	Keiserberg (Austria)	
P04	Lac Knife (Québec)	AA
P05	Calumet & Clot (Québec), Bogala (Sri Lanka)	
P06	Gallatin & Madison Counties (Montana)	
	Q - Gems and Semi-Precious Stones (diamonds under N)	
Q01		Cry Lake, Ogden Mountain
Q02		Hill 60, Arthur Point, Cassiar
Q03*		
Q04*	Thunder Bay (Ontario), Artigas (Uruguay), Maraba (Brazil)	
Q05*		
Q06	Chivor and Muzo districts (Columbia)	
Q07	Habachtal (Austria), Leysdorp (South Africa), Socoto (Brazil)	
Q08	Coober Pedy (Australia)	
Q09	Umba (Tanzania), Kinyki Hill (Kenya)	
Q10	Yogo Gulch (Montana)	
Q11		
	R - Industrial Rocks	
R01		Dunsmuir shale, Sumas Mountain
R02	Wabamun shales (Alberta)	Nanaimo shale, Saturna Island
R03	Riviére á Pierre (Québec), Black Hills (South Dakota)	Nelson Island
R04	Vermont, Alabama, Georgia	Marblehead, Anderson Bay (Texada Island)
R05		Haddington Island
R06*		Saturna Island, Newcastle Island
R07		Moberley, Nicholson
R08*	Southowram (England)	Salmo, Revelstoke
R09		Texada Island, Quatsino Belt
R10		Crawford Bay, Rock Creek
R11		Meagher Mountain, Buse Lake
R12		Frenier, Francois Lake
R13	Blue Mountain (Ontario)	Trident Mountain
R14	Spruce Pine alaskite (North Carolina)	
R15*		McAbbee, Gissome
	S- Other	
S01	Broken Hill (Australia), Aggeneys district (South Africa)	Cottonbelt, River Jordan, Ruddock Creek

A - Organic

Mineral Deposit Profiles

Profile Title		Authors
A01	Peat	Z.D. Hora, 2007
A02	Lignite	B.D. Ryan, 1995
A03	Sub-bituminous coal	B.D. Ryan, 1995
A04	Bituminous coal	B.D. Ryan, 1995
A05	Anthracite	B.D. Ryan, 1995

A01 - Peat

by Z.D. Hora[1]

Hora, Z.D., 2007. Peat. Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, mineral deposit profile, published on website, 4 p.

IDENTIFICATION

SYNONYMS: Sphagnum moss, horticultural peat, peat bog, humus peat, fen peatland, muskeg, organics, non-permafrost bogs.

COMMODITIES (BYPRODUCTS): Horticultural peat, pollution control peat, filtration peat, energy (fuel) peat.

EXAMPLES (British Columbia – Canada/International): Burns bog, Pitt River bog, Fort Nelson Lowland peats, Peace River Lowland peats; *Alberta, Quebec, New Brunswick, Ireland, Germany, Netherlands, Finland, Russia.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Peatlands are classified into two categories: bogs and fens.

Bogs receive their water only from precipitation and have low water flow, whereas fens are affected by mineral-rich ground and/or surface waters. Bogs have shallow water tables (generally about 50 cm below the peat surface). Land surfaces are generally poorly drained, level and may be slightly raised above the surrounding area. They may be treed. Peat bogs are acidic (pH below 4.5) and dominated by species of Sphagnum, feather moss, lichens, and ericaceous shrubs.

Fens also have water tables at or just above surface and land surfaces are gently sloping to almost level. The vegetation is dominated by sedges, reeds, brown mosses, Sphagnum moss and ericaceous shrubs.

TECTONIC SETTING: Unimportant. Peat deposit formation is dependent largely on climatic and terrain conditions.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Peat deposits occur in topographic depressions often caused by melting ice in glacial tills or flat plains, usually overlying relatively impermeable materials, such as glaciolacustrine sediments and clay-rich tills. They are common in areas with poorly organized drainage systems and can occur locally on gentle slopes where precipitation is high and evaporation low. Stable regional water tables, anaerobic conditions and decreased nutrient availability are important for peat development. These factors lead to a substantial decrease in decomposition rates and a net accumulation of peat.

AGE OF MINERALIZATION: In Canada, most peatlands have formed since the end of the last ice age, about 13,000 to 10,000 years BP. Significant peat formation typically occurred after large areas that had been inundated by glacial lakes had drained, or after oceanic and lacustrine areas were uplifted by the postglacial isostatic rebound of the land. In British Columbia, peatland development was slow until after the warm and dry mid-Holocene period terminated around 4000 to 5000 years ago.

HOST/ASSOCIATED ROCK TYPES: Peatland. Associated sediments are marl deposits; organic-rich sediments; gyjatta; diatomaceous earth; overlie a variety of surficial deposits including clay till, glaciolacustrine and glaciofluvial sediments, ice contact deposits, and alluvium.

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[1] Retired, British Columbia Geological Survey, Victoria, British Columbia, Canada

A01 - Peat

DEPOSIT FORM: Commonly, surface layers of weakly decomposed Sphagnum moss, up to several metres thick, are underlain by well decomposed sedge and/or Sphagnum peat, typically a few metres thick. In most deposits, the total depth of organic material is less than 10 metres. Some coalescing peat bogs can cover areas of several thousands of hectares in size.

TEXTURE/STRUCTURE: Peat is a soft, fibrous material with moisture content in its natural state of over 90%. Sphagnum moss has a high water-holding capacity (it can hold 15 to 20 times its weight in water), high cation exchange capacity, high pore space, low bulk density and high permeability.

ORE MINERALOGY: (Principal and *subordinate*): Sphagnum peat, sedge peat, shrub and root fragments. There are about 85 species of Sphagnum known in North America.

GANGUE MINERALOGY: (Principal and *subordinate*): Surface vegetation, stumps, sediment or marl interbeds.

ALTERATION MINERALOGY: Well decomposed sedge and/or brown peat moss (suitable as fuel peat).

WEATHERING: Decomposition of the organic matter is required to produce peat; various degrees of decomposition are preferred depending on the final product type.

ORE CONTROLS: The formation and localization of peat is a dynamic, continuous process, influenced by a number of factors, including climate and topography. The best quality Sphagnum peat develops as a slightly elevated dome that is raised above the water table. Boreal regions are the host of most peatlands in Canada.

GENETIC MODEL: Peatland formation is largely dependent on climatic and hydrogeologic factors. Peat accumulates in areas where water remains standing throughout the year due to a positive water balance. Organic material derived from vegetation builds up when the rate of accumulation is greater than the rate of decomposition. This balance is usually achieved in areas of temperate climate. Under higher temperatures, such as those in the tropics, vegetation growth is favoured but the rate of decomposition is rapid so that the accumulation of organic matter is low. Stabilized water levels, anaerobic conditions and decreased nutrient availability lead to a substantial decrease in decomposition rates, which results in the development of peat accumulating ecosystems. The rate of accumulation can be as much as 1-2 mm/year, but generally may average from 0.6-0.7 mm/ year in many Canadian peatlands.

ASSOCIATED DEPOSIT TYPES: Marl (B11), gyjatta, lacustrine diatomite (F06), glacial, glaciolacustrine and glaciofluvial sand and gravel deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: not applicable

GEOPHYSICAL SIGNATURE: Ground penetrating radar has been used successfully in Sweden and Alaska to obtain three-dimensional pictures of peat bogs.

OTHER EXPLORATION GUIDES: Organic deposits occur in topographic depressions, along drainage ways, particularly on nearly level areas with poor drainage, and also on some slopes where precipitation is high and evaporation is low, such as northern coastal areas in BC. Air photo interpretation and remote sensing can identify peat landforms on the surface but ground truthing is needed to establish the subsurface nature of the deposit. Ground investigations include evaluations of surface vegetation, depth of the peat, Von Post degree of decomposition, size of the deposit, pH of the peat, botanical composition and identification of moss species present.

A01 – Peat

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Published data on individual deposits are rare, but according to the Canadian Sphagnum Peat Moss Association, peat quality must meet market requirements regarding composition – the preferred composition is a weakly decomposed Sphagnum peat with a minimum content of shrubs and roots. The majority of producing sites have Sphagnum layers 1 to 4 metres thick. An aerial extent of 50 hectares is usually required, but some bogs may cover several thousands of hectares.

ECONOMIC LIMITATIONS: In North America, a thickness of 2 metres and an area of 50 hectares is generally considered the minimum for economic viability. The site must have good potential to build an enhanced drainage system, be close to infrastructure (particularly road access), and have a low-density tree cover. Local climate should have dry periods without much rain during the main harvest period.

END USES: Most of the peat is sold as compressed bales for use in the horticultural and nursery industries; some is used in soil mixes and other greenhouse and gardening products. Peat is important in environmental clean-up operations as absorbent and filtration media. Globally, about 13% is used as a fuel (*e.g.,* in Russia, Finland, Ireland and Germany).

IMPORTANCE: In Canada, peatlands comprise over 12% of the land surface area, although much of this area is not viable for peat production. Less than 0.02% of the surface area of Canada has been used for peat production. Canadian peat production averages 700,000 to 800,000 tonnes annually with a value over $90 million/year. The main producing provinces are New Brunswick and Quebec, with Alberta ranked third. British Columbia’s peat production was from the Fraser delta, which was mined out in the 1970s. Peat in Canada is produced from 45 deposit areas in 8 provinces; most of the production is exported to the USA and overseas, particularly Japan. Because of a steady growth of peat in Canada's boreal regions, over 50 million tonnes of peat accumulate every year in Canada compared to 700,000 to 800,000 tonnes annually produced. Reclamation and restoration of mined-out areas can be accomplished by impeding the drainage. Experience from eastern Canada indicates that in 5 to 20 years (depending on local circumstances) the mined-out areas can be restored into ecologically balanced systems.

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A02 - Lignite

by Barry Ryan[1]

Ryan, B.D., 1995. Lignite. In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 5–7.

IDENTIFICATION

SYNONYM: Brown coal.

COMMODITIES (BYPRODUCTS): Coal, coal liquids, (tar, gas, leonardite).

EXAMPLES (British Columbia - *Canada/International*): Hat Creek (092INW047); Skonun, Queen Charlotte Islands; Coal River (mapsheet 94M10W*); Estevan (Saskatchewan); Texas (USA)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Seams of brown to black coal hosted by clastic sedimentary rocks. It can still contain some imprints of the original vegetation. Wet and dense with a dull lustre. Slacks (disintegrates) on exposure to air.

TECTONIC SETTINGS: Stable continental basins; shelves on the trailing edge of continents; foreland (molasse) basins; back-arc basins; fault blocks, often associated with strike-slip movement to limit sediment influx.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: An area of slow sedimentation, in fresh water, with few or no marine incursions. Delta; shoreline swamp; raised swamp; lake; floating vegetation mats.

AGE OF MINERALIZATION: Quaternary; Tertiary; occasionally older.

ASSOCIATED ROCK TYPES: Sedimentary rocks exhibiting evidence of fresh and or shallow water deposition; carbonaceous mudstones; siltstones and sandstones, often with cross-stratification and other sedimentary structures of shallow water origin.

DEPOSIT FORM: Lignite seams generally conform with regional bedding; sometimes seams are deposited in areas of local subsidence such as fault-controlled blocks or sink holes in karst topography, in which case deposits may be lens shaped. Occasionally seams can be thickened/deformed by surface slump, glacial drift or faulting. Seams may pinch out or split on the regional scale.

TEXTURE/STRUCTURE: Lignite retains a dull matted appearance and is composed mainly of the lithotype huminite. It is banded and jointed. Footwall sediments are often penetrated by roots or weathered to clay (seatearth).

COAL SEAMS / ASSOCIATED MINERAL MATTER: Lignite is defined as coal with a R_{max} value of less than 0.4%. In outcrop it contains between 30 to 40% moisture. It usually contains a high percentage of the maceral vitrinite and lower percentages of fusinite and liptinite. Mineral matter occurs in the lignite seams as bands, as finely intermixed material of authogenic or detrital origin (inherent mineral matter) and as secondary material deposited in fractures and open spaces. Inherent mineral matter includes pyrite, siderite and kaolinite. It may be dissimilar to that of the surrounding rocks.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

A02 – Lignite

WEATHERING: Weathering of lignite reduces the calorific value by oxidizing the carbon-hydrogen complexes. Minerals such as pyrite oxidize to sulphates. Secondary carbonates are formed.

ORE CONTROLS: The regional geometry of coal seams is controlled by sedimentary features such as extent of the delta, trend of the shoreline, and trend of sand-filled river channels. Subsequent deformation, such as faulting and folding, is important for higher rank coals.

ASSOCIATED DEPOSIT TYPES: Peat (A01), sub-bituminous coal (A03), paleoplacers (C04).

COMMENTS: Lignite has the lowest rank of all classes of coal (Rmax less than 0.4 %).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Geochemistry is generally not used as a prospecting tool for lignite.

GEOPHYSICAL SIGNATURE: Lignite has a low density. Resistivity is variable but can be low for lignite. Surface geophysical techniques include direct-current profiling, refraction and reflection seismic and gravity. Subsurface or bore-hole techniques include gamma logs, neutron logs, gamma-gamma density logs, sonic logs, resistivity logs and caliper logs.

OTHER EXPLORATION GUIDES: Presence of: a down-slope coal bloom; nonmarine sediments; coal spar in the sediments; small oily seeps. Presence of lignite seams can also be detected by methane escaping through the surrounding sediments and burn zones where the lignite outcrop has burnt, baking the surrounding sediments.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The heat value of lignite is low. Gross heating value on a moist ash-free basis is 15 to 20 MJ/kg. Net useable heat will be lower because of the high moisture content and included mineral matter. Mine reserves range from tens to hundreds of million tonnes.

ECONOMIC LIMITATIONS: Lignite is a bulk commodity which is expensive to transport. The low heating value and tendency for spontaneous combustion usually restrict lignite to local uses. The ratio of tonnage to useable heat is low so that there is a large amount of waste material generated.

END USES: Steam generation in turbines for electrical generation. Feed for liquefaction and gasification.

IMPORTANCE: Major source of fuel used for local electrical power generation. Approximately 10 to 20 Mt of lignite per year are required to support 1 MW of power generation capability.

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A03 - Sub-bituminous Coal

by Barry Ryan[1]

Ryan, B.D., 1995. Sub-bituminous coal. In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 9–11.

IDENTIFICATION

SYNONYMS: Steam coal, thermal coal, black lignite.

COMMODITIES (BYPRODUCTS): Coal, coal liquids, (tar, gas).

EXAMPLES (British Columbia - *Canada/International*): Princeton (092HSE089), Tulameen (092HSE209), Quesnel (093B036), Tuya River (104J044); *Whitewood and Highvale mines (Alberta, Canada), Powder River Basin (USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Seams of black to brown coal hosted by clastic sedimentary rocks. The coal is banded dull and bright. Generally hard, sometimes the texture of the original vegetation is partially preserved.

TECTONIC SETTINGS: Stable continental basins; shelves on the trailing edge of continents; foreland (molasse) basins; back-arc basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: An area of slow sedimentation in fresh water with few or no marine incursions. Can be produced by fault blocks associated with strike-slip movement to limit sediment influx. Delta; shoreline swamp; raised swamp; lake; floating vegetation mats.

AGE OF MINERALIZATION: Often Tertiary but can be older.

HOST/ASSOCIATED ROCK TYPES: Sedimentary rocks exhibiting evidence of non-marine deposition. Carbonaceous mudstones, siltstones and sandstones are the most common, often with cross-stratification and other sedimentary structures formed in shallow water.

DEPOSIT FORM: Coal seams generally conform with regional bedding; sometimes seams are deposited in areas of local subsidence, such as fault-controlled blocks or sink holes in karst topography, in which case deposits may be lens shaped. Occasionally seams can be thickened/deformed by surface slump, glacial drift or faulting. Seams may pinch out or split on a local or regional scale.

TEXTURE/STRUCTURE: Sub-bituminous coal is usually composed mostly of clarain and vitrain. Footwall sediments are often penetrated by roots or weathered to clay (seatearth).

COAL SEAMS/ASSOCIATED MINERAL MATTER: Sub-bituminous coal has R_{max} values in the range of 0.4 to 0.6%. In outcrop it can contain up to 30 % moisture. It usually contains a high proportion of vitrinite and lesser amounts of fusinite and liptinite. Mineral matter is in the coal as rock bands, as finely intermixed material of authogenic or detrital origin (inherent mineral matter) and as secondary material deposited in fractures and open spaces. Inherent mineral matter includes pyrite, siderite and kaolinite.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

A03 - Sub-bituminous Coal

WEATHERING: Weathering of sub-bituminous coal reduces the calorific value by oxidizing the carbon-hydrogen complexes. Minerals in the mineral matter will also oxidize. Pyrite oxidizes to sulphates. Secondary carbonates are formed.

ORE CONTROLS: The regional geometry of the seam/seams is controlled by sedimentary features, such as the extent of the delta, trend of the shoreline, and trend of sand-filled river channels. Deformation (faulting and folding) is important in some deposits.

ASSOCIATED DEPOSIT TYPES: Lignite (A02); bituminous coal (A04), Shale-hosted Ni-Zn-Mo-PGE (E16), Phosphate - upwelling type (F07).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Geochemistry is generally not used as a prospecting tool for coal.

GEOPHYSICAL SIGNATURE: Coal has a low density. Resistivity is variable to high. Surface techniques include direct-current profiling, refraction and reflection seismic, and gravity. Subsurface or bore-hole techniques include gamma logs, neutron logs, gamma-gamma density logs, sonic logs, resistivity logs and caliper logs.

OTHER EXPLORATION GUIDES: Presence of: a down-slope coal bloom; coal spar; small oily seeps or methane escaping through the surrounding sediments. Zones where the coal outcrops have ignited and burnt to some depth underground.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Gross heating value on an ash-free moist basis is 20 to 27 MJ/kg. Net useable heat will be lower because of the high moisture content and the presence of ash. Mine reserves range up to hundreds of millions of tonnes. The sub-bituminous coal resources of B.C. Tertiary coal basins commonly range up to 200 Mt (Hat Creek exceptional with 1000 Mt).

ECONOMIC LIMITATIONS: Coal is a bulk commodity which is expensive to transport. The moderate heating value and tendency for spontaneous combustion means that sub-bituminous coal is usually used locally for electrical power generation. The ratio of tonnage to useable heat is low so that there is a larger proportion of waste material (water, fly ash and slag) generated when burnt than for higher rank coals.

END USES: Steam generation in turbines for electrical generation. Feed for liquefaction or gasification.

IMPORTANCE: Approximately 8 to 10 Mt of sub-bituminous coal is required to generate 1 MW per year.

REFERENCES

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A04 - Bituminous Coal

by Barry Ryan[1]

Ryan, B.D., 1995. Bituminous coal. In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 13–15.

IDENTIFICATION

SYNONYMS: Metallurgical coal, coking coal, humic coal.

COMMODITIES (BYPRODUCTS): Coal, coke, (coal liquids, tar, gas).

EXAMPLES (British Columbia - *Canada/International*): Line Creek (082GNE020), Quintette (093I 010, 011, 019, 020); *Sydney coalfield (Nova Scotia, Canada), Sydney coalfield (Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Seams of black coal hosted by clastic sedimentary rocks. Coal is banded bright and dull. Generally hard with well-developed cleats.

TECTONIC SETTINGS: Stable continental basins; shelves on the trailing edge of continents; foreland (molasse) basins; back-arc basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: An area of slow sedimentation in fresh water with few or no marine incursions. Can be produced by fault blocks associated with strike-slip movement to limit sediment influx. Delta; shoreline swamp; raised swamp; lake; floating vegetation mats.

AGE OF MINERALIZATION: Generally older than Tertiary; major deposits are Cretaceous, Permian or Carboniferous in age.

ASSOCIATED ROCK TYPES: Sedimentary rocks exhibiting evidence of non-marine deposition; carbonaceous mudstones; siltstones and sandstones often with cross-stratification and other sedimentary structures of fluvial/alluvial or deltaic origin.

DEPOSIT FORM: Coal seams generally conform with regional bedding; sometimes seams are deposited in areas of local subsidence, such as fault-controlled blocks. Seams may be thickened/deformed by faulting, folding and shearing. Seams may pinch-out or split on a local or regional scale.

TEXTURE/STRUCTURE: Bituminous coal is usually composed mostly of clarain and vitrain. Footwall sediments are often penetrated by roots or weathered to clay (seatearth).

COAL SEAMS/ASSOCIATED MINERAL MATTER: Bituminous coal has Rmax values in the range of 0.5 to 2.0%. In outcrop it can contain up to 15% moisture. It usually contains a high percentage of the maceral vitrinite; at higher ranks liptinite is difficult to detect; the amount of fusinite is variable. Mineral matter is in the coal seams as rock bands, as finely intermixed material of authogenic or detrital origin (inherent mineral matter) and as secondary material deposited in fractures and open spaces. Inherent mineral matter includes pyrite, siderite and kaolinite. It may be dissimilar to that of the surrounding rocks.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

A04 - Bituminous Coal

WEATHERING: Weathering of the bituminous coal reduces the calorific value by oxidizing the carbon-hydrogen complexes. It also destroys the agglomerating (coke making) properties. Minerals such as pyrite oxidize to sulphates. Secondary carbonates are formed. These transformations may also damage the coking properties.

ORE CONTROLS: The geometry of the seam/seams is controlled by sedimentary features, such as extent of the delta, trend of the shoreline, and trend of sand-filled river channels. Deformation (faulting and folding) is also important.

ASSOCIATED DEPOSIT TYPES: Sub-bituminous coal (A03), Anthracite (A05), Shale-hosted Ni-Zn-Mo-PGE (E16), Phosphate - upwelling type (F07).

COMMENTS: Bituminous coal is widely used for making coke by the steel industry because of its agglomerating properties.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Geochemistry is generally not used as a prospecting tool for coal.

GEOPHYSICAL SIGNATURE: Bituminous coal has a low density. Resistivity is variable to high. Surface techniques include direct-current profiling, refraction and reflection seismic, and gravity. Subsurface or bore-hole techniques include gamma logs, neutron logs, gamma-gamma density logs, sonic logs, resistivity logs and caliper logs.

OTHER EXPLORATION GUIDES: Presence of: a down-slope coal bloom; nonmarine sediments; coal spar. Presence of methane escaping through the surrounding sediments.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Numerous tests quantify the coking ability of bituminous coal, they measure rheology, melting and petrographic properties of the coal as well as the chemistry of the ash. The gross heating value of bituminous coal is 27 to 33 MJ/kg on an ash-free moist basis. Net useable heat will be lower because of the presence of ash. Mine tonnages generally range from 10 to 1000 Mt.

ECONOMIC LIMITATIONS: Coal is a bulk commodity which is expensive to transport. Bituminous coal has a high market value because of its coking properties and high heating value. The ratio of tonnage to useable heat is good so that there is a lower proportion of waste material (such as water, fly ash and slag) generated than for other ranks of coals.

END USES: Coke; steam generation in turbines for electrical generation.

IMPORTANCE: Generally bituminous coal is used for coke making, weathered and non-agglomerating bituminous coal is utilized for power generation. Only source for coke used in the steel industry.

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Smith, G.G. (1989): Coal Resources in Canada; *Geological Survey of Canada,* Paper 1989-4, 146 pages.

A05 - Anthracite

by Barry Ryan[1]

Ryan, B.D., 1995. Anthracite. In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 17–19.

IDENTIFICATION

SYNONYMS: Hard coal, stone coal, smokeless fuel.

COMMODITIES: Coal, carbon.

EXAMPLES (British Columbia - *Canada/International)*: Klappan (104H 020, 021, 022), Panorama South (104A 082)*; Canmore (Alberta, Canada), Pennsylvania coalfields (USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Seams of black coal hosted by clastic sedimentary rocks. Coal is well cleated with bright and dull bands. Anthracite often exhibits a high lustre and is not dusty.

TECTONIC SETTINGS: Stable continental basins; shelves on the trailing edge of continents; foreland (molasse) basins; back-arc basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: An area of slow sedimentation in fresh water with few or no marine incursions. Can be produced by fault blocks associated with strike-slip movement to limit sediment influx. Delta; shoreline swamp; raised swamp; lake; floating vegetation mats.

AGE OF MINERALIZATION: Generally older than Tertiary; major deposits are Cretaceous, Permian or Carboniferous in age.

HOST/ASSOCIATED ROCK TYPES: Sedimentary rocks exhibiting evidence of non-marine deposition; carbonaceous mudstones; siltstones and sandstones often with cross-stratification and other sedimentary structures formed in fluvial/alluvial deltaic settings.

DEPOSIT FORM: Anthracite seams generally conform with regional bedding. Seams are often thickened/deformed by faulting, folding, shearing and thrusting. Seams may pinch-out or split on a local or regional scale.

TEXTURE/STRUCTURE: Anthracite is usually composed mostly of the lithotypes clarain and vitrain.

COAL SEAMS/ASSOCIATED MINERAL MATTER: Anthracite has R_{max} values over 2.0%. In outcrop anthracite can contain up to 5 % moisture. It usually contains a high percentage of the maceral vitrinite but because of the high rank the rheological and chemical differences between vitrinite and the inert macerals are small. Liptinite is difficult to identify at the anthracite rank. Mineral matter is in the coal seams as rock bands, as finely intermixed material of authogenic or detrital origin (inherent mineral matter) and as secondary material deposited in fractures and open spaces. Inherent mineral matter includes pyrite, siderite and kaolinite. It may be dissimilar to that of the surrounding rocks.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

A05 - Anthracite

WEATHERING: Weathering of anthracite reduces the calorific value by oxidizing the carbon-hydrogen complexes. Minerals in the mineral matter will also oxidize. Pyrite oxidizes to sulphates. Secondary carbonates are formed.

ORE CONTROLS: Deformation (folding, faulting and thrusting) is very important. The regional geometry of the seam/seams may also be influenced by sedimentary features, such as extent of delta, trend of the shoreline, and trend of sand-filled river channels.

ASSOCIATED DEPOSIT TYPES: Bituminous coal (A04), Shale-hosted Ni-Zn-Mo-PGE (E16), Phosphate - upwelling type (F07).

COMMENTS: Anthracite is the highest rank coal. At this rank agglomerating properties have been destroyed and heating value decreased somewhat from the maximum obtained by low-volatile bituminous coal. Anthracite releases little smoke when burnt.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Geochemistry is generally not used as a prospecting tool for anthracite.

GEOPHYSICAL SIGNATURE: Anthracite has a low density. Resistivity is variable to high. Surface techniques include direct-current profiling, refraction and reflection seismic, and gravity. Subsurface or bore-hole techniques include gamma logs, neutron adsorption logs, gamma-gamma density logs, sonic logs, resistivity logs and caliper logs.

OTHER EXPLORATION GUIDES: Presence of down-slope coal bloom; fresh water depositional structures; coal spar. Presence of anthracite seams can also be detected by escaping methane.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The heat value of anthracite is good and similar to that of medium-volatile bituminous coal. Gross heating values are 30 to 33 Mj/Kg on an ash-free moist basis. Net useable heat will be lower because of the presence of ash. The mine reserves of anthracite generally range from 10 to 100 million tonnes. They are generally smaller than the strip or open pit thermal or metallurgical coal mines.

ECONOMIC LIMITATIONS: Anthracite is a bulk commodity which is expensive to transport. Anthracite as low-ash lumps can be more than twice as valuable as bituminous coal, in which case it is shipped widely. Sold as fine anthracite briquettes with a moderate ash content, it has about the same dollar value as bituminous thermal coal.

END USES: Source for carbon. Specialized smelting applications, smokeless fuel for heating.

IMPORTANCE: As low-ash large lumps it is an important source of carbon in the chemical industry.

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Smith, G.G. (1989): Coal Resources in Canada; *Geological Survey of Canada,* Paper 1989-4, 146 pages.

B - Residual/Surficial/Supergene

	Profile Title	Authors
B01*	Laterite Fe	
B02*	Laterite Ni	
B03*	Laterite-Saprolite Au	
B04*	Bauxite Al	
B05	Residual kaolin	Z.D. Hora, 2007
B06*	dropped - Fireclay	
B07*	Bog Fe, Mn, U, Cu, Au	
B08*	Surficial U	
B09	Carbonate-hosted, Nonsulphide Zn-Pb (supergene)	S. Paradis and G.J. Simandl, 2011
B10*	Gossan Au-Ag	
B11*	Marl	
B12	Sand and Gravel	Z.D. Hora, 2007

‘* An asterisk after the alphanumeric code indicates that the mineral deposit profile is not in this compilation.

B05 - Residual Kaolin

by Z.D. Hora[1]

Hora, Z.D., 2007. Residual kaolin: mineral deposit profile. Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, pp. 2.

IDENTIFICATION

SYNONYMS: Primary kaolin, china clay, chinastone.

COMMODITIES (BYPRODUCTS): Kaolin (sometimes silica sand, construction aggregate, mica).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Lang Bay (092F 137), Sumas Mountain (092GSE004), Buse Lake (092INE123); *Spruce Pine district (North Carolina, USA), Germany, Cornwall, Saxony, France, Czech Republic, Ukraine.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: In situ alteration (or kaolinization) of feldspathic rocks, such as granite, gneiss, syenite, arkose and leucocratic volcanic ash, by tropical or sub-tropical weathering into kaolinite saprolite. Weathered zones may thicken considerably where sheer and fracture zones or hydrothermally altered zones act as conduit for groundwater of meteoric origin.

TECTONIC SETTINGS: Continental and continental margin setting. Stable continental basins and lowlands, foreland basins and shelves with grabens and downfaulted blocks.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High rate of chemical weathering with low rate of physical erosion, basement composed of feldspathic rocks and their weathered or altered equivalents, with ground water circulation. Lacustrine basins and tropical swamp environment. Kaolinization should be taking place in areas lacking physical erosion.

AGE OF MINERALIZATION: Globally, most of producing deposits are of Carboniferous to Lower Tertiary age. Kaolinite can be of any post Late Paleozoic age, and is forming currently in some tropical regions.

HOST/ASSOCIATED ROCK TYPES: Feldspathic rocks of metamorphic origin – gneisses (Denmark, Spain, Ukraine), schists and phyllites (Germany, South Africa, Australia), granitic intrusions (North Carolina, Saxony, Cornwall, Czech Republic), arkoses and arkosic sandstones (Czech Republic, Germany, France) or volcanic ash (Buse Lake, Czech Republic) / Laterite, bauxite.

DEPOSIT FORM: Slab, irregular mantle, trough. Weathered crust – saprolite with intensity and depth of kaolinization depending on permeability of the original host. Along faults, mylonitic and hydrothermally altered zones the kaolinic weathering can reach a depth of over 200 metres. The depth of the economically viable zone is quite variable and usually up to 50 metres as it depends on local subsidence, such as fault-controlled blocks, the original surface morphology and host rock permeability.

ORE MINERALOGY [Principal and *subordinate*]: Kaolinite, halloysite, *dickite, nakrite*

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, sometimes feldspar, *mica, pyrite, siderite, tourmaline, zircon, rutile*

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B05 - Residual Kaolin

ALTERATION MINERALOGY: Basic mineralogy is not changed by alteration, but it may remove dark organic matter, iron hydroxide, carbonate, residual feldspar and in general improve the quality of kaolinite resource.

WEATHERING: High alumina minerals like diaspor, gibbsite, boehmite. Lateritic and/or pisolitic bauxite.

PRODUCT CONTROLS: The intensity of kaolinization and the presence of detrimental components, particularly iron and titanium are important. Some deleterious contamination depends on the type of original host rock and presence of minerals, such as biotite.

GENETIC MODELS: The alteration results from surface weathering and groundwater movement below the surface. Kaolin minerals form under physical and chemical conditions at relatively low temperature and pressure. The most common parent minerals are feldspars and muscovite. Feldspathic rocks weather readily to kaolinite and quartz under favourable conditions of high rainfall, rapid drainage, temperate to tropical climate, a low water table and adequate water movement to leach soluble components. Heat producing radiogenic decay within some granites may lead to convective circulation of heated groundwater and enhance the alteration process.

ASSOCIATED DEPOSIT TYPES: Sedimentary kaolin (E07), residual bentonite, coal (A02, A03, A04), silica sand, expanding shale (R02), cement "shales" (R01), some vermiculite deposits.

COMMENTS: Some deposits have a multiple process of kaolinization, where hydrothermal alteration was overprinted by residual weathering. Cornwall and New Zealand are two examples. In both cases the residual overprint resulted in improved kaolin quality.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Absence of sodium and potassium, increase in aluminum and silica.

GEOPHYSICAL SIGNATURE: Seismic and resistivity techniques are successfully used in kaolin exploration. Conductive clays respond to resistivity and low clay density provide enough contrast for seismic survey. Aerial electromagnetic survey can delineate weathered profile even under tens of metres thick overburden.

OTHER EXPLORATION GUIDES: Regional unconformities, coal and basal claystone in sedimentary basins.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Residual deposits have in general 15 to 20% kaolin recovery. Different end uses have specific requirements on the quality of processed kaolin. This may include presence of impurities, like iron hydroxides, titanium dioxide, sodium and potassium, some other clay minerals, brightness and particle size. Because of the need for sophisticated processing to obtain a quality commercial product, present commercial producers operate plants with capacity from 50,000 tonnes of processed kaolin per year and up.

ECONOMIC LIMITATIONS: Distribution of kaolin deposits globally is very uneven. Therefore, the trade in processed kaolin is routinely crossing both the continents and oceans. In North America, for example, the west coast paper industry is importing large quantities of kaolin from eastern states like South Carolina and Georgia. Also, processed kaolin from Brazil is currently selling in Europe and Asia. Replacement by other minerals is limited to only some end uses.

B05 - Residual Kaolin

END USES: The annual US production of kaolin is in the order of 9 million tonnes per year. About half of kaolin in North America is used by paper industry, and about 25% in variety of ceramics. The rest is used in a numerous other end uses, like filler in plastics, rubber, and paints, cosmetics and pharmaceutics, catalyst and catalyst carrier, silicon chemicals, specialty cement, and refractory products.

IMPORTANCE: Important kaolin source worldwide, less in North America because of large secondary kaolin deposits in Alabama, Georgia and South Carolina.

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B09 - Carbonate-hosted, Nonsulphide Zn–Pb (supergene)

by S. Paradis[1] and G.J. Simandl[2]

Paradis, S., and Simandl, G.J., 2011. Carbonate-hosted, nonsulphide Zn (supergene) mineral deposit profile B09: In: Geological Fieldwork 2010, Ministry of Forests, Mines and Lands, British Columbia Geological Survey, Paper 2010-1, pp. 211–216.

IDENTIFICATION

SYNONYMS: Zinc-oxides, Calamines, Galman.

COMMODITIES (BYPRODUCTS): Zn, Pb (Ag, Cu, barite, Cd).

EXAMPLES (British Columbia - *Canada/International*): Redbird (MINFILE 082FSW024), Lomond (MINFILE 082FSW018), Reeves MacDonald (MINFILE 082FSW026), Annex (MINFILE 082FSW219), Caviar (MINFILE 082FSW060), HB (MINFILE 082FSW004), Oxide (MINFILE 082FSW022), Cariboo Zinc (which comprises Canopener, DeBasher (MINFILE 093A 050), Flipper Creek, Dolomite Flats, Main (MINFILE 093A 065), Gunn, and Que (MINFILE 093A 062); *Leadville (Colorado, USA), Balmat (New York, USA), Sierra Mojada, Mapimi (Mexico), Accha, Mina Grande (Peru), Ariense (Brazil), Tynagh, Silvermines and Galmoy (Ireland), La Calamine (Belgium), Reocin (Spain), Silesia-Cracow district (Poland), San Giovanni (Italy), Lavrion (Greece), Touissit (Morocco), Um Gheig (Egypt), Zamanti district (Turkey), Jabali (Yemen), Angouran, Mehdiabad, Irankuh, Kuh-e-Surmeh (Iran), Shaimerden (Kazakhstan), Skorpion (Namibia), Padaeng (Thailand), Long Keng (Myanmar), Cho Dien (Vietnam), Jinding, Qiandong Shen Shen (China), Magellan (Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Nonsulphide deposits are commonly hosted in carbonate rocks. The main minerals are hemimorphite, smithsonite, hydrozincite, cerussite, Fe-oxyhydroxides (including goethite), and hematite. The deposits are broadly divided into three subtypes: the more common – 1) direct replacement and 2) wallrock replacement; and the less common – 3) residual and karst-fill. Direct replacement deposits have similar shape as the sulphide protore from which they are derived and may contain vestiges of sulphide mineralization. Wallrock replacement deposits are located at various distances from the protore, have simpler mineralogy and higher Zn/Pb ratio than direct replacement deposits, and occur as irregular masses encrustations, tabular bodies, and open-space fillings. Residual and karst-fill deposits form generally small, high grade, irregular bodies of partly consolidated material that may have detrital component. Some nonsulphide deposits may share characteristics of more than one of these subtypes.

TECTONIC SETTING(S): Supergene nonsulphide deposits derived from Mississippi Valley-type (MVT) and Irish-type deposits are located in carbonate platform settings, typically in relatively undeformed orogenic foreland rocks, commonly in foreland thrust belts inboard of clastic rock-dominated passive margin sequences, and in continental rift systems. Those derived from sedimentary exhalative (SEDEX) deposits are located in intracratonic or continental margin environments in fault-controlled basins and troughs. Volcanic-hosted massive sulphide (VHMS)-derived supergene nonsulphide deposits are emplaced under extensional crustal regime, such as oceanic or back-arc spreading ridges, continental rifts, back-arc basins, oceanic ridges close to continental margins, and rift environment within, or perhaps behind, an oceanic or continental margin arc.

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B09 - Carbonate-hosted, Nonsulphide Zn–Pb (supergene)

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Hostrocks of supergene nonsulphide Zn-Pb deposits are mostly deposited in platform successions within shallow and deep water environments. The nonsulphide deposits are found in both arid and tropical environments; however, many of the best supergene nonsulphide deposits recognized to date formed in semi-arid environments. Some are found in cold, wet climates at higher latitudes.

AGE OF MINERALIZATION: Ages of nonsulphide mineralization are commonly poorly constrained. Ore formation coincides with or postdates the exhumation of the hostrocks and generally postdates the main tectono-metamorphic event. Most of nonsulphide zones are comparable to those of the related Cretaceous to late Tertiary *(i.e.,* Paleocene to Pliocene) primary sulphides (*i.e.* stratabound zones and/or and younger times.

HOST / ASSOCIATED ROCK TYPES: Dolostone, limestone, dolomitized limestone and argillaceous carbonate are the most common hostrocks. Siliciclastic rocks, such as calcsilicate rocks, carbonaceous black shale, siltstone, cherty argillite, quartz-rich conglomerate and arkosic meta-arenites, and volcaniclastic and metasedimentary rocks are also potential hosts.

DEPOSIT FORM: The direct replacement deposits (also referred to as “red ores”) occur as a) irregular and poorly defined masses that replaced primary sulphides and carbonate hostrocks (Figure 1), whereby selective replacement within specific horizons may yield stratabound morphologies; and b) veins and open-space fillings within primary breccias of sulphide mineralization and carbonate hostrocks (Figure 2), where the morphologies of the nonsulphide zones are comparable to those of the related primary sulphides (*i.e.* stratabound zones and/or crosscutting pipes, fracture-fill zones, veins). The depth of oxidation can be variable from a few metres to several hundred metres. The wallrock replacement deposits are Zn-rich irregular and lens-shaped or tabular (subvertical to subhorizontal) bodies adjacent to or distal to direct replacement bodies. The residual and karst-fill deposits occur as accumulations of ferruginous, “earthy” and hemimorphite-clay mixtures, within karst cavities that cut through the replacement or open-space filling mineralization. These deposits have, irregular geometry, and can form high-grade nonsulphide bodies. Geometry is controlled by basement topography.

TEXTURE / STRUCTURE: Nonsulphides form irregular stratabound masses, pods or lenses; breccias of sedimentary and tectonic origin, disseminations, fracture fill, and veins are also very common. Due to intense oxidation, the primary textures of sulphides and hostrock are often obscured. Ore textures are varied and complex, ranging from massive to highly brecciated, from compact to powdery and from vuggy to dense. Nonsulphide minerals occur as earthy to crystalline aggregates replacing primary sulphides and/or carbonate hostrocks (Figures 3 and 4). They form crusts, concretions, and stalactites on outer surfaces, and botryoidal, colloform and crystalline aggregates of euhedral and subhedral crystals in intergranular voids, cavities, fractures, and breccias.

ORE MINERALOGY (Principal and subordinate): Smithsonite, hemimorphite, hydrozincite, sauconite, cerussite, anglesite, litharge, pyromorphite, mimetite, and plumbojarosite, *minrecordite, zincian aragonite, willemite, goslarite, loseyite, descloizite, hetaerokite, hydrohetaerolite, chalcophanite, hopeite, aurichalcite, woodruffite, tarbuttite, scholzite*. Where the sulphide-bearing protolith was not entirely converted to nonsulphides, primary sulphides remain intermixed with the nonsulphide minerals to form “mixed ores”. The primary sulphides may contain anglesite-coated nodules of galena and remnants of sphalerite. Chalcocite, malachite, and azurite are present in some deposits.

GANGUE MINERALOGY (Principal and subordinate): Carbonates (dolomite, calcite, aragonite), hematite, goethite, other Fe-oxyhydroxides, *gypsum, minor quartz*.

B09 - Carbonate-hosted, Nonsulphide Zn–Pb (supergene)

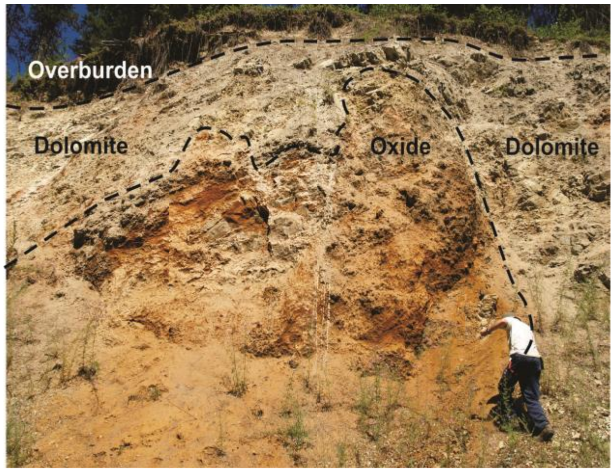

Figure 1. Lomond deposit; a supergene direct replacement nonsulphide deposit, British Columbia.

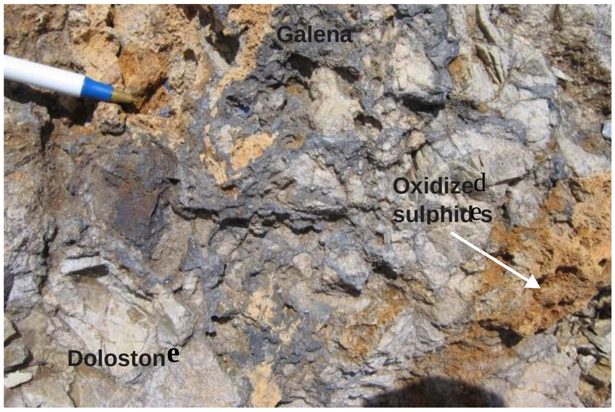

Figure 2. Galena and nonsulphides forming part of a vein-breccia system crosscutting the host dolostone, Cariboo Zinc property, east-central British Columbia.

Figure 3. Hemimorphite-rich mineralization, Oxide deposit, southeastern British Columbia. The hemimorphite replaced the carbonate groundmass.

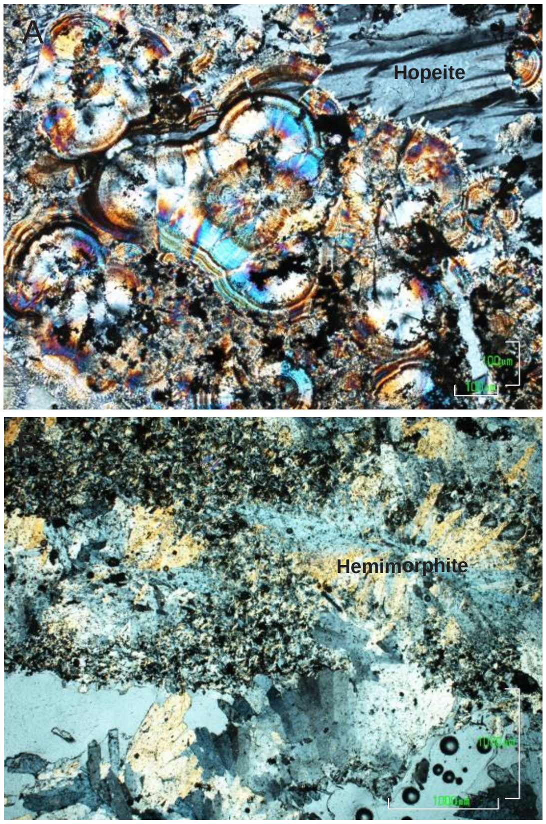

Figure 4. Microphotographs (polarised light) of A) concentric aggregates of radiating crystals of hemimorphite replacing the carbonate groundmass and tabular crystals of hopeite filling up crosscutting veinlets, and B) aggregates of tabular crystals of hemimorphite lining cavities.

Figure 5. Typical bright red stain caused by reaction of “Zinc Zap” solution with zinc-rich mineralization, east-central British Columbia.

B09 - Carbonate-hosted, Nonsulphide Zn–Pb (supergene)

ALTERATION MINERALOGY: Coarse crystalline dolomite spatially associated with MVT-type protore may survive in proximity to nonsulphide deposits and contrast with regional finely crystalline dolostone. Local alteration may also include silicification and rare secondary barite, both a result of the alteration and breakdown of feldspar (*e.g.*, Skorpion). The sulphide weathering and near surface alteration of protore corresponds to formation of supergene mineralization.

WEATHERING: The nonsulphide mineralization forms by weathering of sulphides. Multicyclic oxidation and leaching of nonsulphides is a part of the ore-forming process and may affect even previously formed wallrock replacement bodies (see genetic model). Such bodies may be gradually converted into porous brown to reddish smithsonite intergrown with hemimorphite. Further leaching may result in mixture of hemimorphite, sauconite, hematite- or goethite-dominated iron oxides, and hematitic chalcedonic silica, and ultimately transformed into a barren goethite-chalcedonic silica rock.

ORE CONTROLS: Most favourable conditions for oxidation are achieved in hot, arid or semiarid climates, which maximize the quantity of metals available for transport by supergene solutions. Sedimentary successions containing carbonate rocks are the most common regional hosts for nonsulphide lead and zinc deposits. In general, the oxidation of the protore takes place above water table. Karst, faulting, fracturing and to lesser extend porosity are important in enhancing the depth and intensity of the oxidation. Major faults represent channels for oxygenated solutions and permit oxidation to depths exceeding 500 m. Faults also increase the reactive surface of hostrocks (*i.e.* provoking changes in pH and Eh). Direct replacement deposits are confined to protore envelope. Wallrock replacement orebodies are commonly located near the level of the paleo and/or present water table.

GENETIC MODEL: Supergene nonsulphide Zn-Pb deposits form when base metal sulphide mineralization is subject to intense weathering and metals are liberated by the oxidation of sulphide minerals. The formation of nonsulphide minerals is influenced by the composition, size and morphology of the preexisting sulphide body. During the formation of a direct replacement deposit, primary ore (protore) is oxidized, and base metals pass into solution and are redistributed and trapped within space originally occupied by the protore. If the base metals liberated by the oxidation of sulphides are not trapped locally, they are transported by percolating waters down and/or away from the sulphide protore, and under favourable geological conditions may form wallrock replacement deposits. Wallrock replacement deposits can be located in proximity to protore or several hundreds of metres away. Lead is less mobile in the supergene environment than zinc, so in general, it is left behind as relict galena nodules and lead carbonate or lead sulphates. Wallrock replacement deposits tend to have higher Zn content and higher Zn/Pb ratios than direct replacement deposits. Residual and karst-fill deposits are formed as accumulations of mechanically and/or chemically transported zinc-rich material in karstic cavities or lows in basement topography. Some nonsulphide zinc deposits are assigned a hypogene origin. These deposits are characterized by willemite or willemite-franklinite-zincite assemblages (Hitzman *et al.*, 2003) and formed at higher in areas lacking deep weathering. Where residual sulphide oxidation is taking place, soil gas geochemical techniques temperatures than the supergene deposits. Their temperature of formation is estimated from less than 100° to nearly 300°C.

ASSOCIATED DEPOSIT TYPES: Mississippi Valley-type Pb-Zn (E12), Irish-type carbonate-hosted Zn-Pb (E13), sedimentary exhalative Pb-Zn-Ag (E14), veins, and Pb-Zn skarns (K02); rarely volcanic-hosted massive sulphide (G04 to G06).

COMMENTS: British Columbia has prospective strata for supergene nonsulphide deposits in the miogeoclinal carbonate platform rocks of the Ancestral North America continental margin and in pericratonic rocks of the Kootenay terrane. The association of many known carbonate-hosted nonsulphide zones with directly underlying massive sulphide orebodies, in combination with nonsulphide mineralogical characteristics, suggests that a large proportion of known nonsulphide mineralized zones in southern and central British Columbia are of the direct replacement type.

B09 - Carbonate-hosted, Nonsulphide Zn–Pb (supergene)

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Colorimetric field test for secondary zinc minerals (“Zinc Zap”) is very useful (Figure 5). Portable hand-held x-ray fluorescence spectrometry was successfully tested in British Columbia on supergene nonsulphide Pb-Zn deposits. Depletion in Zn, Pb, Cu, Fe, and Mn in and around former Zn-bearing sulphide gossans. Readily detectable positive anomalies of Zn and Pb in residual soils and stream sediments; elevated concentrations of Cu, Fe, Ag, Mn, As, and Cd can also be detected. Analysis of heavy mineral concentrates (identification of Zn-Pb nonsulphides) in stream and overburden may be effective in areas lacking deep wethering. Where residual sulphide oxidation is taking place, soil gas geochemical techniques (SO2 surveys) may be an applicable exploration technique. Many supergene minerals, such as hydrozincite and smithsonite, give distinct spectral responses in the short-wave infrared portion of the spectrum. Hyperspectral imaging holds promise as a useful tool for accurate mapping of structures, lithologies, and alteration.

GEOPHYSICAL SIGNATURE: There is no simple approach to use geophysical methods in exploration for nonsulphide-bearing Pb-Zn. The mineralogy, textures, homogeneity, friability, porosity, and degree of saturation by water vary widely. These properties affect the density, resistivity, magnetic susceptibility, and seismic properties of the rocks. Interpretation methodologies may be district specific. Where sulphide mineralization is present at depth, methodology used in exploration for MVT, VHMS, and SEDEX deposits applies.

OTHER EXPLORATION GUIDES: Most of the supergene nonsulphide base metal deposits are derived from the oxidation, or near-surface weathering, of primary carbonate-hosted sulphide deposits, such as Mississippi Valley-type, sedimentary exhalative, Irish-type or vein-type deposits and, to lesser extent, Pb-Zn skarns and rarely volcanic-hosted massive sulphide. Any carbonate-hosted, sulphide zinc district that has undergone geochemically mature weathering in semiarid to wet climatic (or paleoclimatic) conditions and concomitant tectonic uplift and/or water table depression is prospective for supergene nonsulphide deposits. Within these settings, exploration could be further focused on areas where favourable water table level, optimum oxido-reduction conditions, permissive hydrological characteristics (permeability and porosity of the hostrocks, karsts, and fracture and fault zones), rocks with ability to control the pH of the metal-bearing solutions, topography and slow(?) rate of uplift, coexisted. Discovery of outcropping supergene Zn-Pb nonsulphide deposits depends on recognition of common nonsulphide ore minerals. Areas not affected by glaciation have higher potential to contain preserved, soft, nonsulphide deposits than glaciated ones.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Tonnages for nonsulphide Zn-Pb deposits range from <1 Mt to 50 Mt with grades of 2% to more than 30% Zn. If mixed ores are considered, some deposits and districts have tonnages comparable to world-class sulphide deposits. Skorpion (Namibia) has 60 Mt of mixed resource grading 6–8% Zn and 1–2% Pb, and 24.6 Mt of oxide resource grading 10.6% Zn. Mehdiabad (Iran) has a mixed oxide-sulphide resource of 218 Mt grading 7.2% Zn, 2.3% Pb, and 51 g/t Ag. Direct replacement nonsulphide Zn-Pb deposits could be also significant sources of Pb, as illustrated by the exploitation of the Magellan deposit, which has ore reserves of 8.5 Mt grading 7.12% Pb.

ECONOMIC LIMITATIONS: The economic value of nonsulphide ores is dependent on the physical setting of individual deposit, the specific characteristics of the mineralogical association and the nature of the gangue minerals. The large, near-surface deposits are amenable to high volume, open pit mining. Underground mining is less common. Depending on the type of ore and mineralogy, a dedicated processing plant may be required. However, there is also the possibility that limited quantities of zinc-rich carbonates or silicate-bearing material (with low levels of impurities) may be used by conventional smelters as a sweetener (instead of Ca carbonate that is commonly used to control the pH) or as source of silica; this should be investigated.

B09 - Carbonate-hosted, Nonsulphide Zn–Pb (supergene)

IMPORTANCE: Nonsulphide deposits were the main source of zinc prior to the 1930s. Following the development of differential flotation and breakthrough in smelting technology, the mining industry turned its attention almost entirely to sulphide ores. Today, most zinc is derived from sulphide ore. The nonsulphide deposits provided roughly 7% of the world's zinc production in 2009. The successful operation of a dedicated processing plant at the Skorpion mine to extract zinc, through direct acid leaching, solid-liquid separation, solvent extraction and electro winning from nonsulphide ore has attracted more attention to these types of deposits. These deposits are attractive targets because they are characteristically low in lead, sulphur and other deleterious elements, offer low-cost onsite production, and are environmentally friendly.

ACKNOWLEDGMENTS

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B12 - Sand and Gravel

by Z.D. Hora[1]

Hora, Z.D., 2007. Sand and gravel, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey mineral deposit profile published on website, 5 p.

IDENTIFICATION

SYNONYMS: Aggregate, granular deposits, fluvial and glaciofluvial sediments, ice-contact deposits, outwash, alluvial sand and gravel, beach sand and gravel.

COMMODITIES (BYPRODUCTS): All-purpose construction aggregate, special fill, railroad ballast (sometimes gold, platinum group elements, garnet, ilmenite, cassiterite, gemstones – diamond, emerald, ruby and sapphire, spinel).

EXAMPLES (British Columbia - *Canada/International*): Colwood Delta, Coquitlam Valley, Sechelt, Stuart River esker complex, *small deposits almost everywhere*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Surficial sediment of sand and gravel deposited as a stream channel fill, fan or delta, usually in late-glacial or post-glacial period. Deposition may have occurred in contact with glacier ice (*e.g.*, esker, kame complexes, crevasse fillings), or beyond the ice margin (*e.g.*, outwash plain, raised delta).

TECTONIC SETTING: Generally unimportant. Sand and gravel deposits occur in high-energy stream sediments in all tectonic belts. In coastal areas, isostatic or tectonic uplift produces raised landforms that are readily mined.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Advancing glaciers incorporate significant quantities of bedrock and surficial materials that are freed during glacial melting and transported by meltwater downstream. Sand and gravel deposits can be divided into glaciofluvial sediments: mainly eskers, crevasse fill and kame complexes and outwash, and fluvial/alluvial sediments that form stream channel deposits, terraces, alluvial fans and deltas. In the early stages of deglaciation, meltwater streams deposited deltaic accumulations where high-energy water flow suddenly entered low-energy lacustrine or marine environments. Those deposits were lifted up during isostatic rebound and can be found along the BC coastline up to 200 metres above present sea level. In the BC interior, raised deltaic gravels and sands are granular facies of glaciolacustrine silts in basins (*e.g.* the Okanagan Valley, Rocky Mountain Trench, or Kamloops and Prince George areas). Alluvial fills in present drainage channels are usually reworked products of earlier glaciofluvial sediments.

AGE OF MINERALIZATION: Mainly Holocene and Pleistocene in glaciated areas, Holocene to Tertiary in unglaciated regions. Pre-Holocene sand and gravel deposits in glaciated terrain in Canada are not usually preserved. In British Columbia, older sand and gravel sediments occur locally (*e.g.*, in the lower part of the sequence in the Coquitlam Valley and in most gravel pits on Saanich Peninsula).

HOST/ASSOCIATED ROCK TYPES: Usually poorly to moderately well-sorted pebble, cobble and/or boulder gravel with variable proportions of fine- to coarse-grained sand; deltaic deposits locally interbedded with glaciomarine or glaciolacustrine silts and clays; ice–proximal glaciofluvial deposits commonly interbedded with till or glaciogenic debris flow deposits; fluvial sands and gravels often overlain by floodplain silts and organic deposits.

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[1] Retired, British Columbia Geological Survey, Victoria, British Columbia, Canada

B12 - Sand and Gravel

DEPOSIT FORM: Depending on their origin, sand and gravel deposits may exhibit a variety of shapes and geomorphic forms including: floodplains, terraces (raised valley-side benches), fans (cone-shaped) and deltas (triangular in plane view) and glaciofluvial kames (irregular hills or hummocks), eskers (ridges up to tens of kilometres long), outwash plains and raised deltas.

TEXTURE/STRUCTURE: Particle size decreases as stream energy decreases and with distance of transport. Particle roundness also decreases with transport distance. In high-energy environments, the deposits are generally more poorly sorted. Internal structure varies with the type of deposit as follows:
Channel and terrace deposits: mainly trough cross-bedded sand and/or gravel sequences; cut-and-fill structures common; capped by floodplain silts, fine sands and organics.
Alluvial delta: usually sand-dominated, grading out into silts and clays; interbedded organic silts and peats common in the topset.
Alluvial fan: poorly sorted sands and gravels, often with diamicton interbeds; crude bedding dips toward the valley centre, generally fining down-dip and from the fan centre to the sides.
Glaciofluvial delta: coarse-grained, steeply dipping, foreset beds; underlain by fine-grained bottomset beds; often capped by fining-up channel-fill (topset) sequences.
Kames and eskers: poorly sorted sands to boulder gravels; commonly with collapse features and kettle holes.

ORE MINERALOGY (Principal and *subordinate*): Composition of aggregate particles depends on the source areas. Provenance is also a major factor in determining the quality of the resulting aggregate product. Bedded and schistose rocks usually provide lower quality products, while massive igneous rocks and metamorphic rocks, such as gneisses and quartzites, produce better quality aggregate. In sedimentary source areas, limestones and cemented sandstones are better than shales, siltstones or weak sandstones.

GANGUE MINERALOGY (Principal): Clay and silt particles and organic pockets must be separated by screening and washing the final product. Also, cobbles and boulders have to be removed or separated and processed by crushing.

ALTERATION MINERALOGY: Soft and weak rocks are a deleterious component of every type of construction aggregate. Prolonged weathering may weaken some otherwise competent rock types. This is particularly true for older Pleistocene and Tertiary deposits in glaciated areas, and for all deposits in non-glaciated areas. Percolating groundwater may result in coating of gravel particles with calcium carbonate, clay or iron hydroxides. Such coatings may negatively affect the strength and durability of bonding with cement in concrete structures.

WEATHERING: Soft and weak rocks and those with high porosity are sensitive to increased physical weathering and deterioration.

ORE CONTROLS: The composition of the bedrock in the source area has a major impact on aggregate quality. A variety of factors influence the usability of granular sediment for individual products, which frequently have distinct quality requirements. Quality of construction aggregate for particular end uses is controlled by a number of physical and chemical parameters specified in ASTM and CSA Standards. The main factors influencing suitability for different end uses are the relative proportions of competent rock types, components reactive with cement like chert, other amorphous silica varieties, volcanic glass, sulphides and organics like peat. Other important criteria include the absence of clay and silt; clean clast surfaces; isometric shapes and granulometric composition. Sometimes in the absence of a quality aggregate, some granular deposits can be improved by more sophisticated processing. Use of a different type or higher proportion of cement in a concrete mix may be another solution.

GENETIC MODEL: Sand and gravel deposits are deposited by high-energy streams draining continental areas, mainly during deglaciation. The main source of the granular material is melting glacier ice containing large quantities of eroded bedrock and sediment. This outwash material is transported by flowing water and deposited in a variety of landforms with granular material as a main component.

ASSOCIATED DEPOSIT TYPES: Placer deposits of gold, PGE, gemstones and garnet (C01, C02, C03).

COMMENTS: Quarried crushed aggregate is an alternative to sand and gravel. Dredging of off-shore sand and gravel or deposits in river channels is taking place locally in British Columbia.

B12 - Sand and Gravel

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: none

GEOPHYSICAL SIGNATURE: Ground penetrating radar can delineate the geometry, structure and thickness of granular deposits provided they are not overlain by clay or clay-rich till. Shallow seismic and resistivity surveys can help outline the thickness and homogeneity of a granular deposit, particularly the presence of clay layers or till, and depth of the groundwater level.

OTHER EXPLORATION GUIDES: Remote sensing and air photo interpretation are used to identify the granular landforms.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grade is determined by ASTM or CSA specifications and can be highly variable, depending on location and intended use. Tonnage also can vary widely. For example, even a small deposit of a few hundred thousand tonnes may be an important source for local use in populated areas. Such a deposit, however, must contain aggregate that does not require complicated processing. Similar examples are borrow pits used in road construction and maintenance. Large, sophisticated operations, like B.C. tidewater pits (*e.g.*, Colwood, Port Mellone, Sechelt, Jervis Inlet) that produce a variety of special products and supply more distant markets, can have tens of millions of tonnes of resource.

ECONOMIC LIMITATIONS: In populated areas, the main limiting factors for developing aggregate resource are availability of land and support of the local community. Transportation costs are often the main economic factor controlling deposit development and may favour the development of hard rock crushing operation closer to the market.

END USES: A broad variety of construction products including ‘pit run’ for general uses and fill, natural stone for buildings and roads, crushed rock for landscaping, road bases, asphalt, gravel driveways and parking lots, concrete aggregate, drainage gravel, and specialty sands, such as those used for sandblasting and masonry sand for mortar and stucco.

IMPORTANCE: Sand and gravel are the main, basic construction materials for building cities and infrastructure. British Columbia uses between 40 and 50 million tonnes of aggregate annually in construction. Building an average family home requires about 100 tonnes of aggregate; for a school it takes approximately 15,000 tonnes; for 1 kilometre of 4-lane highway between 40 and 60 thousand tonnes of aggregate are needed.

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C - Placer

Mineral Deposit Profiles

	Profile Title	Author
C01	Surficial placers	V.M. Levson, 1995
C02	Buried-channel placers	V.M. Levson and T.R. Giles, 1995
C03	Marine placers	V.M. Levson, 1995
C04*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

C01 - Surficial Placers

by Victor M. Levson[1]

Levson, V.M., 1995. Surficial placers. In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 21–23.

IDENTIFICATION

SYNONYMS: Holocene placer deposits; terrace placers; fluvial, alluvial, colluvial, eolian (rare) and glacial (rare) placers.

COMMODITIES (BYPRODUCTS): Au, PGEs and Sn, {locally Cu, garnet, ilmenite, cassiterite, rutile, diamond and other gems - corundum (rubies, sapphires), tourmaline, topaz, beryl (emeralds), spinel - zircon, kyanite, staurolite, chromite, magnetite, wolframite, sphene, barite, cinnabar}. Most of the minerals listed in brackets are recovered in some deposits as the principal product.

EXAMPLES (British Columbia - *Canada/International*): Fraser River (Au), Quesnel River (Au), Tulameen district (PGEs); *North Saskatchewan River (Au, Alberta, Canada), Vermillion River (Au, Ontario,Canada), Rivière Gilbert (Au, Québec, Canada), Klondike (Au, Yukon, Canada), Rio Tapajos (Au, Brazil), Westland and Nelson (Au, New Zealand), Yana-Kolyma belt (Au, Russia), Sierra Nevada (Au, California, USA), Goodnews Bay(PGE, Alaska, USA), Emerald Creek (garnet, Idaho, USA), Rio Huanuni and Ocuri (Sn, Bolivia), Sundaland belt (Sn, Thailand).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Detrital gold, platinum group elements and other heavy minerals occurring at or near the surface, usually in Holocene fluvial or beach deposits. Other depositional environments, in general order of decreasing importance, include: alluvial fan, colluvial, glaciofluvial, glacial and deltaic placers.

TECTONIC SETTINGS: Fine-grained, allochthonous placers occur mainly in stable tectonic settings (shield or platformal environments and intermontane plateaus) where reworking of clastic material has proceeded for long periods of time. Coarse, autochthonous placer deposits occur mainly in Cenozoic and Mesozoic accretionary orogenic belts and volcanic arcs, commonly along major faults.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Surficial fluvial placer concentrations occur mainly in large, high-order, stream channels (allochthonous deposits) and along bedrock in high-energy, steep-gradient, low-sinuosity, single-channel streams (autochthonous deposits). Concentrations occur along erosional surfaces at the base of channel sequences. Alluvial fan, fan-delta and delta deposits are distinct from fluvial placers as they occur in relatively unconfined depositional settings and typically are dominated by massive or graded sands and gravels, locally with interbedded diamicton. Colluvial placers generally develop from residual deposits associated with primary lode sources by sorting associated with downslope migration of heavy minerals. Glaciofluvial and glacial placers are mainly restricted to areas where ice or meltwater has eroded pre-existing placer deposits. Cassiterite, ilmenite, zircon and rutile are lighter heavy minerals which are distributed in a broader variety of depositional settings.

AGE OF MINERALIZATION: Mainly Holocene (rarely Late Pleistocene) in glaciated areas; generally Tertiary or younger in unglaciated regions.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

C01 - Surficial Placers

HOST/ASSOCIATED ROCK TYPES: Well sorted, fine to coarse-grained sands; well rounded, imbricated and clast-supported gravels.

TEXTURE/STRUCTURE: Grain size decreases with distance from the source area. Gold typically fine grained (< 0.5 mm diameter) and well rounded; coarser grains and nuggets rare, except in steep fluvial channel settings where gold occurs as flattened flakes. Placer minerals associated with colluvial placer deposits are generally coarser grained and more angular.

ORE MINERALOGY (principal and *subordinate*): Au, PGE and cassiterite (*Cu, Ag and various industrial minerals and gemstones*).

GANGUE MINERALOGY: Quartz, pyrite and other sulphides and in many deposits subeconomic concentrations of various heavy minerals, such as magnetite and ilmenite.

ALTERATION MINERALOGY: Fe and Mn oxide precipitates common; Ag-depleted rims of Au grains increase in thickness with age.

ORE CONTROLS: In fluvial settings, placer concentrations occur at channel irregularities, in bedrock depressions and below natural riffles created by fractures, joints, cleavage, faults, foliation or bedding planes that dip steeply and are oriented perpendicular or oblique to stream flow. Coarse-grained placer concentrations occur as lag concentrations where there is a high likelihood of sediment reworking or flow separation, such as at the base of channel scours, around gravel bars, boulders or other bedrock irregularities, at channel confluences, in the lee of islands and downstream of sharp meanders. Basal gravels over bedrock typically contain the highest placer concentrations. Fine-grained placer concentrations occur where channel gradients abruptly decrease or stream velocities lessen, such as at sites of channel divergence and along point bar margins. Gold in alluvial fan placers is found in debris-flow sediments and in interstratified gravel, sand and silt. Colluvial placers are best developed on steeper slopes, generally over a weathered surface and near primary lode sources. Economic gold concentrations in glaciofluvial deposits occur mainly along erosional unconformities within otherwise aggradational sequences and typically derive their gold from older placer deposits.

GENETIC MODEL: Fluvial placers accumulate mainly along erosional unconformities overlying bedrock or resistant sediments such as basal tills or glaciolacustrine clays. Basal gravels over bedrock typically contain the highest placer concentrations. Overlying bedded gravel sequences generally contain less placer minerals and reflect bar sedimentation during aggradational phases. Frequently the generation of more economically attractive placer deposits involves multiple cycles of erosion and deposition.

ASSOCIATED DEPOSIT TYPES: Fluvial placers commonly derive from hydrothermal vein deposits and less commonly from porphyry and skarn deposits. PGE placers are associated with Alaskan-type ultramafics (M05). Allochthonous fluvial placers are far traveled and typically remote from source deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalous concentrations of Au, Ag, Hg, As, Cu, Fe, Mn, Ti or Cr in stream sediments. Au fineness (relative Ag content) and trace element geochemistry (Hg, Cu) of Au particles can be used to relate placer and lode sources.

GEOPHYSICAL SIGNATURE: Ground penetrating radar especially useful for delineating the geometry, structure and thickness of deposits with low clay contents, especially fluvial terrace placers. Shallow seismic, electromagnetic, induced polarization, resistivity and magnetometer surveys are locally useful. Geophysical logging of drill holes with apparent conductivity, naturally occurring gamma radiation and magnetic susceptibility tools can supplement stratigraphic data.

C01 - Surficial Placers

OTHER EXPLORATION GUIDES: Panning and other methods of gravity sorting are used to identify concentrations of gold, magnetite, hematite, pyrite, ilmenite, chromite, garnet, zircon, rutile and other heavy minerals. Many placer gold paystreaks overlie clay beds or dense tills and in some camps these ‘false bottom’ paystreaks are important.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits are typically high tonnage (0.1 to 100 Mt) but low grade (0.05-0.25 g/t Au, 50-200 g/t Sn). Placer concentrations are highly variable both within and between individual deposits.

ECONOMIC LIMITATIONS: The main economic limitations to mining surficial placer deposits are typically low grades and most deposits occur below the water table. Environmental considerations are also an important limiting factor as these deposits often occur near, or within modern stream courses.

IMPORTANCE: Placer gold deposits account for more than two-thirds of the world's gold reserves and about 25% of known total production in British Columbia. Recorded placer production has represented 3.5% of B.C.’s total gold production in the last twenty years. Prior to 1950, it was approximately 160 000 kg. Actual production was significantly larger. Placer mining continues to be an important industry in the province with annual average expenditures of more than $30 million over a survey period from 1981 to 1986. Shallow alluvial placers also account for a large part of world tin (mainly from SE Asia and Brazil) and diamond (Africa) production.

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C02 - Buried-Channel Placers

by Victor M. Levson and Timothy R. Giles

Levson, V.M. and Giles, T.R., 1995. Buried-channel placers. In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 25–28.

IDENTIFICATION

SYNONYMS: Paleoplacer deposits; paleochannel deposits; fluvial and alluvial placers.

COMMODITIES (BYPRODUCTS): Mainly Au and PGE {also Cu, Ag, garnet, cassiterite, rutile, diamond and other gems: corundum (rubies, sapphires), tourmaline, topaz, beryl (emeralds), spinel; zircon, kyanite, staurolite, chromite, magnetite, ilmenite, barite, cinnabar}. Most of the minerals listed in brackets are recovered as byproducts in some mines.

EXAMPLES (British Columbia and *Canada*/*International*): Williams Creek (Au, 093H 119), Bullion (Au, 093A 025), Lightning Creek (Au, 093H 012), Otter Creek (Au, 104N 032), Spruce Creek (Au, 104N 034); *Chaudière Valley (Au, Québec, Canada), Livingstone Creek (Au, Yukon, Canada), Valdez Creek (Au, Alaska, USA), Ballarat (Au, Victoria, Australia), Bodaibo River (Au, Lena Basin, Russia), Gibsonville (Sn, New South Wales, Australia), Ringarooma (Sn , Tasmania, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Detrital gold, platinum group elements and other heavy minerals occurring in buried valleys (typically with at least several metres of overlying barren material, usually till, clay or volcanic rocks), mainly as channel-lag and gravel-bar deposits. See description of surficial placers (C01) for general information about alluvial placer deposits.

TECTONIC SETTINGS: Coarse-grained, paleochannel placer Au deposits occur mainly in Cenozoic and Mesozoic accretionary orogenic belts and volcanic arcs, commonly along major faults that may also control paleodrainage patterns. PGE-bearing deposits commonly associated with accreted and obducted oceanic terranes. Fine-grained paleoplacers also may occur in stable tectonic settings (shield or platformal environments) where reworking of clastic material has proceeded for long periods of time.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Mainly incised paleochannels in mountainous areas including: high-gradient (generally >0.05, less commonly >0.1), narrow bedrock-floored valleys (paleogulches); high-level, abandoned tributary valleys with intermediate gradients (typically 0.01 to 0.1); large, buried trunk valleys (on the order of 100 m deep, a few hundred metres wide and >1 km long) with low channel gradients (generally <0.02 in mountainous reaches and <0.001 in plateau areas); channels buried in modern alluvial valleys with gradients similar to the modern streams. The first two settings are dominated by high-energy, low-sinuosity, single-channel, coarse-grained autochthonous placer deposits, whereas the latter two are characterized by autochthonous and allochthonous placers deposited in wandering gravel-bed river, braided stream and alluvial fan environments. In most paleochannels, coarse-grained placer concentrations occur mainly along channel floors or along other erosional surfaces such as at the base of cut-and-fill sequences; in meandering stream environments finer grained placers also occur along point bar margins and in other areas of slack water.

AGE OF MINERALIZATION: Tertiary and Pleistocene. Older paleoplacers (excepting the Proterozoic Witwatersrand placers) are rare, due to poor long-term preservation of deposits in high-relief, subaerial environments. Pleistocene paleoplacer deposits in British Columbia generally predate at least the last glaciation.

C02 - Buried-Channel Placers

HOST/ASSOCIATED ROCK TYPES: Coarse (pebble to boulder), rounded gravels (or conglomerate), commonly with sandy interbeds or lenses. Gravels usually imbricated, clast supported, open work or with a sandy matrix, and typically with abundant resistant rock types (quartzite, vein quartz, chert, basalt, granite) and minor, less resistant, lithologies (shale, siltstone, schist, etc.). Au placers are commonly associated with rock types hosting epithermal or mesothermal vein deposits. PGE placers occur with ultramafic hostrocks. Paleoplacers can be buried under a variety of materials, including glacial till, glaciolacustrine silts and clays, glaciofluvial sands and gravels, marine sediments and basalt flows.

DEPOSIT FORM: Highly variable and laterally discontinuous; paystreaks typically thin (< 2 m), lens shaped and tapering in the direction of paleoflow; usually interbedded with barren sequences.

TEXTURE/STRUCTURE: Typically well rounded, flattened flakes or plates of low sphericity; coarse, more spherical nuggets common in high-gradient channels; fine (flour) gold common in distal stream reaches; evidence of primary crystal structure very rare.

ORE MINERALOGY (principal and *subordinate*): Au nuggets, flakes and grains and PGE minerals, (*Cu, Ag, and various industrial minerals and gemstones*).

GANGUE MINERALOGY: Quartz, pyrite and other sulphides and in many deposits subeconomic concentrations of various heavy minerals, especially magnetite and ilmenite.

ALTERATION MINERALOGY: Fe and Mn oxide precipitates common. Clay alteration of unstable clasts and matrix in some deposits.

ORE CONTROLS: Dominant controls on the geographic distribution of ore include the location of paleodrainage channels, proximity to bedrock sources, and paleorelief. Paleochannels are locally controlled by faults and less resistant rock units. Stratigraphically, placers accumulate mainly at the base of erosional successions along unconformities overlying bedrock or resistant sediments such as basal tills or glaciolacustrine clays. Overlying bedded gravel sequences generally contain less placer minerals and reflect bar sedimentation during aggradational phases. Sedimentologic factors controlling placer accumulations are discussed in Profile C01 (Surficial Placers).

GENETIC MODEL: For an explanation of formation of alluvial placers see surficial placers (C01). Placer deposits are buried when base level rises or channel abandonment occurs. Factors inducing these changes include glaciation, volcanism, stream capture and cutoff, or rising sea level.

ASSOCIATED DEPOSIT TYPES: Paleochannel placer deposits are associated with alluvial fan and fan-delta paleoplacer deposits in some areas (see comments below). Autochthonous fluvial and alluvial placers commonly derive from hydrothermal vein deposits. PGE placers are associated with Alaskan-type ultramafics.

COMMENTS: Alluvial fan and fan delta paleoplacer sequences comprise a distinct subtype of buried placer deposits. They occur in relatively unconfined depositional settings compared to paleochannel placer deposits and typically are dominated by massive or graded, poorly sorted gravels and sands, locally with interbedded diamicton. They are generally lower grade and larger volume than fluvial deposits but they contain relatively uniform placer concentrations. Paleofan deposits are mainly local in origin as indicated by high clast angularity and local derivation. Placer minerals occur in both poorly sorted debris-flow sediments and interstratified fluvial gravels and sands. Concentrations are commonly highest at sites of subsequent fluvial degradation.

C02 - Buried-Channel Placers

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalous concentrations of Au, Ag, Hg, As, Cu, Fe and Mn in stream sediments. Gold fineness (relative Ag content) and trace element geochemistry (Hg, Cu) can be used as a signature to identify lode sources.

GEOPHYSICAL SIGNATURE: Shallow seismic refraction and reflection techniques are useful for delineating paleochannel geometry and depth to bedrock. Electromagnetic, induced polarization, resistivity and magnetometer surveys are locally useful. Geophysical logging of drill holes with apparent conductivity, naturally occurring gamma radiation and magnetic susceptibility tools can supplement stratigraphic data.

OTHER EXPLORATION GUIDES: Exploration should focus on sites of natural overburden removal, such as along glacial meltwater channels, and areas underlain by Tertiary fluvial deposits. Buried placers are commonly preserved below glacial lake sediments, on the lee-side of bedrock highs where glacial erosion was minimal and along narrow valleys oriented transversely to the regional ice-flow direction. Airphoto interpretation and satellite imagery data can aid exploration for buried valley placers. Concentrations of magnetite, hematite, pyrite, ilmenite, chromite, garnet, zircon, rutile and other heavy minerals can be used to indicate placer potential.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Placer concentrations in fluvial deposits are highly variable both within and between individual deposits. In paleochannel gold placers, grades of 0.5 to 5 g/m^3 Au are typical, although grades as high as 75 g/m^3 Au are reported. The values, however, do not include overburden dilution factors which can reduce grades tenfold or more. Deposit sizes are also highly variable, ranging from 1000 t to 10 Mt.

ECONOMIC LIMITATIONS: The main economic limitation to locating, evaluating and mining paleochannel placer deposits is the thick overburden which results in high stripping ratios. Over-consolidation of tills and other sediments due to glaciation makes overburden stripping difficult and is a major limitation inhibiting exploitation of these buried deposits.

IMPORTANCE: Placer gold deposits account for more than two-thirds of the world's gold reserves and about 25% of known total production in British Columbia. Buried-channel placers have been under developed in British Columbia and other countries because of difficulties in locating deposits and high overburden to ore stripping ratios.

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C03 - Marine Placers

by Victor M. Levson[1]

Levson, V.M., 1995. Marine placers. In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 29–31.

IDENTIFICATION

SYNONYMS: Beach, coastal or shoreline placers; offshore placer deposits; coastal dune placers (rare).

COMMODITIES (BYPRODUCTS): Ti (ilmenite, rutile), Zr (zircon), Sn, Au, PGEs; (locally Ag, Th, REE, monazite, yttrium, magnetite, garnet, diamonds and other gems).

EXAMPLES (British Columbia - *Canada/International*): Graham Island (PGE, Au), Queen Charlotte Sound (Au); *Country Harbour (Au, Nova Scotia, Canada); Nome (Au, Alaska, USA); Bermagui (Au, Australia), Westland and Nelson provinces (Au, New Zealand); Starke (ilmenite, Florida, USA); Atlantic beaches (ilmenite, zircon, Brazil); Sherbo deposit; rutile (Sierra Leone); Rosetta sand spit (ilmenite, magnetite, zircon, Egypt); Kerala and Quilon (ilmenite, zircon, monazite, India).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Detrital gold, ilmenite, cassiterite, platinum group elements and other heavy minerals occurring at the present or paleoseafloor surface. They usually occur in Holocene raised or submarine beach or strandline deposits along wave-dominated shorelines, but can also be found in coastal dunes, drowned fluvial channels, or as offshore relict lag concentrations.

TECTONIC SETTINGS: Placers occur mainly along cratonic margins where reworking of clastic material has proceeded for long periods of time. The margins of Cenozoic and Mesozoic accretionary orogenic belts and volcanic arcs are also important settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Marine placers form in exposed, shoreline or nearshore environments in areas of active winnowing by waves and long-shore or tidal currents. They occur along present beaches and are also preserved as relict submerged deposits or raised strandlines that formed during glacially induced, low or high sea level stands. Beach placers accumulate mainly in the upper foreshore and backshore depositional environments. Geological settings include sand spits, barrier islands, coastal dunes, buried marine scarps, drowned fluvial deposits and submerged residual or lag deposits overlying bedrock or till.

AGE OF MINERALIZATION: Mainly Holocene (rarely Late Pleistocene) in glaciated areas; generally Tertiary or younger in unglaciated regions.

HOST ROCK TYPES: Well sorted, medium to coarse-grained sands overlying fine-grained shallow marine deposits; some lag gravel concentrations over till or bedrock.

DEPOSIT FORM: Paystreaks follow strandlines in shoreline environments and are thin (often <1 m), long (>100 m, often > 1 km) and narrow (<50 m); usually interbedded with barren sequences; titaniferous sands are up to 20 m thick in Queen Charlotte Sound.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

C03 - Marine Placers

TEXTURE/STRUCTURE: Au is typically very fine grained (< 0.5 mm diameter), well rounded, flattened and of high fineness; coarser Au (~1 mm diameter) occurs in relict lag gravels.

ORE MINERALOGY (principal and *subordinate*): Native Au, ilmenite, rutile, cassiterite, PGEs, zircon, magnetite (*Ag, gemstones, garnet, monazite, various industrial minerals*).

GANGUE MINERALOGY: Quartz, pyrite and other sulphides and in many deposits subeconomic concentrations of various heavy minerals.

WEATHERING: Leaching (*e.g.* Fe from ilmenite) and destruction of unstable minerals may result in residual enrichment of the deposit.

ORE CONTROLS: Heavy mineral concentrations occur along stable shorelines where long-term sorting and winnowing by wave or current action occurs; richest pay streaks usually follow strandlines marked by beach gravels or coquina accumulations; common over clay beds, till or bedrock; occurrence often controlled by the extent of onshore placer or bedrock sources.

ASSOCIATED DEPOSIT TYPES: Coastal placer concentrations commonly associated with present or former fluvial or deltaic surficial placers (CO1).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalous concentrations of Au, As, Fe, Sn, Ti, Zr, REE, Th, Y and U in shoreline or nearshore sediments.

GEOPHYSICAL SIGNATURE: Ground penetrating radar useful for delineating the geometry, structure and thickness of sandy shoreline deposits. Shallow seismic, electromagnetic, induced polarization, resistivity and magnetometer surveys are locally useful (*e.g.* IP anomalies from ilmenite).

OTHER EXPLORATION GUIDES: Panning and other methods of using gravity sorting to identify concentrations of gold, ilmenite, zircon, rutile, magnetite or other heavy minerals.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits are typically high tonnage (0.1 to 100 Mt) but low grade (*e.g.* 0.05-0.25 g/t Au, 50-200 g/t Sn); higher grade deposits are small (*e.g.* Graham Island beach deposits 120 m long, 15 m wide and 15 cm thick [1000 t] contain up to 20 g/t Au and 70 g/t Pt). Surface relict gravels offshore of Nome contain 920 ppb Au. Placer concentrations are highly variable both within and between individual deposits.

ECONOMIC LIMITATIONS: The main economic limitations to mining surficial placer deposits are the typically low grades and their location near or below the water table. Offshore placers may occur as much as 100 m below present sea level. Environmental concerns have placed severe restrictions on development in many areas.

IMPORTANCE: Beach placers account for a significant part of the world’s Ti production (mainly from Australia, India, Brazil and Florida) and are an important source of Au, zircon, magnetite, garnet, monazite and diamonds.

C03 - Marine Placers

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D - Continental Sedimentary and Volcanic Rocks

Name		Authors
D01	Open-system zeolites	R.A. Sheppard and G.J. Simandl, 1999
D02	Closed-basin zeolites	R.A. Sheppard and G.J. Simandl, 1999
D03	Volcanic redbed Cu	D.V. Lefebure and B.N Church, 1996
D04*	included in D05 as a subtype - basal uranium	
D05	Sandstone U±V	B.N. Church and D.V Lefebure, 1999
D06*	Volcanic-hosted U	
D07	Iron Oxide Cu±Au±P±REE	G.E. Ray and D.V. Lefebure, 2000

‘* An asterisk after the alphanumeric code indicates that the mineral deposit profile is not in this compilation.

D01 - Open-System Zeolites

by R.A. Sheppard[1] and G.J Simandl[2]

Sheppard, R.A., and Simandl, G.J., 1999. Open-system zeolites. In: Selected mineral deposit profiles, volume 3 - Industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 19–22.

IDENTIFICATION

SYNONYM: In the field it may be practically impossible to distinguish these deposits from burial metamorphic zeolites.

COMMODITIES: Clinoptilolite, mordenite, chabazite, phillipsite, heulandite.

EXAMPLES: (British Columbia (MINFILE #) - *Canada/ International*): Clinoptilolite, Asp Creek (092HSE164), Bromley Vale Zeolite (092HSE166), Tailings Tephra (092HSE167), Sunday Creek (092HSE168); *clinoptilolite, John Day Formation, (Oregon, USA), clinoptilolite and mordenite, Miocene Paintbrush Tuff, Calico Hills and Crater Flat Tuffs, Nye County (Nevada, USA), phillipsite and chabazite, Yellow tuffs near Naples (Italy), clinoptilolite, Death Valley Junction, (California, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Microcrystalline zeolites (clinoptilolite, chabazite, mordenite, phillipsite) hosted by relatively thick, generally non-marine, tephra sequences. The ore zones are 10s to 100s of metres thick and commonly exhibit a more or less vertical zonation of zeolites and associated silicate minerals within the host sequence. The zeolites crystallized in the post-depositional environment over periods ranging from thousands to millions of years.

TECTONIC SETTINGS: Active or unmetamorphosed, continental, arc-related or other insular volcanic complexes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Non-marine and shallow marine basins in volcanic terrains. Depositional basins may be fault bounded. Many deposits form in fluviatile and lacustrine volcanic sequences, but some are hosted by shallow marine or subaerial tuffaceous deposits. Typical regional depositional environments contain thick sequences of vitric tuffs affected by diagenesis or very low-grade metamorphism.

AGE OF MINERALIZATION: Mesozoic to Holocene, but most are Cenozoic. Zeolite deposits in British Columbia are Cretaceous or Tertiary.

HOST/ASSOCIATED ROCK TYPES: The zeolite-bearing rocks are hosted by volcanic ash and tuff beds with minor intercalated flows. Silicic tuffs commonly were deposited as non-welded ash flows. Other rock types include fluviatile mudstone, sandstone, conglomerate and diatomite.

DEPOSIT FORM: Stratabound, stratiform or lens-shaped, mineral zonation may cross-cut the bedding. Thickness of the zeolitic tuffs in major deposits may range from 100's to 1000's of metres. Areal extent is commonly 100's to 1000's of square kilometres. Minor deposits and minable portions of above described zeolitic tuffs may be less than 30 metres in thickness.

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D01 - Open-System Zeolites

TEXTURE/STRUCTURE: Finely crystalline, commonly bedded, similar to bedded diatomite or bentonite. The common local attribute is vertical zonation of authigenic silicate minerals. In silicic tuff sequences, the alkali-rich siliceous zeolites (clinoptilolite and mordenite) in the upper part of the deposit are commonly replaced at depth by analcime, potassium feldspar and/or albite. A similar sequence occurs in burial diagenetic deposits.

ORE MINERALOGY [Principal and *subordinate*]: Clinoptilolite, chabazite, mordenite, phillipsite.

GANGUE MINERALOGY [Principal and *subordinate*]: Authigenic smectite, mixed layer illite-smectite, opal - (cristobalite/tridymite), quartz, plagioclase, microcline, sanidine, biotite, muscovite, calcite; *pyrogenic crystal fragments, volcanic rock fragments, unreacted vitric material*.

ALTERATION MINERALOGY: Zeolitization is the ore forming process (see ore mineralogy). Early zeolite minerals are further modified during burial diagenesis. In silicic tuff sequences, the alkali-rich siliceous zeolites (clinoptilolite and mordenite) in the upper part of the deposit are commonly replaced at depth by analcime, potassium feldspar and/or albite. In some cases, the zonation may be enhanced or overprinted by hydrothermal alteration related to intrusive activity.

WEATHERING: Zeolitic tuffs commonly resist weathering and may be ledge formers.

ORE CONTROLS: Grain size and permeability of host tuff; flow of meteoric water downward in an open hydrologic system; hydrolysis and solution of vitric material by the subsurface water in the upper part of the system raised the pH, activity of SiO_2 and content of dissolved solids to values where zeolites crystallized. These result in a vertical or near-vertical zonation of zeolites and other authigenic minerals. Composition of the vitric material and the characteristics of the solutions may have dictated which zeolite species precipitated. For example, clinoptilolite and mordenite are common in silicic tuffs, but chabazite and phillipsite are common in mafic or trachytic tuffs. In many cases the composition of the glassy protolith is believed to determine the mineralogy of the deposit. Trachyte to phonolite glassy protoliths with low Si/Al ratios (≤3.0) may favour the formation of phillipsite and chabazite, while a more felsic protolith may favour formation of clinoptilolite. Chabazite forms within the systems characterized by low Na/K ratio, whereas phillipsite dominates where the protolith has a high Na/K ratio. Conversion of zeolite to an assemblage of alkali feldspar-quartz can occur at a later stage if the stability field of zeolites is exceeded.

GENETIC MODELS: It is nearly universally accepted that zeolite formation is linked to syn- and post- depositional reaction of volcanic glass with relatively alkaline solutions. The zonation of the open-system type of zeolite deposit is in many cases similar to the upper zones of burial diagenesis (burial metamorphism) that affected thick sequences of silicic, vitric tuffs. Zeolitization temperatures are believed to be less than 100°C, but higher temperatures are estimated for some of the deposits. In many cases, there is controversy as to whether the fluids are “low temperature hydrothermal solutions”, “diagenetic fluids” or “heated meteoritic waters”. The genetic process probably varies from one deposit to another. There may be some overlap between different fluid types in the same deposit and also in the terminology used by individual authors.

ASSOCIATED DEPOSIT TYPES: Deposits that may occur in the same geographic area include pumice (R11), bentonite (E06), diatomaceous earth (F06), volcanic-hosted precious opal (Q11), peat (A01) and coal (A02 and possibly A03).

COMMENTS: In British Columbia, clinoptilolite is a major constituent of zeolite deposits.

D01 - Open-System Zeolites

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: None recognized. In most cases, zeolites can be detected and positively identified only by direct analytical techniques, such as x-ray diffraction. Lithogeochemistry may be a useful tool.

GEOPHYSICAL SIGNATURE: Possible use of color-composite imagery from airborne multispectral scanner data to distinguish zeolitic tuffs.

OTHER EXPLORATION GUIDES: Very low grade or unmetamorphosed volcaniclastic sequences typically containing large proportions of ignimbrites. Vertical zonation of zeolites and associated authigenic silicate minerals in thick (100s to 1000s of metres) tuffaceous sequences. This vertical zonation commonly is (from top to bottom) unaltered vitric material - smectite to clinoptilolite to mordenite to opal-(cristobalite-tridymite) to analcime to potassium feldspar to quartz and then to albite and quartz. This zonation may cut across bedding.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The value of zeolite deposits varies depending on the end product use and zeolite species present. Properties, such as cation exchange capacity for radionuclides, heavy metals or NH^+_4, are more meaningful than grade. This is because these properties are commonly different for the same zeolite species originating from two distinct deposits. The zeolite content of better deposits currently mined is estimated to have zeolite content above 60 %, but may reach over 80%. Deposits supplying materials to control the odor to local farms may have zeolite content well below 50%, but must be close to the market.

ECONOMIC LIMITATIONS: Virtually all mines are open pit. The cost of the transportation to the market is the most important non-technical parameter. The Si/Al ratio, cation exchange capacity and adsorption capacity for various gases are important technical parameters. Hardness and attrition resistance of zeolitic tuff (commonly affected by abundance of opal-cristobalite-tridymite or quartz) are important in processing and end use. Crystal size of the zeolite is < 2μm to 30μm and can affect the adsorption of gases and the extent and rapidity of cation exchange. Color (due to iron staining) and the abundance of non-zeolitic minerals may limit use. Environmental regulations vary from one jurisdiction to another. Some of the zeolite minerals such as erionite and mordenite may be classified as asbestiform. Free silica occurs commonly in the zeolite ores. Excessive concentrations of asbestiform particles or free silica in the ground product may limit its marketability.

END USES: Natural zeolites are used for effluent treatment, mine waste management, pet litter, barn deodorizers, soil conditioners, aquaculture, animal feed additive and construction materials, including pozzolan materials. Higher-priced synthetic zeolites dominate in manufacturing, oil industry / chemical applications and detergent industry. Natural zeolites are used in ion-exchange and adsorption applications, for example, clinoptilolite to remove NH^{4+} in tertiary sewage treatment and phillipsite to remove Cs and Sr from radioactive materials. Removal of heavy metals from industrial and mine drainage, currently achieved by direct addition of lime or soda, may be done in the future by zeolites. Heavy metal removal, particularly in acid mine drainage, has potential for a growing market.

IMPORTANCE: Important sources of natural clinoptilolite and mordenite. Bentonite, attapulgite and other materials known for their high absorbency may be cost effective alternatives to zeolites for specific ion exchange applications.

D01 - Open-System Zeolites

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D02 - Closed-Basin Zeolites

by R. A. Sheppard[1] and G. J. Simandl[2]

Sheppard, R.A., and Simandl, G.J., 1999. Closed-basin zeolites. In: Selected mineral deposit profiles, volume 3 - Industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 23–26.

IDENTIFICATION

SYNONYMS: “Closed-system" zeolite deposits.

COMMODITIES: Analcime, chabazite, clinoptilolite, erionite, mordenite, phillipsite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): *Lake Tecopa (California, USA), Bowie Deposit (Arizona, USA), Jersey Valley Deposit (Nevada, USA), Lake Magadi (Kenya).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Microcrystalline zeolite-bearing vitric tuff that consists chiefly of analcime, chabazite, clinoptilolite, mordenite, phillipsite and sometimes erionite. Deposit may consist of one or several stacked zeolite layers separated by sub-economic or barren beds.

TECTONIC SETTINGS: Varied tectonic settings. Closed hydrographic basins in either block-faulted terrains (such as the Basin and Range province), trough valleys associated with rifting (such as the Eastern Rift Valley of Kenya) or as Tibet-type grabens formed in a compression environment (such as Emet and Kirka basins, Turkey).

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: These deposits form in lacustrine basins that receive silica-rich, vitric, volcanic material. The saline lake water is commonly of sodium carbonate-bicarbonate variety, with a pH of 9 or greater. These lakes are common in arid and semi-arid regions where annual evaporation exceeds rainfall.

AGE OF MINERALIZATION: Late Paleozoic to Holocene; most deposits are Cenozoic.

HOST/ASSOCIATED ROCK TYPES: Most favourable hostrocks are rhyolitic to dacitic, vitric tuffs, especially those that are alkali-rich. Associated rocks are bedded evaporites (trona, halite, borates), mudstone, diatomite, bedded or nodular Magadi-type chert, oil shale, conglomerates and sandstones.

DEPOSIT FORM: Stratabound; several distinct, overlying beds may be zeolitized. The thickness of the zeolitic tuffs commonly ranges from 10 cm to 10 m. Areal extent is commonly tens to hundreds of square kilometres.

TEXTURE/STRUCTURE: Finely crystalline individual tuff beds show lateral zonation from unaltered glass near the shore, to zeolites and then to potassium feldspar in the center of the paleobasin.

ORE MINERALOGY [Principal and *subordinate*]: Analcime, chabazite, clinoptilolite, erionite, mordenite, phillipsite. Several of these ore minerals commonly coexist within a given deposit.

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D02 - Closed-Basin Zeolites

GANGUE MINERALOGY [Principal and *subordinate*]: Authigenic smectite, mixed layer illite/smectite, silica (opal, cristobalite/tridymite), quartz, searlesite, dawsonite, potassium feldspar, ± calcite, ± dolomite, biotite, sanidine, sodic plagioclase, hornblende, volcanic glass.

ALTERATION MINERALOGY: In certain highly alkaline and saline lacustrine deposits, siliceous and alkalic zeolites have been replaced during late burial diagenesis by analcime or potassium feldspar in the central part of the basin.

WEATHERING: Zeolitic tuffs resist weathering and are ledge formers in the lacustrine sequence. Local yellow to brown stains related to hydrous iron oxides.

ORE CONTROLS: Chemical composition of the protolith glass and grain size and permeability of the host vitric tuff are the key parameters. Salinity, pH, and ratios of alkali and alkaline-earth ions in the pore water are other important factors. Zeolite deposits are not preserved in rocks where metamorphism exceeded zeolite facies conditions.

GENETIC MODEL: Microcrystalline zeolites form during early diagenesis of silicic, vitric tuffs deposited in closed hydrographic basins. The zeolites crystallize in the post-depositional environment over thousands to hundreds of thousands of years by reaction of the vitric material with saline, alkaline pore water trapped during lacustrine sedimentation. Locally, zeolites also form from detrital clays, feldspar, and feldspathoids and from chemically precipitated aluminosilicate gels in the same depositional environment.

ASSOCIATED DEPOSIT TYPES: Continental-basin bedded evaporites (trona, halite, borates), diatomite (F06), and finely crystalline, disseminated fluorite in lacustrine rocks. Li-rich trioctahedral smectites (hectorite, saponite and stevensite) may be closely associated with borates.

COMMENTS: There are zeolite-bearing tuffs in British Columbia, however, no associated evaporite minerals, no boron enrichment, and no lateral zonation characteristic of closed-basin zeolites are reported.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: The lacustrine environment of sodium carbonate-bicarbonate type that is favourable for closed basin zeolites may also be enriched in boron and lithium.

GEOPHYSICAL SIGNATURE: Possible use of color-composite imagery from airborne multispectral scanner data to distinguish zeolitic alteration.

OTHER EXPLORATION GUIDES: Unmetamorphosed or very low metamorphic-grade environments. Molds of evaporitic minerals, associated dolomitic mudstone, occurrence of Magadi-type chert. Concentric zonation and lateral gradation in a basinward direction of unaltered volcanic glass to alkali-rich, silicic zeolites to analcime and then to potassium feldspar in the central part of the depositional basin. Zeolites are finely crystalline and resemble bedded diatomite, feldspar or bentonite in outcrop. Combination of X-Ray diffraction and ammonia cation exchange capacity (CEC) are essential in the early screening of zeolite prospects.

D02 - Closed-Basin Zeolites

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The cutoff grade varies greatly. For example, a 10 to 20 centimetre thick ore bed at Bowie contains 60 to 80% chabasite. Obviously, this zone would not have been economic if the main ore mineral was clinoptilolite. Most of the commercial clinoptilolite deposits contain between 50% and 90% zeolite.

ECONOMIC LIMITATIONS: Distance to the market is an important limitation for materials used in agricultural and construction applications. High-value specialty zeolites are international travelers. Production is typically from open pits with as much as 30 m of overburden. Mining costs reported by Holmes (1994) vary from US$ 3 to 6 per ton. Ground natural zeolites are selling for US$30 to 120 for low-value industrial use, but small tonnages of specialty products for the radioactive waste market can sell for more than $US 1000.00 per ton. Environmental regulations vary from one jurisdiction to another. Some of the zeolite minerals, such as erionite and mordenite, may be classified as asbestiform, a designation that reduces the market for the product. Free silica occurs commonly in the zeolite ores. Excessive concentrations of free silica or fibrous particles in the ground product may severely limit its marketability.

END USES: Zeolites have many agricultural uses, for example as preservative agents (desiccants), soil conditioners, fertilizer extenders, herbicides, pesticide and fungicide carriers, animal food additives and odor controllers. They are used in aquaculture for ammonia removal. Other uses are as dimension stone, light weight aggregate, pozzolan and for treatment processes, such as natural gas purification, nuclear waste treatment and disposal, and oil spill, sewage and effluent cleanup. Chabazite and clinoptilolite are used in heat exchange systems. Most of the non-construction uses are based on the ion-exchange and adsorption properties of zeolites. Cation exchange capacity and adsorption capacity for various gases are important. For example, chabazite is used to remove CO_2 and H_2S from sour natural gas while clinoptilolite can remove NH^{4+} in tertiary sewage treatment and in pet-litter and base metals from effluents. The Si/Al ratio and exchangeable cation ratios of the zeolites affect certain uses. Crystallite size of the zeolite is < 2 μm to 30 μm and can affect the adsorption of gases and the extent and rapidity of cation exchange.

IMPORTANCE: This deposit type contains the largest variety of zeolite species and it is an important source of chabazite, erionite, and phillipsite. Naturally occuring zeolites are substantially less expensive than synthetic zeolites; however, the latter are preferred in many applications because they are monomineralic, have less variability in product properties, or have useful properties that can not be matched by natural products. Bentonite, attapulgite, activated carbon, silica gel are viable substitutes for zeolite in a number of applications.

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D03 - Volcanic Redbed Cu

by David V. Lefebure[1] and B. Neil Church[1]

Lefebure, D.V., and Church, B.N., 1996. Volcanic redbed Cu. In: Selected mineral deposit profiles, volume 2 - Metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 5–7.

IDENTIFICATION

SYNONYMS: Basaltic Cu, volcanic-hosted copper, copper mantos.

COMMODITIES (BYPRODUCTS): Cu (Ag).

EXAMPLES (British Columbia - *Canada/International*): Sustut Copper (094D 063), Shamrock (092HNE092), NH (093L 082), North Star (094D 032); *White River (Yukon, Canada), 47 Zone and June, Coppermine River area (Northwest Territories, Canada) Mountain Grill and Radovan (Alaska, USA), Calumet-Hecla and Kearsarga, Keweenaw Peninsula (Michigan, USA), Mantos Blancos, Ivan and Altamira (Chile).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Chalcocite, bornite and/or native copper occur in mafic to felsic volcanic flows, tuff and breccia and related sedimentary rocks as disseminations, veins and infilling amygdules, fractures and flowtop breccias. Some deposits are tabular, stratabound zones, while others are controlled by structures and crosscut stratigraphy.

TECTONIC SETTINGS: These deposits occur in intracontinental rifts with subaerial flood basalt sequences and near plate margins with island-arc and continental-arc volcanics.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Continental to shallow-marine volcanic settings which formed in “low to intermediate latitudes” with arid to semi-arid environments. The metamorphic grade is sub-greenschist.

AGE OF MINERALIZATION: Proterozoic to Tertiary.

HOST/ASSOCIATED ROCK TYPES: Amygdaloidal basaltic lavas, breccias and coarse volcaniclastic beds with associated volcanic tuffs, siltstone, sandstone and conglomerate are the most common rock types. The volcanics may cover the spectrum from basalt to rhyolite composition. Redbed sedimentary rocks are common and often exhibit shallow water sedimentary structures (small-scale crossbedding, mud cracks, algal mats). Any of these units may host the deposits, although typically it is the mafic volcanics that have widespread elevated background values of copper due to the presence of native copper or chalcocite in amygdules, flow breccias or minor fractures.

DEPOSIT FORM: Many deposits are tabular lenses from a few to several tens of metres thick which are roughly concordant with the host strata over several hundred metres. Other deposits are strongly influenced by structural controls and crosscut the stratigraphy as veins, veinlets, fault breccias and disseminated zones.

TEXTURE/STRUCTURE: Disseminations, open-space fillings, veins and some replacement textures. Open spaces may be amygdules, cavities in flowtop breccias or fractures. Mineralization is commonly fine-grained, although spectacular examples of copper “nuggets” are known.

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D03 - Volcanic Redbed Cu

ORE MINERALOGY [Principal and *subordinate*]: Chalcocite, bornite, native copper, digenite, djurleite, *chalcopyrite*, *covellite*, *native silver* and *greenockite*. *Iron sulphides, including pyrite, typically peripheral to the ore.* Some deposits are zoned from chalcocite through bornite and chalcopyite to fringing pyrite. Copper-arsenic minerals, such as domeykite, algodonite and whitneyite, occur in fissure veins in the Keewenaw Peninsula.

GANGUE MINERALOGY [Principal and *subordinate*]: Typically little or no gangue; *hematite, magnetite, calcite, quartz, epidote, chlorite and zeolite mineral*s.

ALTERATION MINERALOGY: Generally, no associated alteration, although many deposits occur in prehnite-pumpellyite grade regionally metamorphosed volcanic rocks with minerals such as calcite, zeolites, epidote, albite, prehnite, pumpellyite, laumontite and chlorite.

WEATHERING: These deposits commonly have no associated gossans or alteration; locally minor malachite or azurite staining.

ORE CONTROLS: Deposits appear to be confined to subaerial to shallow-marine volcanic sequences commonly with intercalated redbeds. One of the major ore controls is zones of high permeability due to volcaniclastics, breccias, amygdules and fractures.

ASSOCIATED DEPOSIT TYPES: Sediment-hosted copper deposits (E04) often occur in the same stratigraphic sequences. The carbonate-hosted copper deposits at Kennicott, Alaska (E02) are associated with basaltic Cu deposits in the Nikolai greenstone.

GENETIC MODELS: Most authors have favoured metamorphism of copper-rich, mafic volcanic rocks at greater depth for the source of the metal-bearing fluids, and subsequent deposition higher in the stratigraphic sequence, in oxidized subaerial hostrocks at lower metamorphic grade. More recently analogies have been drawn to diagenetic models for sediment-hosted Cu deposits which predate the metamorphism. Low-temperature fluids migrating updip along permeable strata to the margins of basins, or along structures, deposit copper upon encountering oxidized rocks. These rocks are typically shallow-marine to subaerial volcanic rocks which formed in arid and semi-arid environments. Both models require oxidized rocks as traps, which requires the presence of an oxygen-rich atmosphere; therefore, all deposits must be younger than ~2.4 Ga.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Simple ore mineralogy produces a very specific geochemical signature for Cu and usually Ag. Lithogeochemical and stream sediment samples may return high values of Cu and Ag, typically high Cu/Zn ratios and low gold values.

GEOPHYSICAL SIGNATURE: Induced polarization surveys can be used to delineate mineralized lenses and areas of more intense veining.

OTHER EXPLORATION GUIDES: Malachite-staining. A red liverwort-like organism (Tentopholia iolithus) is often found in abundance on the surface of outcrops with copper mineralization in northern British Columbia.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The deposits range in size from hundreds of thousands to hundreds of millions of tonnes grading from less than 1% Cu to more than 4% Cu. Silver values are only reported for some deposits and vary between 6 and 80 g/t Ag. Sustut contains 43.5 Mt grading 0.82% Cu. The Calumet conglomerate produced 72.4 Mt grading 2.64% Cu.

D03 - Volcanic Redbed Cu

ECONOMIC LIMITATIONS: Only a few deposits have been high enough grade to support underground mines and the majority of occurrences are too small to be economic as open pit operations.

IMPORTANCE: The Keweenaw Peninsula deposits in Michigan produced 5 Mt of copper between 1845 and 1968. Otherwise production from basaltic copper deposits has been limited; the only currently operating mines producing significant copper are in Chile. However, there are numerous deposits of this type in British Columbia which underlines the potential to find significant copper producers.

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D05 - Sandstone U±V

by B.N. Church[1] and D.V. Lefebure[1]

Church, B.N., and Lefebure, D.V., 1999. Sandstone U±V: Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey mineral deposit profile, website, p. 4.

IDENTIFICATION

SYNONYMS: Western States-type or Colorado Plateau-Wyoming type. There are a variety of types, partially defined by morphology, including basal, roll (roll front) and tabular (peneconcordant, blanket or trend).

COMMODITIES (BYPRODUCTS): U, V; frequently U is the only product, some deposits produce only V; (Ra was recovered from some deposits between 1910-1923).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Roll-type - *Crow Butte (Nebraska, USA), Highland Mine (Wyoming, USA), Uravan Belt (Colorado).* Tabular-type - *Ambrosia Lake, Laguna, Gallup (New Mexico, USA), Korzekwa (Texas, USA), Lisbon Valley (Utah, USA).* Basal-type - Blizzard (082ENE046), Tyee (082ENW053), Fuki (082ENE015); *Sherwood mine (Washington, USA), Juniper (USA), Urgeirica (Portugal), St. Pierre (France), Tono and Ningyo Toge (Japan).* Unassigned - *Sierras Pampeñas, Sierra de Cordóba (Argentina), Aïr Massif (Niger), Mount Eclipse (Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Disseminated, microcrystalline uranium minerals, such as uraninite and coffinite, occur in pore spaces and as replacements of matrix, clasts and plant debris in alluvial sandstone, conglomerate, sand or gravel. Roll-type - Irregular zones at an alteration contact which can crosscut bedding. Tabular-type - Elongate, lens-shaped masses that parallel bedding with associated humite. Basal-type - Sinuous zones in stream gravels and sands covered by cap rocks, usually lava flows.

TECTONIC SETTINGS: Continental platform and coastal plains. Many deposits formed following uplift which provided favourable topographic conditions.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The host sedimentary sequences form in continental fluvial environments, commonly within arid drainage basins. They are often deposited in basins from 20 to 250 kilometres across, although basal deposits form within more restricted paleostream channels.

AGE OF MINERALIZATION: Important sandstone uranium deposits are principally post-Silurian; basal deposits are generally Tertiary age.

HOST/ASSOCIATED ROCK TYPES: Host rocks are well-sorted, arenaceous sedimentary rocks (commonly fluvial or alluvial fan), or more rarely tuffaceous volcanic rocks, overlain by relatively impermeable mudstones or other rocks. Organic material is abundant in many, but not all, mineralized beds. Conglomerate, sandstone, siltstone, mudstone, limestone and volcaniclastic units are also found associated with sandstone U±V deposits. Felsic tuffs are particularly common. In a few cases regolith breccia is found on nearby older basement rocks. Basal deposits are commonly capped with volcanic flows and the host rocks are unconsolidated or loosely consolidated sands and gravels.

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D05 - Sandstone U±V

DEPOSIT FORM: Roll-type - The U deposits occur along the boundaries of irregular, tongue-shaped zones of altered sandstone which vary from less than a metre to a few tens of metres in thickness and can extend kilometres horizontally. Individual deposits are tens of centimetres to metres wide (occasionally as much as 60 metres) and extend up to hundreds of metres along the alteration front. In cross-section, the deposits are often crescent-shaped with the concave side pointing up-dip (hence the term "roll front") as the mineralization follows curving alteration front and crosscuts the bedding. Tabular -type - Typically these are stratiform U deposits which range from less than a metre up to several metres in thickness and are up to hundreds of meters wide and several kilometres long. In some localities roll and tabular deposits occur at multiple horizons (stacked). Basal-type - These gently-dipping, "shoe-string" stratiform lenses range from a few meters to a few tens of metres thick and up to several hundred metres in length. They frequently occur at the base of sediments immediately overlying basement rocks (commonly granitic).

TEXTURE/STRUCTURE: The ore is often megascopically unidentifiable, unless oxidized to coloured, secondary uranium minerals, and can be difficult to distinguish from carbonaceous material in the sandstones. Mineralization coats sand grains, fills the interstices between grains or replaces carbonaceous material.

ORE MINERALOGY [Principal and *subordinate*]: Uraninite (UO_2, usually black and sooty) and coffinite ($USiO_4$) are the most common minerals; however, U, V and Mo can occur in a variety of other minerals, such as *autunite - salecite - ningyoite (uranyl phosphates), uranous coatings,uraniferous humites, montroseite, roscoelite (V-mica), tyuyamunite, uranophane, corvusite, hewettite and ferrimolybdite*. Sometimes pyrite or marcasite, jordisite and rarely *Zn, Pb and Cu sulphides*. At the Tono deposit U is present in uranian zeolite (clinoptilolite), U-calcite and U-apatite.

GANGUE MINERALOGY [Principal and *subordinate*]: Calcite, siderite, goethite, hematite.

ALTERATION MINERALOGY: Iron oxides (goethite, limonite and ferroselite) form in oxidized sandstone; carbonaceous material can be destroyed. Tabular deposits are related to large areas of relict TiO_2 minerals derived from detrital ilmenite and magnetite and formation of authigenic silicate minerals and dolomite. Smectite alteration identified in overlying mudstones at the Tono deposit.

WEATHERING: Uranium in rocks and minerals is leached and U^{+4} is oxidized to U^{+6} to form bright yellow to yellowish-green secondary minerals, such as autunite, uranophane, carnotite and tobernite. These often remain as coatings on the sandstone grains or the U^{+6} can dissolve in groundwater as one of the uranyl carbonate complex ions.

ORE CONTROLS: The principal ore controls are permeable fluvial sediments containing carbonaceous matter and pyrite or humite; a source of U, uplift concurrent with sedimentation; and proximity to an oxidizing environment. Sandstone U±V deposits are generally hosted by unmetamorphosed or weakly metamorphosed rocks.

GENETIC MODELS: The U is derived from granitic, pegmatitic or volcanic rocks (felsic or alkalic) and transported by oxidized groundwater as bicarbonate and tricarbonate complexes under mostly neutral to alkaline conditions. When these solutions encounter reducing environments, uranium minerals are precipitated. Anaerobic conditions can result in coalification of plant material and/or produce pyrite from iron minerals which will reduce oxidized fluids. Tabular-type deposits may contain layers of authigenic organic matter which impregnate the sandstone and reduce oxidized fluids. In some deposits sour natural gas (H_2S-rich) has migrated into the sediments and sulphidized them. In current genetic models the U is believed to have been introduced shortly after deposition of the host sediments, probably during diagenesis and before lithification. Semiarid climates appear to be desireable to allow for vegetation to be incorporated in the sediments and yet limit the volume of groundwater. Roll front-type deposits are believed to form from two fluids, a descending oxidized U-bearing fluid encountering a reducing fluid. The descending fluid alters the sandstone and deposits U at an oxidation-reduction interface. Over time the interface can migrate down dip by oxidation and solution on the up dip side of the ore zone and reduction and redeposition on the down dip side. With continued addition of U from an external source the mineralized zone would grow in size and grade.

D05 - Sandstone U±V

Tabular-type deposits are less well understood. One possible model is that layers of authigenic organic matter or humate formed in the sandstone or sand near the existing water table. Some U was precipitated with the humate and probably more was adsorped later. The alteration and uraniferous humate may have been emplaced prior to deposition of the overlying formations. For basal deposits the U is transported in cool, mildly alkaline, CO_2-rich meteoric waters derived from surface runoff or groundwater ascending along deep structures. Lava flows or mudstones provide impermeable cap rocks that ensure the mineralized groundwater flows down dip through, and is deposited in, permeable sands and gravels. The U is deposited when the groundwater encounters organic trash and/or reductant minerals, such as pyrite, within anaerobic, fluvial gravels and sands beneath a cap rock.

ASSOCIATED DEPOSIT TYPES: Sediment-hosted Cu (E04) and sandstone Pb (E05). U can occur associated with lignite coal (A02). Some sandstone U±V deposits in northern Italy may be related to volcanic-hosted deposits (D06). Several molybdenum-U mineralized zones with similar characteristics to sandstone U±V deposits have been identified in South Dakota. Bog U (B07) and calcrete U (B08) deposits can be found in the same general region as sandstone U±V deposits, but are obviously much younger.

COMMENTS: In some cases changes in groundwater hydrology can cause a formerly oxidized area to be re-reduced and a sandstone U-V deposit may exist totally within pyritiferous sandstone, not at an oxidation-reduction interface.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: U anomalies in surface waters in most arid areas and in stream sediments in wetter areas. In ground water and stream sediments, small amounts of V, Mo, Se, locally Cu, Ag and lesser Zn, Ni, Co may be introduced with U, while Mn may be depleted. Helium water sample anomalies can extend hundreds of metres, well beyond anomalous U. Roll-type deposits exhibit a geochemical zoning near the interface across the roll front from Se (inside) to U to U+Mo to Mo (halo in little altered rocks). Radon and helium, the only gaseous daughter products of U, can migrate upwards to surface from deposits.

GEOPHYSICAL SIGNATURE: Significant radioactive anomalies for daughter products of U that may be detected by airborne or ground surveys. Tabular deposits exhibit a low magnetic susceptibility.

OTHER EXPLORATION GUIDES: U occurrences in spatially-associated granitic, pegmatitic or felsic volcanic rocks. Secondary U minerals resulting from oxidation are bright yellow to yelowish-green colours. Roll-type deposits are often located at the boundary between different coloured sandstones - a reduced facies which is typically light gray to nearly white and the oxidized tongues can be shades of pink, yellow and brown. Basal-type deposits typically form near the headwaters of the paleodrainage system. In British Columbia they are typically near margins of Miocene/Pliocene basaltic sheets in areas where granitic rocks are exposed in the basement.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The grade for sandstone U±V deposits is very variable; grab samples may contain more than 1% U. Roll and Tabular-types -The highest grades are usually within a metre of the alteration front. They contain 100’s to 100 000’s of tonnes grading from 0.1 to 0.2% U (Bell, 1995). Basal-type: Grades range from 0.03 to 0.216% U_3O_8 for deposits ranging from 500,000 to 2,200,000 tonnes. The Blizzard deposit contains 2.2 Mt grading 0.181% U at a cutoff grade of 0.025 % U_3O_8 over 1 m; Tyee deposit has reserves of 2.056 Mt grading 0.031% U and Cup Lake contains 2.250 Mt grading 0.037% U. Some roll type sandstone U±V deposits contain significant V with little U. There has been by-product production of V from some American deposits.

D05 - Sandstone U±V

ECONOMIC LIMITATIONS: Some deposits have not been developed because of environmental and political concerns. Underground and conventional open pit mines operated in the United States for many years but are generally too low grade to be economic at current prices (1997). Most sandstone U deposits in the United States are being exploited by in situ leaching.

END USES: Primarily utilized for electrical power generation. Also used for metallurgical, medical and military uses.

IMPORTANCE: Sandstone U deposits were a major U resource until the 1970's, particularly in the United States. In Canada this deposit type has not been exploited and it accounts for only a few per cent of the country's U reserves.

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D07 - Iron Oxide Cu±Au±P±REE

By Gerald E. Ray[1] and David V. Lefebure[1]

Ray, G.E., and Lefebure, D.V., 2000. A synopsis of iron oxide ± Cu ± Au ± P ± REE deposits of the Candelaria-Kiruna-Olympic Dam family: In: Geological Fieldwork 1999, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey, Paper 2000-1, pp. 267–271.

IDENTIFICATION

SYNONYMS: IOCG; Olympic Dam, Kiruna, Ernest Henry or Candelaria types; iron oxide breccias and veins; apatite iron ore; volcanic-hosted magnetite; iron oxide-rich deposits; Proterozoic iron oxide (Cu-U-Au-REE) deposits.

COMMODITIES: Fe, Cu, Au, Ag, U and P. There is also a potential for byproduct REE's, Ba, Mo, Co and F.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Iron Range (82FSE014, 082FSE015); *Sue-Diane (Northwest Territories, Canada); Wernecke breccias (Yukon, Canada); Pea Ridge, Pilot Knob and Boss-Bixby (Missouri, USA); Cerro de Mercado (Durango district, Mexico); Olympic Dam (Gawler district, South Australia); Ernest Henry, Osborne (Cloncurry district, Australia); Kiirunavaara (Kiruna district, Sweden); Candelaria, Punta del Cobre, El Algarrobo, Boqueron Chanar, Manto Verde and El Romeral (Chilean Iron Belt); Monterrosas, Eliana, Raul, Condestable, Marcona (Peru); Vergenoeg (South Africa); Bafq (Iran); Mangula (Zimbabwe); Shimyoka, Kantonga, and Kitumba prospects (Mumbwa district, Zambia). Other possible examples include Salobo and Igarape Bahia (Carajas district, Brazil) and the Bulagidun prospect (North Sulawesi, Indonesia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Hydrothermal hematite and/or low-Ti magnetite-rich mineralization which may be hosted by sedimentary, igneous or metamorphic rocks. These deposits exhibit a wide range of morphologies, including multiphase breccia pipes and sheets, veins, stockworks, diatremes and both concordant and crosscutting tabular bodies. Mineralization varies from sulphide-poor magnetite ± apatite ore bodies (e.g. Kiirunavaara, El Algarrobo, El Romeral) to more sulphide-rich hematite ± magnetite deposits ± Cu ± Au ± Co ± U ± REE's (e.g. Olympic Dam, Ernest Henry and Candelaria).

TECTONIC SETTING: Proterozoic deposits are found in rifted cratonic settings whereas many Phanerozoic examples lie close to major linear structures in an Andean, continental margin, volcanic arc setting.

DEPOSITIONAL ENVIRONMENT/ GEOLOGICAL SETTING: The depth-range in which these deposits form is uncertain. Some deposits (e.g. Salobo) may have developed in a very shallow, possible exhalite environment; others (e.g. Olympic Dam; Cerro de Mercado) formed at near surface levels <1 km), whilst depths down to 6 km are speculated for some magnetite-albite dominated systems (Oreskes and Hitzman, 1993). Deposits are commonly associated with long-lived brittle-ductile fractures, narrow grabens or rifts that may, in part, be coeval with host-rock deposition.

AGE OF MINERALIZATION: Proterozoic to Tertiary. Many of the better known deposits are mid-Proterozoic (1.2 to 1.9 Ga). However, the Chilean and Peruvian Iron Belt examples are of Cretaceous age.

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HOST/ASSOCIATED ROCK TYPES: The Fe oxide mineralization crosscuts, or is conformable with, a wide variety of sedimentary, igneous and metamorphic rocks, including mafic flows, felsic volcanic breccias, tuffs, clastic sedimentary rocks, granites, gabbros, diorites, granodiorites and syenites. Prograde garnet-pyroxene ± scapolite skarn mineral assemblages may develop where the fluids are Ca-rich and high temperature, or where reactive calcareous host-rocks are present. Some deposits are associated with very coarse grained actinolite-apatite veins and breccias (crystals >3 cm long), and large volumes of sediment-hosted hematite-rich “ironstone” or iron oxide-bearing volcanic rocks.

DEPOSIT FORM: Highly variable. Sub-horizontal to steeply inclined, discordant to concordant pod-like zones, dike-like veins, lenses, tabular bodies, pipes and stockworks. The iron-rich veins and tabular zones may reach hundreds of metres in width and have a strike length of many kilometres.

TEXTURE/STRUCTURE: The Cu-Au mineralization may be hosted in the Fe oxide matrix as disseminations, micro-veinlets and as rare mineralized clasts. Textures indicating replacement and microcavity filling are common (e.g. tuff lapilli may be selectively replaced by iron oxides). Intergrowths between minerals are noted. Hematite and magnetite may display well developed crystals, interlocking mosaics, and tabular or bladed textures. Hematite varies from specular to massive to botryoidal (kidney ore). Some deposits are characterized by matrix-supported hydrothermal, polymictic and multiphase breccias. Breccia textures are highly variable; they may grade from core zones containing 100% Fe to weakly fractured and Fe-veined host-rock on the margins. Breccias may be difficult to recognize in hand sample as the same apparent Fe oxide phase may comprise both the fragments and matrix. Many breccias contain clasts of magnetite, hematite, fresh to altered country rock, quartz, calcite and older breccia material supported in a matrix of younger iron oxides and /or calcite. If Ca-rich host-rocks are present, fragments of garnet-pyroxene ± scapolite skarn overgrown by iron oxides may be seen. Breccia fragments are generally angular to sub-angular although rounded and mechanically milled clasts are not uncommon. They range up to > 10 m in diameter, but tend to be <15 cm wide. Contacts with the unbrecciated host-rocks are frequently gradational over scale of centimetres to metres. Hematite breccias often display a diffuse wavy layered texture of red and black hematite, and some microbreccias have thin, hair-like veins of hematite. Replacement (pseudomorphing) of early magnetite by hematite (martite) may be a common feature.

ORE MINERALOGY: These vary from low sulphide-bearing magnetite-apatite deposits with actinolite±pyroxene (e.g. Kirunavaara, El Romeral) to more sulphide-rich, polymetallic hematite-magnetite deposits (e.g. Olympic Dam, Candelaria). The principal ore minerals are hematite (includes specularite, botryoidal hematite and martite), low-Ti magnetite, bornite, chalcopyrite, chalcocite and pyrite. Subordinate minerals include digenite, molybdenite, covellite, native copper, carrolite, cobaltite, Cu-Ni-Co arsenates, pyrrhotite, pitchblende, uranite, coffinite, autunite, brannerite, bastnaesite, monazite-xenotime, florencite, native silver and gold and silver tellurides. At Olympic Dam, the native gold, uraninite, coffinite, bastnaesite and florencite are very fine grained; gold is disseminated either in the breccia matrix or as inclusions in the sulphides whereas bastnaesite and florencite occur in the matrix as grains, crystals and crystal aggregates.

GANGUE MINERALOGY: Gangue is intergrown with ore minerals as veins, as clasts in breccias or as disseminations. Principal gangue minerals include albite, K-feldspar, sericite, carbonate, chlorite, quartz, amphibole, pyroxene, massive silica, biotite and apatite. Lesser amounts of fluorapatite, fluorite, barite, epidote, rutile, titanite, monazite, ilvaite, tourmaline and allanite may also occur. The amphiboles include hastingsite and tschermakitic varieties as well as Cl-rich hornblende. Hematite breccias are frequently cut by veins, up to 10 cm wide, containing fluorite, barite, siderite, hematite and sulphides.

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ALTERATION MINERALOGY AND ZONING: Hitzman et al. (1992) note that at greater depths, alteration in these systems comprises large (>1 kilometre wide) zones of Na-Fe metasomatism (early albite- actinolite-magnetite, apatite and late epidote); if Ca-rich host-rocks are present, Fe-rich garnet-clinopyroxene ±scapolite skarn assemblages may form (e.g. Candelaria, Chile; Kiruna, Sweden; Shimyoka and Kantonga prospects, Zambia). Overlying the Na-Fe alteration, at intermediate depths, are extensive haloes of K-Fe-rich alteration (K-feldspar, secondary biotite, sericite, magnetite, actinolite, chlorite); intense chloritization may result in almost total destruction of the hydrothermal biotite. The upper parts of the hydrothermal systems tend to be marked by lower temperature Si-Fe-K assemblages (massive silica-quartz-sericite-specular hematite-chlorite).

Olympic Dam has intense sericite and hematite alteration with increasing hematite towards the centre of the breccia bodies at higher levels. Close to the deposit, the sericitized feldspars are rimmed by hematite and cut by hematite veinlets. Adjacent to hematite breccias the feldspar, rock flour and sericite are totally replaced by hematite. Chlorite or K-feldspar alteration predominates at depth. Quartz, fluorite, barite, carbonate, rutile, orthoclase and epidote are also present.

The Kiruna orebodies contain scapolite and albite with actinolite-epidote alteration in the mafic wallrocks; up to 20 wt % apatite is also reported. Some Chilean and Peruvian Phanerozoic examples contain tourmaline (e.g. Manto Verde, Monterrosas) and this mineral also occurs at Kiirunavaara and Olympic Dam.

WEATHERING: In certain weathering environments, pervasive kaolin-clay alteration may develop as well as some supergene alunite veins. In arid environments, a blanket containing secondary Cu, Cu-Mn and U phosphates, oxides, sulfates and chlorides may be present (e.g. turquoise, torbernite, brochantite, antlerite, atacamite). Supergene enrichment of Cu and U is possible; examples include the pitchblende veins in the Great Bear Magmatic Zone.

ORE CONTROLS: There are strong structural ore controls in most deposits although in some (e.g. Candelaria) stratigraphy also plays an important role. Deposits are hosted by rocks adjacent to brittle-ductile fractures or narrow grabens that have undergone repeated transcurrent and extensional movement. They may cluster along linear arrays more than 100 km long and >10 km wide and be spaced 10-30 km along the trend. Many older deposits (e.g. Kiirunavaara, Olympic Dam, Ernest Henry) are hosted by mid-Proterozoic continental crustal rocks and past exploration has focused largely on fractures that cut these packages. However, recognition of younger deposits (e.g. Bafq, Chilean and Peruvian Iron Belts) demonstrates that fault zones in Phanerozoic volcanic arcs are also important exploration targets.

GENESIS: Studies by (e.g. Oreskes and Einaudi, 1990; Hitzman et al., 1992; Oreskes and Hitzman, 1993; Borrok et al., 1998; Gow et al., 1994) suggests that these deposits are hydrothermal in origin. However, there is disagreement about this interpretation and whether or not these diverse orebodies should be grouped as a single deposit type. Barton and Johnson (1996) suggest that evaporites provided a source for chlorides and the sodium alteration in some deposits; this involves a process of non-magmatic fluids circulating through evaporites, and being drawn into an intrusion-centered hydrothermal system. A magmatic-syngenetic versus volcanic-epigenetic origin of the Kiruna (Sweden) and El Laco (Chile) magnetite mineralization is still hotly debated (e.g. Parak, 1975; Nystrom and Henriquez, 1994). In some cases the mineralization appears to be younger than, and unrelated to the hosting igneous rocks (e.g. Ernest Henry, Candelaria), but later studies at Olympic Dam (Johnson and Cross, 1995; Campbell et al., 1998) suggest that the hosting granite is only slightly older (circa 8 Ma) than the mineralization. Sm-Nd data from Olympic Dam (Johnson and McCulloch, 1995) indicate a mantle-derived origin for the mineralization. However, many examples lack an identifiable plutonic source; hence the origin of the hydrothermal fluids and composition of the assumed parent magmas are unknown.

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ASSOCIATED DEPOSIT TYPES: On a wide district scale, these Fe oxide±Cu±Au±REE deposits may be associated with volcanic-hosted U orebodies, alkaline and calc-alkaline porphyry Cu-Au deposits, supergene U and/or Cu blankets or veins, and hematite-rich massive iron-stones. Some sedex-type Pb-Zn-Ag deposits are found in the same geological setting as Fe oxide deposits, although there is no proven genetic relationship. Examples of this broad regional association include Broken Hill and Olympic Dam, Mount Isa and Ernest Henry (Australia), Kabwe and the Shimyoka, Kantonga, and Kitumba prospects (Zambia), and Sullivan and the Iron Range prospect (British Columbia). In the latter case, however, the age of the Iron Range prospect relative to the Sullivan deposit is unknown.

COMMENTS: Hitzman et al. (1992) note that the magnetite in these deposits is generally low in Ti (<0.5% TiO2), in contrast to the magnetite associated with anorthosites, gabbros and layered mafic intrusions. Some carbonate-hosted Fe oxide-Cu-Au±REE deposits with a skarn gangue resemble calcic island-arc Fe skarns; both deposit types contain low-Ti magnetite, Fe-rich and Mn-poor garnets and hedenbergitic clinopyroxenes, and sporadic Cu, Au and Co geochemical anomalies. Also, both types tend to have early albitic alteration, sporadic younger K-feldspar development and similar textures (hydrothermally brecciated magnetite and magnetite veins and dikes). Unlike Fe oxide-Cu-Au deposits, however, island-arc Fe skarns are strongly controlled by pluton margins, they contain relatively little hematite and lack anomalous REE’s and U.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalously high values for Fe, Cu, U, Au, Ag, Co, REE’s (Ce, La, Nd, Pr, Sm, Gd) ±P±F±B±Mo±Y±As ±Bi ±Te±Mn ±Se and ±Ba in associated rocks and in stream sediments. The light REE’s tend to be concentrated in minerals such as allanite, epidote, bastnaesite, florencite, monazite, xenotime or apatite.

GEOPHYSICAL SIGNATURE: Large positive gravity anomalies related to the Fe oxides. Regional aeromagnetic anomalies related to magnetite and/or coeval igneous rocks. Radiometric anomalies (detectable by ground and airborne gamma-ray spectrometer surveys) occur with polymetallic deposits containing U mineralization or K alteration. IP was a useful tool in exploring the Candelaria deposit (Ryan et al., 1995).

OTHER EXPLORATION GUIDES: Promising areas are those with narrow rift structures and deep-seated brittle-ductile fault zones. Favorable features along such structures include the presence of: (1) extensional or trans-tensional movement, (2) zones of albite, K-feldspar, sericite, chlorite, apatite, epidote, tourmaline, fluorite, actinolite, garnet ± pyroxene ±scapolite skarn or silica-rich alteration, (3) Fe oxides, particularly in breccias, stockworks and veins, (4) sodic or potassically-altered intrusions, (5) U oxides and/or REE-enriched alteration, and (6) secondary Cu phosphates. The favorable linear belts may exceed 100 kilometres in length and be tens of kilometres wide.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits may exceed 1000 Mt grading >20 % Fe. Reserves for the following deposits are:

- Olympic Dam - 2000 Mt grading 1.6% Cu, 0.06% U_3O_8, 3.5 g/t Ag and 0.6 g/t Au with a measured and indicated resource in a large number of different ore zones of 450 Mt grading 2.5% Cu, 0.08 % U_3O_8, 6 g/t Ag, 0.02% Co and 0.6 g/t Au with ~2000 g/t La and ~3000 g/t Ce (Reeves et al., 1990);
- Ernest Henry - 166 Mt averaging 1.1 % Cu and 0.5 g/t Au (quoted in Williams, 1999);
- Sue-Dianne - 8.16 Mt averaging 0.8% Cu, up to 150 ppm U and locally significant gold (Gandhi, 1989);
- Kiruna district - > 2000 Mt grading 50-60% Fe and an average apatite content of 0.9 % (quoted in Williams, 1999);
- Candelaria - 366 Mt averaging 1.08 % Cu, 0.26 g/t Au and 4.5 g/t Ag (Ryan et al., 1995).

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ECONOMIC LIMITATIONS: The larger, sulphide-poor Fe oxide deposits are a potential economic source for Fe and P in areas with easy access and existing infrastructure. However, the more sulphide-rich Fe oxide deposits with Cu-Au-Ag mineralization are currently more attractive economically.

IMPORTANCE: These deposits continue to be significant producers of Fe and represent an important source of Cu, Au, P, U and possibly REE's.

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E - Sediment-Hosted

	E - Sediment-Hosted	Authors
E01*	Almaden Hg	
E02	Carbonate-hosted Cu±Pb±Zn	E.A.G. Trueman, 1998
E03	Carbonate-hosted disseminated Au-Ag	T. Schroeter and H. Poulsen, 1996
E04	Sediment-hosted Cu-Ag-Co	D.V. Lefebure and D.J. Alldrick, 1996
E05	Sandstone Pb	D.F. Sangster, 1996
E06	Bentonite	Z.D. Hora, 1999
E07	Sedimentary kaolin	Z.D. Hora, 1999
E08	Carbonate-hosted talc	G.J. Simandl and S. Paradis, 1999
E09	Sparry magnesite	G.J. Simandl and K. Hancock, 1999
E10*	Mississippi Valley-type barite±fluorite	
E11*	Mississippi Valley-type fluorite±barite	
E12	Mississippi Valley-type Pb-Zn (hypogene)	D.J. Alldrick and D.F. Sangster, 2000
E13	Irish-type carbonate-hosted Zn-Pb	T. Höy, 1996
E14	Sedimentary exhalative Zn-Pb-Ag	D. MacIntyre, 1995
E15	Blackbird sediment-hosted Cu-Co	T. Höy, 1995
E16	Shale-hosted Ni-Zn-Mo-PGE	D.V. Lefebure and R.M Coveney Jr., 1995
E17	Sediment-hosted barite	S. Paradis, G.J. Simandl, D.G. MacIntyre & G.J. Orris, 1999
E18	Carbonate-hosted, nonsulphide Zn	S. Paradis and G.J. Simandl, 2012

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

E02 - Carbonate-Hosted Cu±Pb±Zn

by E.A.G. (Ted) Trueman[1]

Trueman, E.A.G., 1998. Carbonate hosted Cu±Pb±Zn: In: Geological Fieldwork 1997, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey, Paper 1998-1, pp. 24B1-24B4.

IDENTIFICATION

SYNONYMS: Tsumeb or Kipushi type.

COMMODITIES (BYPRODUCTS): Cu, Pb, Zn, Ge (Ag, Ga, As, Cd).

EXAMPLES (British Columbia - *Canada/International*): Blue (Minfile 94F 005); *Grinnell and Kanuyak Island (Northwest Territories, Canada), Kennecott, Ruby Creek and Omar (Alaska, USA), Apex (Utah, USA), Gortdrum (Ireland), Tsumeb and Kombat (Namibia), Kipushi (Zaire), M'Passa (Congo), Timna (Israel), Nifty (Australia), and portions of Dongchuan deposits (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Irregular, discordant bodies of Cu sulphides (bornite, chalcopyrite, chalcocite, tennantite), sometimes with significant galena and sphalerite, form massive pods, breccia/fracture fillings and stockworks in carbonate or calcareous sediments. Igneous rocks are absent or unrelated to the deposition of metals.

TECTONIC SETTING: Intracratonic platform and rifted continental margin sedimentary sequences; typically gently folded and locally faulted.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Host carbonate sediments were deposited in shallow marine, inter-tidal, sabkha, lagoonal or lacustrine environments and are often overlain disconformably by oxidized sandstone-siltstone-shale units. Largest deposits are within thick sedimentary sequences.

AGE OF MINERALIZATION: Hosts rocks are Middle Proterozoic to Triassic; the largest deposits are in Upper Proterozoic rocks. Mineralization is at least slightly younger than host lithologies and may have spanned a large time interval.

HOST / ASSOCIATED ROCK TYPES: Dolomite or limestone, often stromatolitic or arenaceous, hosts the mineralization within a sequence which typically includes fine to coarse grained clastic sediments and evaporite. Occasionally basalt flows are nearby or part of sequence. Intrusive rocks are absent or different age than mineralization.

DEPOSIT FORM: The pipe-like to tabular deposits are irregular, discordant and often elongated in one direction up to 2 000 m or more. In cross section, deposits can be up to 100 by 200 m or 60 by 500 m in size. Sometimes Zn-Pb rich mantos project from the main zone of mineralization as replacement bodies parallel to bedding.

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[1] Trueman Consulting Ltd., Denman Island, British Columbia, Canada

E02 - Carbonate Hosted Cu±Pb±Zn

TEXTURE / STRUCTURE: Massive, stringer/stockwork and disseminated mineralization styles occur and grade into one another; clots of sulphides are common. Features characteristic of a karst environment, including collapse breccias, are typical. Two or more breccia types may be present as a result of karst dissolution and hydrothermal fracturing. Open spaces within deposits are common. Narrow bodies or irregular masses of arenaceous sediment may occur within deposit. These clastics may have developed as a result of dissolution of an arenaceous carbonate host, with accumulation of clastic lag sediments, or by clastic sedimentation into karst openings as a result of submergence.

ORE MINERALOGY (Principal and subordinate): Chalcopyrite, bornite, chalcocite, tennantite (*tetrahedrite*), galena, sphalerite, pyrite, enargite, *renierite, germanite, arsenopyrite, marcasite, magnetite, gallite, Co-Ni arsenides, carrollite, molybdenite and others*. Deposits contain low to moderate Fe; pyrite may be common or virtually absent. Cu is sometimes crudely zoned vertically in deposits relative to Fe with the Cu-rich phases closer to surface. Cu may also be spatially partitioned with respect to Pb-Zn.

GANGUE MINERALOGY (Principal and *subordinate*): Dolomite, quartz, calcite, barite, fluorite, clay minerals, sericite, hematite, siderite and minor *pyrobitumen*.

ALTERATION MINERALOGY: Dolomite, silica, calcite and argillic alteration. Deposits are usually coincident with a zone of dolomitization. Dolomitization may be pre-, syn- and/or post-mineralization, and may extend 100’s of metres beyond mineralization. Vuggy openings are often lined with calcite or baroque dolomite.

WEATHERING: Wide variety of secondary products form especially limonite, goethite, Cu minerals (malachite, azurite, dioptase), cerussite and smithsonite. Some deposits are deeply oxidized (Kennecott, Tsumeb, Apex) as a result of fluid circulation through/along solution cavities, faults/fractures and bedding planes. Oxidation is typically developed at surface but there may also be an oxidized profile at considerable depth (>1,000m) as a result of continuation/reactivation of fluid flow along bedding planes aquifers.

ORE CONTROLS: The openings in carbonate rocks are created by brecciation, karsting, faulting, and/or alteration. Deposits form in proximity to a redox boundary between reduced carbonates and oxidized clastic sediments or occasionally oxidized basalt. Evaporites in the sedimentary sequences may have enhanced brine salinity and contributed sulphur.

GENETIC MODEL: Pre-mineralization plumbing systems were created by karsting, collapse zones, faulting/fracturing, collapse related to evaporite removal, and/or bedding plane aquifers and were enhanced by volume reduction during dolomitization, ongoing carbonate dissolution and hydrothermal alteration. Oxidized, diagenetic fluids scavenged metals from clastic sediments and their source area, with deposition in open spaces in reduced carbonates, often immediately below an unconformity. In a few examples, nearby basalts could have provided Cu. Fluid inclusion data indicate mineralizing solutions were saline and generally low temperature, in the 100-240ºC range. Mineralization may have been initiated soon after host sediments became indurated and was likely a prolonged event, possibly continuing intermittently over 100’s of millions of years in larger deposits. Deposits are basically formed through diagenetic processes and are an integral part of basin evolution. In some deposits, different fluids could have prevailed within oxidized and reduced strata leading to different metal sources - this could explain why only some deposits have a significant Zn-Pb-Ge component.

ASSOCIATED DEPOSIT TYPES: Genetic processes which form carbonate-hosted Cu±Pb±Zn may be analogous to stratiform Cu (E04), carbonate hosted Zn-Pb (E12), unconformity U (I16) and sandstone U (D05) deposit types. Carbonate hosted Cu±Pb±Zn deposits have many similarities with carbonate hosted Zn-Pb deposits (E12), and are possibly a link between these deposits and stratiform Cu (E04).

E02 - Carbonate Hosted Cu±Pb±Zn

COMMENTS: Deposits often occur in the same basin as stratiform Cu or carbonate-hosted Zn-Pb deposits. Other possible candidates for this type include: Mount Isa Cu, Kilgour, Yah Yah and Cooley (Australia), Nite and Ellesmere (Northwest Territories, Canada), Lord Aylmer and Acton Vale (Quebec, Canada).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Dominantly elevated Cu but Zn, Pb, As, Ag and Ge are key indicators in rock samples; subtle Cu stream silt geochemical anomalies occur in proximity to some deposits. Other elements which may be useful pathfinders are Co, Ga, Bi, Cd, V, Mo and Ba.

GEOPHYSICAL SIGNATURE: Resistivity, IP and gravity could be useful but there are no definitive tools.

OTHER EXPLORATION GUIDES: Tectonically disturbed zones and karsted areas within carbonate/oxidized clastic couplets of major basins are regional targets. Dolomitized zones should be carefully examined. Deposits often occur in clusters and/or in proximity to associated deposit types. Deposits oxidize readily forming gossans with secondary Cu and Fe minerals; many other secondary products and malachite-coated nuggets of copper sulphides may be present. Thermal maturation anomalies and clay mineral zoning, as applied to carbonate hosted Zn-Pb and unconformity uranium deposits, may be useful tools.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Tsumeb produced ~30 million tonnes at 4.0% Cu, 9.0% Pb and 3.2% Zn. Production plus reserves at Kipushi are believed to be about 70 million tonnes at 4.8% Cu, 8.8% Zn and 0.5% Pb. Kennecott production was 4.4 million tonnes at 12.4% Cu and 95 g/t Ag. These three deposits are the most significant producers and also reflect the highest average grades for Cu (Kennecott), Pb (Tsumeb) and Zn (Kipushi). The Ruby Creek resource is 90 million tonnes grading 1.2% Cu. Ge and Ga were produced at Tsumeb, Kipushi(?) and Apex; Apex grades were in the order of 0.06% Ge and 0.03% Ga.

ECONOMIC LIMITATIONS: Although several deposits have been partially mined by open pit methods, the elongate morphology usually requires underground mining. The complex suite of metallic minerals in some deposits could complicate metallurgy.

IMPORTANCE: Gross and unit metal values can be very high. Few significant deposits are recognized; however, the type is poorly understood and exploration efforts have been minimal.

ACKNOWLEDGEMENTS: Work leading to this summary was supported by BHP Minerals Canada Ltd. and their Canadian Exploration Manager, Neil le Nobel. Numerous other geologists have enhanced my understanding of this deposit type, including Tom Pollock, Murray Hitzman, Rod Kirkham, Hans Trettin and Arno Günzel. Dave Lefebure and Trygve Höy reviewed drafts and significantly improved this profile.

E02 - Carbonate-Hosted Cu±Pb±Zn

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E03 - Carbonate-hosted Disseminated Au-Ag

by Tom Schroeter[1] and Howard Poulsen[2]

Schroeter, T., and Poulsen, H., 1996. Carbonate-hosted disseminated Au-Ag:
In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 9–12.

IDENTIFICATION

SYNONYMS: Carlin-type gold, sediment-hosted micron gold, siliceous limestone replacement gold, invisible ("no-seeum") gold.

COMMODITIES (BYPRODUCTS): Au (Ag). In rare cases Ag dominates over Au.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Golden Bear? (104K 079); *parts of Brewery Creek (Yukon, Canada), Carlin, Getchell, Cortez, Gold Acres, Jerrett Canyon, Post and Gold Quarry (Nevada, USA), Mercur (Utah, USA), Mesel? (Indonesia), Guizhou (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Very fine grained, micron-sized gold and sulphides disseminated in zones of decarbonated calcareous rocks and associated jasperoids. Gold occurs evenly distributed throughout hostrocks in stratabound concordant zones and in discordant breccias.

TECTONIC SETTINGS: Passive continental margins with subsequent deformation and intrusive activity, and possibly island arc terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Host rocks to the Nevadan deposits were deposited in shelf-basin transitional (somewhat anoxic) environments, formed mainly as carbonate turbidites (up to 150 m thick), characterized by slow sedimentation. These rocks are presently allochthonous in thrust fault slices and have been overprinted by Miocene basin and range extension. There are Mesozoic to Tertiary felsic plutons near many deposits.

AGE OF MINERALIZATION: Mainly Tertiary, but can be any age.

HOST/ASSOCIATED ROCK TYPES: Hostrocks are most commonly thin-bedded silty or argillaceous carbonaceous limestone or dolomite, commonly with carbonaceous shale. Although less productive, non-carbonate siliciclastic and rare metavolcanic rocks are local hosts. Felsic plutons and dikes are also mineralized at some deposits.

DEPOSIT FORM: Generally tabular, stratabound bodies localized at contacts between contrasting lithologies. Bodies are irregular in shape, but commonly straddle lithological contacts which, in some cases, are thrust faults. Some ore zones (often higher grade) are discordant and consist of breccias developed in steep fault zones. Sulphides (mainly pyrite) and gold are disseminated in both cases.

TEXTURE/STRUCTURE: Silica replacement of carbonate is accompanied by volume loss so that brecciation of hostrocks is common. Tectonic brecciation adjacent to steep normal faults is also common. Generally less than 1% fine-grained sulphides are disseminated throughout the hostrock.

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[1] British Columbia Geological Survey, Vancouver, British Columbia, Canada

[2] Geological Survey of Canada, Ottawa, Ontario, Canada

E03 - Carbonate-hosted Disseminated Au-Ag

ORE MINERALOGY [Principal and subordinate]: Native gold (micron-sized), *pyrite with arsenian rims, arsenopyrite, stibnite, realgar, orpiment, cinnabar, fluorite, barite, rare thallium minerals*.

GANGUE MINERALOGY [Principal and *subordinate*]: Fine-grained quartz, barite, clay minerals, carbonaceous matter (late-stage calcite veins).

ALTERATION MINERALOGY: Strongly controlled by local stratigraphic and structural features. Central core of strong silicification close to mineralization with silica veins and jasperoid; peripheral argillic alteration and decarbonation (“sanding”) of carbonate rocks common in ore. Carbonaceous material is present in some deposits.

WEATHERING: Nevada deposits have undergone deep supergene alteration due to Miocene weathering. Supergene alunite and kaolinite are widely developed and sulphides converted to hematite. Such weathering has made many deposits amenable to heap-leach processing.

GENETIC MODELS:

a) Epithermal model: Once widely accepted but now discounted for most deposits. Mineralization was thought to result from shallow Miocene magmatism related to basin and range extension. New discoveries of deep orebodies, overprinting basin and range deformation, and recognition of a supergene origin of alunite have cast doubt on this model.
b) Distal skarn model: Currently very popular because many deposits occur near intrusions, skarns and calcsilicate rocks. Carbonate-hosted disseminated gold is thought to be related to collapse of intrusion-centred porphyry-type hydrothermal systems. Although compelling for many deposits, this model fails to explain several districts (e.g., Jerritt Canyon; Guizhou, China) where no related magmatism has been observed.
c) Deep crustal fluid model: Recently proposed to account for inferred deep mixing of different fluids from different reservoirs as demanded by light stable isotopic and fluid inclusion data. Variants of this model imply only indirect links to magmatism, suggest a single Paleogene age for the Nevadan deposits and relate them to a unique period of pre-basin and range crustal extension and associated faults that are controlled by pre-existing Paleozoic and Mesozoic structures.

ORE CONTROLS: 1. Selective replacement of carbonaceous carbonate rocks adjacent to and along high-angle faults, regional thrust faults or bedding. 2. Presence of small felsic plutons (dikes) that may have caused geothermal activity and intruded a shallow hydrocarbon reservoir or area of hydrocarbon-enriched rocks, imposing a convecting geothermal system on the local groundwater. 3. Deep structural controls are believed responsible for regional trends and may be related to Precambrian crystalline basement structures and/or accreted terrane boundaries.

ASSOCIATED DEPOSIT TYPES: Porphyry (L04, L05), Au, W or Mo skarns (K04, K05, K07), polymetallic manto (J01).

COMMENTS: British Columbia: 1. Limestone fault slices (part of accreted Stikine terrane) which have been intruded by felsic plutons, especially near high-angle fault zones, may host deposits (*e.g*., Golden Bear mine area). 2. Interior Plateau region - if carbonate units present - potential basin and range setting.

E03 - Carbonate-hosted Disseminated Au-Ag

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Two geochemical asemblages - Au+As+Hg+W or ? Mo and As+Hg+ Sb+Tl or Fe. NH_3 important in some deposits. Au:Ag 10:1 or greater. Anomalous values in rock: As (100-1000 ppm); Sb (10-50 ppm); Hg (1-30 ppm).

GEOPHYSICAL SIGNATURE: Resistivity lows for some deposits. Aeromagnetic surveys may highlight spatially associated intrusions, skarns if present and possibly regional trends.

OTHER EXPLORATION GUIDES: In Nevada the deposits exhibit regional alignments or trends. Satellite imagery is useful to identify regional structures.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grades range from 1 to 35 g/t Au and deposit sizes from 1 to 150 Mt of ore. For 43 significant deposits the median tonnages and grades for low-grade oxide and higher grade hypogene deposits are 20 Mt grading 1.2 g/t Au and 6 Mt containing 4.5 g/t Au, respectively. Supergene deposits amenable to heap leaching typically grade 1-2 g/t Au; whereas, production grades for deposits with hypogene ore typically grade 5 to 10 g/t or greater.

ECONOMIC LIMITATIONS: Parts of deposits are amenable to open-pit mining and heap leaching (especially oxidized zones), but roasting and autoclave extraction is required for more refractory ores. New discoveries of high-grade hypogene ore have resulted in increased underground mining.

IMPORTANCE: Between 1965 and 1995, deposits along the Carlin Trend (70 x 10 km), have yielded approximately 750 t of Au. Deposits that are unquestionably of this type are not presently known in Canada but may be present.

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E03 - Carbonate-hosted Disseminated Au-Ag

Schroeter, T.G. (1986): Muddy Lake Project; *in* Geological Fieldwork, 1985, *B. C. Ministry of Energy, Mines and Petroleum Resources*, Paper 1986-1, pages 175-183.

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E04 - Sediment-hosted Cu-Ag-Co

by David V. Lefebure[1] and Dani J. Alldrick[1]

Lefebure, D.V., and Alldrick, D.J., 1996. Sediment-hosted Cu±Ag±Co: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 13–16.

IDENTIFICATION

SYNONYMS: Sediment-hosted stratiform copper, shale-hosted copper, Kupferschiefer-type, redbed Cu, Cu-shale, sandstone Cu.

COMMODITIES (BYPRODUCTS): Cu, Ag (Co, Pb, Zn, rarely PGE, Au, U, Va).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Roo (082GSW020), Commerce (082GSE065), Chal 4 (092K068); *Redstone (Northwest Territories, Canada), Kennicott (Alaska, USA), Spar Lake (Troy), Rock Creek and Montanore (Montana, USA), White Pine (Michigan, USA), Creta (Oklahoma, USA), Corocoro (Bolivia), Mansfield-Sangerhausen and Spremberg, Kupferschiefer district (Germany), Konrad and Lubin (Poland), Dzherkazgan (Kazakhstan), Copper Claim (Australia), Kamoto and Shaba, Zambia-Zaire copperbelt (Zaire).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stratabound disseminations of native copper, chalcocite, bornite and chalcopyrite in a variety of continental sedimentary rocks including black shale, sandstone and limestone. These sequences are typically underlain by, or interbedded with, redbed sandstones with evaporite sequences. Sulphides are typically hosted by grey, green or white strata.

TECTONIC SETTINGS: Predominantly rift environments located in both intracontinental and continental-margin settings; they can also occur in continental-arc and back-arc settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The characteristic presence of redbed and evaporite sequences points to deposition of sediments in a hot, arid to semi-arid paleoclimate near the paleoequator. The host rocks are produced in a variety of local anoxic depositional environments, including deltaic sediments, Sabkha-type lagoonal carbonate basins or high intertidal mudflats, and shallow “coal basins”.

AGE OF MINERALIZATION: Proterozoic or younger; Middle Proterozoic, Permian and early Mesozoic most favourable ages.

HOST/ASSOCIATED ROCK TYPES: Most deposits are hosted by pale gray to black shale, but some are found in sandstone, siltstone, limestone, silty dolomite, laminated carbonate units (sabkha origin) and quartzites. Favourable horizons contain reactive organic matter or sulphur. Algal mats, mudcracks and scour-and-fill structures indicative of shallow-water deposition are common. Local channel-conglomerate beds sometimes contain wood fragments. The associated sequence includes redbed sediments, evaporites and sometimes volcanics. In many cases the rift-related layered rocks rest unconformably on older basement rocks.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

E04 - Sediment-Hosted Cu-Ag-Co

DEPOSIT FORM: Orebodies are generally conformable with the bedding, although in detail ore may transgress bedding at low angles and is typically more transgressive near the margins of the deposit. Mineralized horizons are from tens of centimetres to several metres thick (rarely more than 5 m); they are often contained within broader zones of anomalous copper values. Tabular ore zones extend laterally for kilometres to tens of kilometres. Less commonly the deposits are elongate lobes. Some deposits have a C-shaped, “roll front” configuration in cross-section. Common lateral and/or vertical zoning is from hematite (barren) > chalcocite > bornite > chalcopyrite > pyrite, or from a chalcocite+bornite core grading to chalcopyrite with peripheral galena and sphalerite.

TEXTURE/STRUCTURE: Sulphides are fine grained and occur as disseminations, concentrated along bedding, particularly the coarser grained fractions, or as intergranular cement. Sharp-walled cracks or veinlets (< 1 cm thick, < than a metre in length) of chalcopyrite, bornite, chalcocite, galena, sphalerite or barite with calcite occur in some deposits, but are not an important component of the ore. Pyrite can be framboidal or colloform. Cu minerals often replace pyrite grains, framboids and nodules; less commonly they form pseudomorphs of sulphate nodules or blade-shaped gypsum/anhydrite grains. They also cluster around carbonaceous clots or fragments.

ORE MINERALOGY [Principal and *subordinate]:* Chalcocite, bornite and chalcopyrite; native copper in some deposits. Pyrite is abundant in rocks outside the ore zones. *Enargite, digenite, djurleite, sphalerite, galena, tennantite, native silver with minor Co-pyrite and Ge minerals*. In many deposits carrollite ($CuCo_2S_4$) is a rare mineral, however, it is common in the Central African Copperbelt.

GANGUE MINERALOGY [Principal and *subordinate]:* Not well documented; in several deposits carbonate, quartz and feldspar formed synchronously with the ore minerals and exhibit zonal patterns that are sympathetic with the ore minerals. They infill, replace or overgrow detrital or earlier authigenic phases.

ALTERATION MINERALOGY: Lateral or underlying reduced zones of green, white or grey colour in redbed successions. In the Montana deposits these zones contain chlorite, magnetite and/or pyrite. Barren, hematite-rich, red zones grade into ore in the Kupferschiefer. Kupferschiefer ore hosts also show elevated vitrinite reflectances compared to equivalent stratigraphic units.

WEATHERING: Surface exposures may be totally leached or have malachite and azurite staining. Near surface secondary chalcocite enrichment is common.

ORE CONTROLS: Most sediment-hosted Cu deposits are associated with the sag phase of continental rifts characterized by deposition of shallow-water sediments represented by redbed sequences and evaporites. These formed in hot, arid to semi-arid paleoclimates which normally occur within 20-30° of the paleoequator. Hostrocks are typically black, grey or green reduced sediments with disseminated pyrite or organics. The main control on fluid flow from the source to redoxcline is primary permeability within specific rock units, commonly coarse-grained sandstones. In some districts deposits are located within coarser grained sediments on the flanks of basement highs. Growth faults provide local controls in some deposits (*e.g*., Spar Lake).

ASSOCIATED DEPOSIT TYPES: Sandstone U (D05), volcanic redbed Cu (D03), Kipushi Cu-Pb-Zn (E02), evaporite halite, sylvite, gypsum and anhydrite (F02); natural gas (mainly CH_4) in Poland.

GENETIC MODELS: Traditionally these deposits have been regarded as syngenetic, analogous to sedex deposits or late hydrothermal epigenetic deposits. Currently most researchers emphasize a two-stage diagenetic model. Carbonaceous shales, sandstones and limestones deposited in reducing, shallow subaqeuous environments undergo diagenesis which converts the sulphur in these sediments to pyrite. At a later stage during diagenesis, saline low-temperature brines carrying copper from a distant source follow permeable units, such as oxidized redbed sandstones, until they encounter a reducing unit. At this point a redoxcline is established with a cuperiferous zone extending “downstream” until it gradually fades into the unmineralized, often pyritic, reducing unit. The source of the metals is unresolved, with possible choices including underlying volcanic rocks, labile sediments, basement rocks or intrusions.

E04 - Sediment-hosted Cu-Ag-Co

COMMENTS: Sediment-hosted Cu includes Sabkha Cu deposits which are hosted by thin-bedded carbonate-evaporite-redbed 'sabkha' sequences.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Cu, Ag, Pb, Zn and Cd are found in hostrocks, sometimes with weaker Hg, Mo, V, U, Co and Ge anomalies. Dark streaks and specks in suitable rocks should be analysed as they may be sulphides, such as chalcocite.

GEOPHYSICAL SIGNATURE: Weak radioactivity in some deposits.

OTHER EXPLORATION GUIDES: Deposits often occur near the transition from redbeds to other units which is marked by the distinctive change in colour from red or purple to grey, green or black. The basal reduced unit within the stratigraphy overlying the redbeds will most often carry the highest grade mineralization.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Average deposit contains 22 Mt grading 2.1 % Cu and 23 g/t Ag (Mosier *et al*., 1986). Approximately 20% of these deposits average 0.24 % Co. The Lubin deposit contains 2600 Mt of >2.0% Cu and ~ 30-80 g/t Ag. Spar Lake pre-production reserves were 58 Mt grading 0.76% Cu and 54 g/t Ag. Montanore contains 134.5 Mt grading 0.74% Cu and 60 g/t Ag, while Rock Creek has reserves of 143.7 Mt containing 0.68 % Cu and 51 g/t Ag.

ECONOMIC LIMITATIONS: These relatively thin horizons require higher grades because they are typically mined by underground methods. The polymetallic nature and broad lateral extent make them attractive.

IMPORTANCE: These deposits are the second most important source of copper world wide after porphyry Cu deposits. They are an interesting potential exploration target in British Columbia, although there has been no production from sediment-hosted Cu deposits in the province. The stratigraphy that hosts the Spar Lake, Montanore and Rock Creek deposits in Montana extends into British Columbia where it contains numerous small sediment-hosted Cu-Ag deposits.

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ACKNOWLEDGEMENTS: Nick Massey contributed to the original draft of the profile.

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E04 - Sediment-hosted Cu-Ag-Co

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E05 - Sandstone-Pb

by D.F. Sangster[1]

Sangster, D.F., 1996. Sandstone Pb: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 17–19.

IDENTIFICATION

COMMODITIES (BYPRODUCTS): Pb (Zn, Ag).

EXAMPLES (British Columbia - *Canada/International*): None in British Columbia; *only two are known in Canada; Yava (Nova Scotia) and George Lake (Saskatchewan), Laisvall (Sweden), Largentière (France), Zeida (Morocco), Maubach and Mechernich (Germany).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Disseminated galena with minor sphalerite, in transgressive basal quartzite or quartzofeldspathic sandstones resting on sialic basement.

TECTONIC SETTING: Platformal deposits commonly found in sandstones resting directly on basement (usually cratonic) of sialic composition.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Hostrocks were deposited in environments ranging from continental fluvial to shallow marine or tidal beach. The most common environment is one of mixed continental and marine character (*i.e.*, paralic). Host rocks in most districts are succeeded by marine sediments, suggestive of marine transgression onto the craton. Terrestrial organic debris, ranging from trace to abundant, is present in most of the post-Devonian deposits. Paleomagnetic data available in several districts indicate a low paleolatitude position (0-30°) for all deposits. Paleoclimatic conditions ranged from warm arid to cool humid but in a majority of cases, were semiarid and warm.

AGE OF MINERALIZATION: Mineralization age has not been established with certainty; however, deposits are found in rocks ranging from Middle Proterozoic to Cretaceous age. Rocks of Late Proterozoic - Early Cambrian and Triassic ages contain a majority of deposits of this type.

HOST/ASSOCIATED ROCK TYPES: Hostrocks are grey or white (never red) quartzitic or quartzo-feldspathic sandstones and conglomerates; they are rarely siltstone or finer grained clastics. Sialic basement rocks, typically granites or granitic gneisses, underly sandstone lead deposits. Shales and associated evaporites as beds, nodules or disseminations are intercalated with the host sandstones.

DEPOSIT FORM: Orebodies are commonly conformable with bedding in the sandstone, especially on a mine scale. In detail, however, the ore zones may actually transgress bedding at a low angle. Sedimentary channels in the sandstone are preferentially mineralized; consequently, most deposits have a generally lensoid form. In plan, ore zones tend to be sinuous and laterally discontinous. Ore zones tend to be delimited by assay, rather than geological, boundaries. Characteristically, a higher grade core is surrounded by material that progressively decreases in grade outward. Rarely, higher grade zones occur in, and adjacent to, steep faults; consequently, in these deposits, many ore zones are narrow, lenticular bodies oriented at high angles to bedding.

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E05 - Sandstone-Pb

TEXTURE/STRUCTURE: The preferred site of ore minerals is as cement between sand grains resulting in disseminated sulphide blebs or spots in massive sandstones or concentrations of sulphides along the lower, more porous portions of graded beds. The disseminated sulphides are not normally homogeneously dispersed throughout the sandstone. Two very common textures are: i) spots, representing local accumulations of galena, as much as 2 cm in diameter. Spots may be randomly distributed in the sandstone or may show a slight preferential alignment parallel to bedding; ii) discontinous galena-rich streaks distributed parallel to bedding, including crossbedding. Where carbonaceous material is present, sulphides fill wood cells or replace cell walls. Concretionary-like sulphide concentrations are abundant in some deposits. Epitaxial quartz overgrowths on detrital quartz grains are very common and in some deposits more abundant within or near ore zones than regionally. Paragenetic studies indicate the epitaxial quartz predates galena.

ORE MINERALOGY [Principal and *subordinate*]: Galena, sphalerite, and pyrite, *chalcopyrite and various Ni-Co-Fe sulphides.* Replacement of sulphides by secondary analogues has been reported in one or more deposits.

GANGUE MINERALOGY [Principal and *subordinate*]: Silica, usually chalcedonic, and various carbonate minerals constitute the most abundant non-sulphide cement.

ALTERATION MINERALOGY: If the hostrocks were originally arkosic, pre-mineralization alteration (sometimes referred to as "chemical erosion") of the host sandstones commonly results in complete, or near-complete, destruction of any feldspars and mafic minerals which may have been present. Otherwise, alteration of quartz sandstone hosts is nil. Neomorphic formation of quartz overgrowths and authigenic clay minerals, however, is a common feature of these deposits; calcite and sulphates are less common cements. Pre-sandstone weathering of granitic basement, as evidenced by the presence of paleoregolith and the destruction of feldspar and mafic minerals, has been observed beneath several deposits.

ORE CONTROLS: 1. Sialic basement; those with average lead content greater than ~30 ppm are particularly significant. 2. Basal portion of grey or white (not red) quartzitic sandstone of a transgressive sequence on sialic basement. The "cleaner" portions, with minimum intergranular material, are the preferred host lithologies because they are more porous. 3. Channels in sandstone, especially on the periphery of the sedimentary basin. These channels may also be evident in the basement.

GENETIC MODEL: Groundwater transport of metals leached from lead-rich basement, through porosity channels in sandstone; precipitation of metals by biogenically-produced sulphide. A genetic model involving compaction of brine-bearing basins by over-riding nappes has been proposed for deposits in Sweden.

ASSOCIATED DEPOSIT TYPES: Sandstone Cu and sandstone U (D05).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Stream sediment and soil geochemical surveys; analyze for Pb and Zn.

GEOPHYSICAL SIGNATURE: Induced polarization anomalies (?)

OTHER EXPLORATION GUIDES: Epitaxial quartz overgrowths are abundant, especially within and near the ore zones. Host sandstones deposited at low paleolatitudes. Sialic basement with high lead content (>30 ppm). Basal quartz sandstone of a transgressive sequence, overlying basement. Channels in sandstone as evidenced by thickening, lateral conglomerate-to-sandstone facies changes, etc. Permeable zones in sandstone (i.e., “cleanest” sandstone, minimum of intergranular clayey material).

E05 – Sandstone-Pb

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits range in grade from 2 to 5% Pb, 0.2 to 0.8% Zn, 1 to 20 g/t Ag; most are less than 10 Mt in size. Because of the disseminated nature of the ore, tonnages and grades can be markedly affected by changes in cut-off grades. At Yava, for example, at cut-off grades of 1, 2, and 3%, tonnages and grades are as follows: 71.2 Mt at 2.09% Pb, 30.3 Mt at 3.01%, and 12.6 Mt at 3.95%, respectively.

ECONOMIC LIMITATIONS: Because of the typically low Pb grades and the general paucity of byproduct commodities, this deposit type has always been a minor player in the world's base metal markets.

IMPORTANCE: In some countries where other sources of Pb are limited, sandstone-Pb deposits have constituted major national resources of this metal (*e.g.* Sweden).

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E06 - Bentonite

by Z.D. Hora[1]

Hora, Z.D., 1999. Bentonite: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 27–29.

IDENTIFICATION

SYNONYMS: Sodium and calcium montmorillonites, montmorillonite clay, smectite clay, volcanic clay, soap clay, mineral soap. Other terms for sodium montmorillonites are sodium bentonite, swelling bentonite, Wyoming or Western bentonite, while calcium montmorillonites are referred to as calcium bentonites, non-swelling bentonite, Southern bentonite or fuller's earth, sub-bentonite.

COMMODITY: Bentonite (many different grades for a variety of applications and end uses).

EXAMPLES (British Columbia (MINFILE #)- *Canada/International*): Hat Creek (0921NW084), Princeton (092HSE151), Quilchena (0921SE138), French Bar (0920 099); *Rosalind (Alberta, Canada), Truax (Saskatchewan, Canada) Morden (Manitoba, Canada), Black Hills District, Big Horn Basin (Wyoming, USA), Gonzales and Lafayette Counties (Texas, USA), Itawambaand and Monroe Counties (Mississippi, USA), Milos (Greece), Landshut (Germany), Sardinia (Italy), Annaka (Japan), Campina Grande (Brazil).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Montmorillonite-rich clay beds intercalated with shales, sandstones and marls which are part of shallow marine or lacustrine environment deposits.

TECTONIC SETTINGS: Virtually all continental or continental platform settings; also common in island arcs.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Bentonite deposits form when volcanic ash is deposited in a variety of freshwater (sometimes alkaline lakes) and marine basins characterized by low energy depositional environments and temperate climatic conditions.

AGE OF MINERALIZATION: Mostly Cretaceous to Miocene age, but are known to be as old as Jurassic and as recent as Pleistocene.

HOST/ASSOCIATED ROCK TYPES: Bentonites are hosted by and associated with argillite, mudstone, siltstone, sandstone, tuff, agglomerate, ignimbrites, marl, shale, zeolite beds and coal.

DEPOSIT FORM: Beds range in thickness from several centimeters to tens of meters and can extend hundreds of kilometres. In island arc environment, bentonite can also occur as lens-shaped bodies with a limited lateral extent.

TEXTURE/STRUCTURE: Bentonite is bedded, with a soapy texture and waxy appearance. It ranges in colour from white to yellow to olive green to brown to blue. In outcrop, bentonite has a distinctive "popcorn" texture.

ORE MINERALOGY [Principal and *subordinate*]: Montmorillonite, *beidellite, illite.*

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

E06 - Bentonite

GANGUE MINERALOGY [Principal and *subordinate*]: Mica, feldspar, quartz, calcite, zeolites, gypsum, *opaline silica, cristobalite, unaltered volcanic glass*. These minerals rarely constitute more than 10% of a commercially viable deposit.

ALTERATION MINERALOGY: Alteration consists of devitrification of the volcanic ash with hydration and crystallization of the smectite mineral. In some instances there is evidence of a loss of alkalies during the alteration. Also, silicification of beds underlying some bentonites indicates downward migration of silica. There is also sometimes an increase in magnesium content compared to parent material. Besides smectite minerals, other alteration products in the volcanic ash include cristobalite, opaline silica, zeolites, calcite, selenite and various iron sulphate minerals.

WEATHERING: Yellow colouration (the result of oxidized iron ions) may improve the colloidal properties of bentonite. Also, weathering may decrease exchangeable calcium and increase exchangeable sodium. Some soluble impurities like calcite, iron sulphates or selenite may be removed by weathering process.

ORE CONTROLS: The regional extent of bentonite deposits is controlled by the limit of the regional deposition environment, paleogeography and distribution of the volcanic pyroclastic unit. Porosity of the host rocks may be important for the alteration process. Deposits in the continental and continental platform settings are the largest.

GENETIC MODELS: Volcanic pyroclastic material is ejected and deposited in shallow marine or lacustrine setting. Bentonite is a product of alteration of the glass component of ashes and agglomerates. Alteration of the glassy pyroclastic material possibly starts when the ash contacts the water or may occur soon after the ash reaches the seafloor or lake bottom. Wyoming bentonites, however, were altered after burial by reaction with diagenetic seawater pore fluids.

ASSOCIATED DEPOSIT TYPES: Other clays, zeolite (D01, D02), lignite coal (A02), sepiolite, palygorskite (F05).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Nil.

GEOPHYSICAL SIGNATURE: Apparent resistivity and refraction seismic survey may help to interpret the lithology.

OTHER EXPLORATION GUIDES: Sedimentary basins with volcanic ash layers. In some locations bentonite layers can form a plane of weakness that results in landslides. Montmorillonite displays popcorn texture on the dry surface.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Montmorillonite content is usually more than 80%. Other properties depend on specifications for particular applications. Published data on individual deposits are very scarce. Typically, commercial beds in Wyoming are 0.9 to 1.5 metres thick. Individual bentonite beds are continuous for several kilometres. The Wilcox mine in Saskatchewan has three bentonite seams - 61, 46 and 30 centimetres thick within a 6 metre thick sequence of shale. In Manitoba, another mine has 6 beds which have a cumulative thickness of about 76 centimetres within a 1 meter sequence.

ECONOMIC LIMITATIONS: Value of the product depends on the type of impurities, colour, size of clay particles, cation exchange capability, rheological properties and structures of the clay. Sodium bentonites are of more interest because of swelling properties and in general higher cation exchange capacity. Calcium bentonites are frequently activated by acids or soda ash to provide better performing product. Economic viability is often determined by the thickness of the overlying strata and overburden. The Wyoming deposits are mined with up to 12 metres of overburden. The 1997 quoted price for Wyoming bentonite is US$25 to 40 a short ton.

E06 - Bentonite

END USES: Main uses for bentonite are in foundry sands, drilling muds, iron ore pelletizing and absorbents. Important applications are also in civil engineering for a variety of composite liners and as a food additive for poultry and domestic animals. (Special uses include filtration in food processing, cosmetics and pharmaceuticals).

IMPORTANCE: Bentonite is an important industrial mineral; about 6 million tonnes are produced annually in North America. Declining markets in drilling mud and pelletizing will likely be easily offset by increasing use in environmental applications like liners and sealers.

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E07 - Sedimentary Kaolin

by Z.D. Hora[1]

Hora, Z.D., 1999. Sedimentary kaolin: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 31–33.

IDENTIFICATION

SYNONYMS: Secondary kaolin deposits, fireclay, underclays, high-alumina clay, china clay.

COMMODITIES (BYPRODUCTS) Kaolin (many different grades for specific applications), ceramic clay, ball clay, refractory clay (cement rock, bauxite, silica sand).

EXAMPLES (British Columbia (MINFILE #) - *Canada*/*International*): Sumas Mountain (92GSE004, 92GSE024), Blue Mountain (92GSE028), Lang Bay (92F 137), Quinsam (92F 319), Giscome Rapids (93J 020); *Cypress Hills (Alberta, Canada), Eastend, Wood Mountain, Ravenscrag (Saskatchewan, Canada), Moose River Basin (Ontario, Canada), Shubenacadie Valley (Nova Scotia, Canada), Aiken (South Carolina, USA), Wrens, Sandersville, Macon-Gordon, Andersonville (Georgia, USA), Eufaula (Alabama, USA), Weipa (Queensland, Australia), Jari, Capim (Brazil).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Beds, lenses and saucer-shaped bodies of kaolinitic claystones hosted by clastic sedimentary rocks, with or without coaly layers or coal seams. They usually occur in freshwater basins filled with sediments derived from deeply weathered, crystalline feldspathic rocks.

TECTONIC SETTINGS: Low-lying coastal plains at continental edge; extension basins in orogenic belts; stable continental basins; back arc basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Clay beds are generally deposited in low energy environments within freshwater basins. Temperate to tropical climatic conditions can produce intensive kaolinitic weathering of feldspathic rocks of granitic composition. The kaolin is then eroded and transported to estuaries, lagoons, oxbow lakes and ponds.

AGE OF MINERALIZATION: Most of the world class deposits are Upper Cretaceous to Eocene age. Some “fireclay” and “underclay” deposits are Late Carboniferous.

HOST/ASSOCIATED ROCK TYPES: Kaolin beds are associated with variably kaolinitic, micaceous sandstones within mudstone, siltstone, sandstone and conglomerate sequences which often are cross-bedded. Coal (sub-bituminous and lignite) may be associated with kaolin beds. Diatomite may also be present.

DEPOSIT FORM: Beds exhibit variable thickness, usually a few metres; sometimes multiple beds have an aggregate thickness of approximately 20 metres. Deposits commonly extend over areas of at least several square kilometers.

TEXTURE/STRUCTURE: Kaolin is soft and exhibits conchoidal or semi-conchoidal fracture; it can be bedded or massive. Most kaolins will slake in water, but some “flint” varieties break into smaller angular fragments only. Depending on kaolin particle size and presence of organic matter, some clays may be very plastic when moist and are usually called “ball clays”.

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E07 - Sedimentary Kaolin

ORE MINERALOGY [Principal and subordinate]: Kaolinite, *halloysite, quartz, dickite, nacrite, diaspor, boehmite, gibbsite*.

GANGUE MINERALOGY [Principal and subordinate]: Quartz*, limonite, goethite, feldspar, mica, siderite, pyrite, illmenite, leucoxene, anatas*.

WEATHERING: The kaolin forms by weathering which results in decomposition of feldspars and other aluminosilicate minerals and removal of fluxing components like alkalies or iron. Post depositional weathering and leaching can produce gibbsitic bauxite. In some deposits, post depositional weathering may improve crystallinity of kaolin particles and increase the size of crystal aggregates.

ORE CONTROLS: The formation and localization of clay is controlled by the location of the sedimentary basin and the presence of weathered, granitic rocks adjacent to the basin, particularly rapidly eroding paleotopographic highs.

GENETIC MODELS: Ideal conditions to produce kaolinitic chemical weathering are high rainfall, warm temperatures, lush vegetation, low relief and high groundwater table. The kaolin is eroded and transported by streams to a quiet, fresh or brackish, water environment. Post-depositional leaching, oxidation, and diagenesis can significantly modify the original clay mineralogy with improvement of kaolin quality.

ASSOCIATED DEPOSIT TYPES: Peat (A01), coal seams (A02, A03, A04), paleoplacers (CO4), some bentonites (EO6), lacustrine diatomite (FO6).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: None. Enrichment in Al does not provide sufficient contrast with host sediments.

GEOPHYSICAL SIGNATURE: Apparent resistivity and refraction seismic surveys can be used in exploration for fireclay beds.

OTHER EXPLORATION GUIDES: Most readily ascertainable regional attribute is sedimentary basins with Upper Cretaceous and Eocene unconformities. Within these basins kaolin occurs with sediments, including coal seams, deposited in low energy environments.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Published data on individual deposits are very scarce. Deposits in Georgia, USA contain 90 to 95% kaolinite. Individual Cretaceous beds are reported to be up to 12 m thick and extend more than 2 km while those in the Tertiary sequence are 10 to 25 m thick and up to 18 km along strike. The Weipa deposit in Australia is 8 to 12 m thick and contains 40 to 70% kaolinite. The Jari deposit in Brazil is reported to contain more than 250 Mt of "good, commercial grade kaolin". Over 200 Mt of reserves "have been proven" at Capim deposit in Brazil. Ball clay deposits in Tennessee and Kentucky consist of kaolin with from 5 to 30% silica; individual deposits may be more than 9 m thick and extend over areas from 100 to 800 m long and up to 300 m wide.

ECONOMIC LIMITATIONS: Physical and chemical properties affect end use. Physical properties include brightness, particle size distribution, particle shape and rheology. Limonite staining is a negative feature. The high level of processing required to meet industry specifications and minimize transportation cost to the end user are the main limiting factors for kaolin use. While local sources compete for low value markets, high quality products may be shipped to users several thousand km from the plant. Most production is from open pits; good quality fireclay seams more than 2 meters thick are sometimes mined underground. Typically, paper coating grade sells for up to US$120, filler grade for up to US$92 and sanitary ceramics grade for $US55 to $65 per short ton (Industrial Minerals, 1997). Refractory and ball clay prices are within the same range.

E07 - Sedimentary Kaolin

END USES: The most important use for kaolin is in the paper industry, both as a filler and coating pigment. A variety of industrial filler applications (rubber, paints, plastics, etc.) are another major end use. Kaolin's traditional use in ceramic products is holding steady, but the refractory use has declined substantially in the last two decades because of replacement by other high performance products.

IMPORTANCE: One of the most important industrial minerals in North America. Over 11 Mt is produced annually and production is on a steady increase.

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E08 - Carbonate-Hosted Talc

by G.J. Simandl[1] and S. Paradis[2]

Simandl, G.J., and Paradis, S., 1999. Carbonate-hosted talc: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 35–38.

IDENTIFICATION

SYNONYMS: "Dolomite-hosted" talc deposits.

COMMODITIES: Talc and/or tremolite. Some of the commercial products derived from carbonate-hosted deposits and marketed as talc, contain over 50% tremolite.

EXAMPLES (British Columbia - *Canada/International*): Gold Dollar (082O 001), Red Mountain (082O 002), Saddle Occurrences (082O 003); *Henderson Talc Deposit (Ontario, Canada), Treasure mine (Montana, USA), Gouverneur Talc (New York State, USA) and Trimouns deposit (France).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Most of the economic carbonate-hosted deposits are lenticular or sheet-like bodies and are concordant with surrounding dolomitic marbles, siliceous dolomitic marbles, dolomites, schists and phyllites. The massive or schistose ore consists mainly of talc ± dolomite, ± tremolite, ± calcite, ± magnesite, ± chlorite, ± serpentine, ± phlogopite.

TECTONIC SETTING: Protolith deposited mainly in pericratonic environments; in most cases the talc formed later within metamorphic, fold or thrust belts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Dolostones, dolomitic marbles or magnesite beds metamorphosed to greenschist facies or lower amphibolite facies represent a typical host environment. Upper amphibolite-grade marbles, where talc would not normally be stable, may contain retrograde talc zones.

AGE OF MINERALIZATION: Mainly Precambrian to Early Paleozoic but may be younger. In most cases syn- or post-metamorphic.

HOST/ASSOCIATED ROCK TYPES: Dolomitic marbles and dolomites are the typical host, however some of the deposits are hosted by magnesite or mica schists. Phyllites, chlorite or mica schists, paragneiss and intrusive and metavolcanic rocks may be present adjacent to, or in the proximity of the talc deposits. Deposits may be crosscut by minor intrusions, such as diabase dikes.

DEPOSIT FORM: In most cases, podiform or deformed, sheet-like bodies oriented subparallel to the compositional layering within marbles and to geologic contacts. They are commonly folded or pinch and swell. Typical dimensions would be 2 to 20 m thick and tens to hundreds of metres along strike and dip. Where fluids were the principal source of heat and/or silica, breccia zones and irregular deposits may occur near fault intersections.

TEXTURE/STRUCTURE: Ore varies from fine-grained, massive or layered talc to coarse talc schists. Pseudomorphs of talc after tremolite are common in deposits that formed after the peak of metamorphism.

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E08 - Carbonate-Hosted Talc

ORE [Principal and *subordinate*]: Talc and *tremolite* (in some ores and commercial products tremolite is a principal constituent*).*

GANGUE MINERALOGY [Principal and *subordinate*]: Dolomite, ± tremolite, ± calcite, ± magnesite, ± chlorite, ± serpentine, and ± phlogopite may be principal gangue minerals. *Pyrite, ± graphite, ± mica, ± dravite, and ± anorthite* are common accessory impurities.

ALTERATION MINERALOGY: In some deposits at least a portion of talc is believed to have formed by retrograde reactions from tremolite. In some cases, there is a replacement of biotite by chlorite and feldspar by sericite or chlorite in the host rock.

WEATHERING: Talc-bearing zones may form ridges where chemical processes dominate and topographic lows where physical weathering and/or glaciation are most important.

ORE CONTROLS: The main controls are the presence of dolomite or magnesite protolith, availability of silica and favourable metamorphic/metasomatic conditions. Talc deposits hosted by carbonate rocks may be divided into several subtypes according to the source of silica and geological setting:
a) contacts between carbonates, usually dolomitic marbles, and silica-bearing rocks, such as biotite-quartz-feldspar gneisses, schists, cherts and quartzites;
b) horizons or lenses of siliceous dolomite or magnesite protolith;
c) crests of folds, breccia zones, faults, and intersections of fault systems that permit circulation of metasomatic fluids carrying silica within dolomite or magnesite host; and
d) carbonates within the contact metamorphic aureole of intrusions, where silica has been derived from adjacent host rock.

GENETIC MODEL: Most carbonate-hosted talc deposits are believed to be formed by the reaction:

$$\text{3 dolomite} + 4\ SiO_2 + H_2O = \text{1 talc} + \text{3 calcite} + 3\ CO_2$$

Silica may be provided either from adjacent quartz-bearing rocks, from silica layers within the carbonates, or by hydrothermal fluids. Absence of calcite in ores from several deposits indicates that talc may have formed in an open system environment and calcium was allowed to escape. The source of heat may be provided by regional metamorphism, contact metamorphism or by heat exchange from hydrothermal fluid. In environments where sedimentary-hosted magnesite deposits are known to occur, talc could have been produced by the reaction:

$$\text{3 magnesite} + 4\ SiO_2 + H_2O = \text{1 talc} + 3\ CO_2$$

In this second reaction calcite precipitation is not expected. This reaction takes place at lower temperature (given identical pressure and X_{CO_2} conditions) than the dolomite reaction, therefore, magnesite may be almost completely converted to talc before dolomite starts to react.
Pseudomorphs of talc after tremolite and the presence of upper amphibolite grade, metamorphic assemblages in host rocks of some of the deposits indicate that talc post-dates the metamorphic peak and is probably of retrograde origin. Depending on the individual deposits, metamorphic or metasomatic (hydrothermal) characteristics may be predominant.

ASSOCIATED DEPOSIT TYPES: Chlorite deposits, marble (R04), high-calcium carbonate (filler-grade) and limestone (R09), dolostone (R10), sedimentary-hosted magnesite deposits (E09) and deposits such as Balmat, which is probably a metamorphosed sedex deposit (E14).

E08 - Carbonate-Hosted Talc

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Talc in residual soils. Systematic study of soils to identify anomalous concentrations of talc using X-ray diffraction has proven successful.

GEOPHYSICAL SIGNATURE: Electromagnetic methods can be used to identify carbonate contacts with other lithologies or talc-related fault zones impregnated with water.

OTHER EXPLORATION GUIDES: Talc occurs within belts of dolomitic rocks in metamorphosed terranes or adjacent to intrusive rocks. Contacts with silica-bearing metasediments or intrusions are favourable loci for deposits.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grade is highly variable. For example, New York state talc ores commonly contain over 50% tremolite.

ECONOMIC LIMITATIONS: Major talc producing countries are China, USA, Finland, France, Brazil and Australia. Underground mining is economically feasible in case of high quality ores, but most mining is by open pit. Actinolite, tremolite and anthophyllite impurities are undesirable because of environmental restrictions on these minerals which limit the utilization of the ore. The most common properties measured to determine possible applications for talc concentrates are: mineral composition, dry brightness (green filter), whiteness, specific gravity, oil absorption, pH, particle size distribution, tapped density, loose density, Hegman fineness and chemical composition, including L.O.I.

END USES: In 1996, almost 1 million tonnes of talc valued at $US 100 million was sold or used in the USA. Talc is used in ceramics (28%), paint (18%), paper (17%), plastics (6%), roofing (11%) and cosmetics (4%). Insecticides, rubber refractories and other applications account for 16% (in USA). Cut or sawed blocks of fine-grained talc (steatite which is also used for carving) may sell for up to $US 2000.00 tonne. Paint and ceramic-grade talc is sold for $US 110.00 to 200.00/tonne, depending on the degree and method of processing. Some filler grades are sold at $US 600.00/tonne and cosmetic-grade talc and surface treated materials may sell for more than $US 2000.00/tonne.

IMPORTANCE: Talc may be substituted by clay or pyrophyllite in ceramics; by high calcium carbonate and kaolin in some paper applications and by other fillers and reinforcing agents in plastics. Talc from carbonate-hosted deposits also has to compete with products derived from ultramafic-hosted talc deposits (M07) in a number of applications. In North America carbonate-hosted deposits supply mainly the ceramic, paint and, to some extent the plastic markets.

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E09 - Sparry Magnesite

by G.J. Simandl[1] and K. Hancock[2]

Simandl, G.J., and Hancock, K., 1999. Sparry magnesite: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 39–41.

IDENTIFICATION

SYNONYMS: Veitsch-type, carbonate-hosted magnesite, crystalline magnesite.

COMMODITY: Magnesite.

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Mount Brussilof (082JNW001), Marysville (082GNW005), Brisco area and Driftwood Creek (082KNE068); *Veitsch, Entachen Alm, Hochfilzen, Radenthein and Breitenau (Austria), Eugui* (*Navarra Province, Spain), deposits of Ashan area, Liaoning Province (China), Satka deposit (Russia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stratabound and typically stratiform, lens-shaped zones of coarse-grained magnesite mainly occurring in carbonates but also observed in sandstones or other clastic sediments. Magnesite exhibits characteristic sparry texture.

TECTONIC SETTING: Typically continental margin or marine platform, possibly continental settings, occur in belts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The host sediments are deposited in a shallow marine environment adjacent to paleobathymetric highs or a lacustrine evaporitic environment.

AGE OF MINERALIZATION: Proterozoic or Paleozoic.

HOST/ASSOCIATED ROCK TYPES: Magnesite rock, dolostone, limestones, chert. Associated with shale, sandstone, conglomerate and volcanic rocks and their metamorphic equivalents.

DEPOSIT FORM: Commonly strata, lenses or rarely irregular masses, typically few hundred metres to several kilometres in strike length. Shortest dimension of the orebody (few to tens of metres) is commonly normal to the bedding planes.

TEXTURE/STRUCTURE: The magnesite-bearing rocks exhibit sparry, pinolitic, zebra-like, or xenotopic (anhedral) textures on the fresh surface. Magnesite or dolomite pseudomorphs after sulphates. "Box-textures", rosettes, monopolar and antipolar growths are locally present.

ORE MINERALOGY: Magnesite.

GANGUE MINERALOGY (Principal and *subordinate*): Dolomite ± quartz ± chert ± talc ± chlorite ± sulphides ± *sulphosalts, ± calcite, ± mica, ± palygorskite, ± aragonite, ± clay* (as veinlets), *organic material*. In highly metamorphosed terrains, metamorphic minerals derived from above precursors will be present.

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E09 - Sparry Magnesite

ALTERATION MINERALOGY: Talc may form on silica-magnesite grain boundaries due to low temperature metamorphism.

WEATHERING: Surface exposures are typically beige or pale brown and characterized by "granola-like" appearance. Most sulphides are altered into oxides in near surface environment.

ORE CONTROLS: Deposits are stratabound, commonly associated with unconformities. They are typically located in basins characterized by shallow marine depositional environments. Lenses may be located at various stratigraphic levels within magnesite-hosting formation.

GENETIC MODELS: There are two preferred theories regarding the origin of sparry magnesite deposits:

1) Replacement of dolomitized, permeable carbonates by magnesite due to interaction with a metasomatic fluid.
2) Diagenetic recrystallization of a magnesia-rich protolith deposited as chemical sediments in marine or lacustrine settings. The sediments would have consisted of fine-grained magnesite, hydromagnesite, huntite or other low temperature magnesia-bearing minerals.

The main difference between these hypotheses is the source of magnesia; external for metasomatic replacement and in situ in the case of diagenetic recrystalization. Temperatures of homogenization of fluid inclusions constrain the temperature of magnesite formation or recrystalization to 110 to 240ºC. In British Columbia the diagenetic recrystalization theory may best explain the stratigraphic association with gypsum and halite casts, correlation with paleotopographic highs and unconformities, and shallow marine depositional features of the deposits.

A number of recent cryptocrystalline sedimentary magnesite deposits, such as Salda Lake in Turkey and the Kunwarara deposit in Queensland, Australia, huntite-magnesite-hydromagnesite deposits of Kozani Basin, Northern Greece, and the magnesite- or hydromagnesite-bearing evaporitic occurrences from Sebkha el Melah in Tunesia may be recent analogs to the pre-diagenetic protoliths for British Columbia sparry magnesite deposits.

ASSOCIATED DEPOSIT TYPES: Sediment-hosted talc deposits (E08) and Mississippi Valley-type deposits (E12) are geographically, but not genetically, associated with sparry magnesite in British Columbia. The magnesite appears older than cross-cutting sparry dolomite that is commonly associated with MVT deposits.

COMMENTS: Sparry magnesite deposits can survive even in high grade metamorphic environments because of their nearly monomineralic nature.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Tracing of magnesite boulders and blocks with pinolitic texture. Magnesite grains in stream sediments.

GEOPHYSICAL SIGNATURE: N/A.

OTHER EXPLORATION GUIDES: Surface exposures are beige, pale brown or pale gray. White fine-grained marker horizons are useful in southwest British Columbia. "Granola-like" weathering texture is a useful prospecting indicator. Magnesite may be identified in the field using heavy-liquids. In British Columbia the deposits are often associated with unconformities, paleotopographic highs within particular stratigraphic horizons.

E09 - Sparry Magnesite

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grades range from 90 to 95% $MgCO_3$ with the resources ranging from several to hundreds of million tonnes. British Columbia deposits are characterized by lower iron content than most of the European deposits.

ECONOMIC LIMITATIONS: There is large but very competitive market for magnesia-based products. China is the largest exporter of magnesite. Quality of primary raw materials, cost of energy, cost of transportation to markets, availability of existing infrastructure, and the quality of finished product are major factors achieving a successful operation.

END USES: Magnesite is used to produce magnesium metal and caustic, dead-burned and fused magnesia. Caustic magnesia, and derived tertiary products are used in chemical and industrial applications, construction, animal foodstuffs and environmental rehabilitation. Fused and dead-burned magnesia are used in high-performance refractories. Magnesium metal has wide range of end uses, mostly in the aerospace and automotive industries. The automotive market for magnesium metal is expected to expand rapidly with current efforts to reduce the weight of vehicles to improve fuel economy and reduce harmful emissions.

IMPORTANCE: Sparry magnesite deposits account for 80% of the world production. Significant quantities of magnesite are also produced from ultramafic-hosted deposits and fine grained or nodular deposits.

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E12 - Mississippi Valley-type Pb-Zn

D. Alldrick[1] and D. Sangster[2]

Alldrick, D.J., and Sangster, D.F., 2000. Mississippi Valley-type Pb-Zn: website, British Columbia Geological Survey, Ministry of Energy, Mines and Petroleum Resources, pp. 4.

IDENTIFICATION

SYNONYMS: Alpine-type Pb-Zn, Appalachian Zn, Low-temperature epigenetic Pb-Zn. Irish-type Zn-Pb (E13) is classified with MVT deposits in some studies.

COMMODITIES (BYPRODUCTS): Pb, Zn, ± Ag (Cd, Ge, barite, fluorite)

EXAMPLES: (British Columbia - *Canada/ International*): Robb Lake (94B 005), Monarch (82N 020), Kicking Horse (82N 282); *(Yukon): Goz (106C 020), Blende (106D 064), Craig (106C 073); Nanisivik, Pine Point, Polaris (Northwest Territories); Gays River (Nova Scotia); Newfoundland Zinc (Newfoundland); Mascot-Jefferson City, Copper Ridge district (Tennessee, United States), Old Lead Belt and Viburnum Trend (Missouri, United States), Tri-State (Oklahoma, Kansas and Missouri, United States); Harberton Bridge (Ireland), Upper Silesia (Poland); Raibl, Bleiberg (Austria).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Epigenetic, low-temperature, stratabound deposits of galena, sphalerite, pyrite and marcasite, with associated dolomite, calcite and quartz gangue in platformal carbonate sequences having primary and secondary porosity.

TECTONIC SETTINGS: Most commonly stable interior cratonic platform or continental shelf. Some deposits are incorporated in foreland thrust belts.

DEPOSITIONAL ENVIRONMENT/GEOLOGIC SETTING: Host rocks form in shallow water, particularly tidal and subtidal marine environments. Reef complexes may be developed on or near paleotopographic basement highs. The majority of deposits are found around the margins of deep-water shale basins; some are located within or near rifts (Nanisivik, Alpine district).

AGE OF MINERALIZATION: Proterozoic to Tertiary, with two peaks in Devonian to Permian and Cretaceous to Eocene time. Dating mineralization has confirmed the epigenetic character of these deposits; the difference between host rock age and mineralization age varies from district to district. Known Yukon deposits are hosted in Proterozoic strata, but true mineralization ages of these epigenetic deposits are poorly constrained.

HOST/ASSOCIATED ROCK TYPES: Host rocks are most commonly dolostone, limestone, or dolomitized limestone. Locally hosted in sandstone, conglomerate or calcareous shale. In Yukon, MVT deposits are hosted in Proterozoic to Paleozoic carbonate rocks of the North American margin: Goz is hosted by dolomite of the Proterozoic Backbone Ranges Formation; the Val and Blende deposits are hosted by Middle Proterozoic Gillespie Group dolomite; and Craig is hosted by dolomite within a late Proterozoic shale unit.

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[2] Geological Survey of Canada, Ottawa, Ontario, Canada

E12 - Mississippi Valley-type Pb-Zn

DEPOSIT FORM: Highly irregular. May be peneconcordant as planar, braided or linear replacement bodies. May be discordant in roughly cylindrical collapse breccias. Individual ore bodies range from a few tens to a few hundreds of metres in the two dimensions parallel with bedding. Perpendicular to bedding, dimensions are usually a few tens of metres. Deposits tend to be interconnected thereby blurring deposit boundaries.

TEXTURE/STRUCTURE: Most commonly as sulphide cement to chaotic collapse breccia. Sulphide minerals may be disseminated between breccia fragments, deposited as layers atop fragments (“snow- on-roof”), or completely filling the intra-fragment space. Sphalerite commonly displays banding, either as colloform cement or as detrital layers (“internal sediments”) between host-rock fragments. Sulphide stalactites are abundant in some deposits. Both extremely fine-grained and extremely coarse-grained textured sulphides minerals may be found in the same deposit. Precipitation is usually in the order pyrite (marcasite) → sphalerite → galena.

ORE MINERALOGY (Principal and *Subordinate*): Galena, sphalerite, barite, fluorite, *chalcopyrite*. Some ores contain up to 30ppm Ag. Although some MVT districts display metal zoning, this is not a common feature. The Southeast Missouri district and small portions of the Upper Mississippi Valley district are unusual in containing significant amounts of Ni-, Co-, and Cu-sulphides.

GANGUE MINERALOGY (Principal and *Subordinate*): Dolomite (can be pinkish), pyrite, marcasite, *quartz, calcite, gypsum*.

ALTERATION MINERALOGY: Extensive finely crystalline dolostone may occur regionally, whereas coarse crystalline dolomite is more common close to ore bodies. Extensive carbonate dissolution results in deposition of insoluble residual components as internal sediments. Silicification (jasperoid) is closely associated with ore bodies in the Tri-State and northern Arkansas districts. Authigenic clays composed of illite, chlorite, muscovite, dickite and/or kaolinite accumulate in vugs; minor authigenic feldspar (adularia).

WEATHERING: Extensive development of smithsonite, hydrozincite, willemite, and hemimorphite, especially in non-glaciated regions (including upstanding hills or monadnocks). Large accumulations of secondary zinc minerals can be mined. Galena is usually much more resistant to weathering than sphalerite. Iron-rich gossans are not normally well-developed, even over pyrite-rich deposits.

ORE CONTROLS: Any porous unit may host ore; porosity may be primary (rare) or secondary. Dissolution collapse breccias are the most common host although fault breccias, permeable reefs, and slump breccias may also be mineralized. Dissolution collapse breccias may form through action of meteoric waters or hydrothermal fluids. Underlying aquifers may be porous sandstone or limestone aquifers; the limestones may show thinning due to solution by ore-bearing fluids.

GENETIC MODELS: Deposits are obviously epigenetic, having been emplaced after host rock lithification. Ore hosting breccias are considered to have resulted from dissolution of more soluble sedimentary units, followed by collapse of overlying beds. The major mineralizing processes appear to have been open-space filling between breccia fragments, and replacement of fragments or wall rock. The relative importance of these two processes varies widely among, and within, deposits. Fluid inclusion data show that these deposits formed from warm (75°- 200°C), saline, aqueous solutions similar in composition to oil-field brines. Brine movement out of sedimentary basins, through aquifers or faults, to the hosting structures is the most widely accepted mode of formation. To move the ore solutions out of the basin clastics and into the carbonates, two main models have been proposed:
A. Compaction-driven fluid flow is generated by over- pressuring of subsurface aquifers by rapid sedimentation, followed by rapid release of basinal fluids.
B. Gravity-driven fluid flow flushes subsurface brines by artesian groundwater flow from recharge areas in elevated regions of a foreland basin, to discharge areas in regions of lower elevation.

E12 - Mississippi Valley-type Pb-Zn

In addition to fluid transport, three geochemical mechanisms have been proposed to account for chemical transport and deposition of ore constituents:

1. Mixing - Base metals are transported by fluids of low sulphur content. Precipitation is effected by mixing with fluids containing hydrogen sulphide; replacement of diagenetic iron sulphides; and/or reaction with sulphur released by thermal degradation of organic compounds.
2. Sulphate reduction - Base metals are transported together with sulphate in the same solution. Precipitation is the result of reduction of sulphate by reaction with organic matter or methane.
3. Reduced sulphur - Base metals are transported together with reduced sulphur. Precipitation is brought about by change in pH, dilution, and/or cooling.

ASSOCIATED DEPOSIT TYPES: Fracture-controlled, fluorine-dominant deposits (with subordinate Ba, Pb, and Zn), such as those of Illinois-Kentucky, the English Pennines and the Tennessee Sweetwater F-Ba- Pb-Zn district (E10, E11). "Irish-type carbonate-hosted Zn-Pb" (E13) is described as a separate deposit type in the BC Mineral Deposit Profiles, others regard these deposits as a variant of MVT deposits. In the latter case, they are viewed as a sub-group of MVT deposits which are associated with tensional regimes and rifts. Oxide zinc deposits (B09) have evolved from weathering and alteration of MVT deposits (Skorpion, Berg Aukas, Namibia.

COMMENTS: British Columbia has prospective strata for MVT deposits in the miogeoclinal carbonate platform rocks along its eastern border. MVT deposits are distinct from syngenetic carbonate-hosted Pb-Zn deposits (Mt. Isa, Australia; E14) and high-temperature epigenetic deposits or mantos (Midway, British Columbia; Santa Eulalia, Mexico; J01).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Readily detectable positive anomalies of Zn in residual soils and stream sediments. Regionally anomalous amounts of Pb, Zn, Cu, Mo, Ag, Co, Ni, Cd, Mg, F in insoluble residues of carbonate rocks. Background lithogeochemical concentrations for unmineralized carbonates: Pb = 9 ppm; Zn = 20; Cu = 4; Ag = 0.01.

GEOPHYSICAL SIGNATURE: Deposits may be detected by IP, resistivity, gravity and EM (CS-AMT/AFMAG) systems. Test seismic lines have yielded ambiguous results. In southeast Missouri magnetic and gravimetric surveys have been used to outline basement topographic highs (knobs) which control the distribution of favourable sites of deposition.

OTHER EXPLORATION GUIDES: Reef complexes in platformal carbonate successions. Proximal to, or updip from, petroleum fields in large (continental-scale) sedimentary basins. Peripheral to basement highs. Aligned along basement lineaments.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Data for individual deposits are difficult to obtain because deposits tend to be interconnected. Most deposits are small and fall in the range 1 to 10 Mt. Grades generallyrange between 5% to 10% combined lead-zinc, with a majority being decidedly zinc rich (Zn/Zn+Pb = 0.8). Silver content is not commonly reported since it typically occurs only in solid solution in base metal sulphides. MVT deposits tend to occur in clusters, usually referred to as districts. The Pine Point district, for example, contains more than 80 deposits, the Upper Mississippi Valley district more than 400. Deposits in such districts, therefore, can collectively contain extremely large tonnages. Of more than 80 deposits in the Pine Point district, 40 were mined for a total production of 80 Mt grading 6.5% Zn and 3% Pb. The largest deposit (X15) was 17.4 Mt and the richest deposit (N81) produced 2.7 Mt of ore grading 12% Zn and 7% Pb. The Robb Lake deposit in British Columbia contains 5.3 Mt grading 5.0% Zn and 2.3% Pb. The Craig deposit of Yukon has a geological resource of 964 500 tonnes averaging 13.5% Pb, 8.5% Zn and 123.4 g/t Ag. The Blende deposit contains a geological resource of 19.4 million tonnes grading 55.9 g/t Ag and 5.85% Pb-Zn.

E12 - Mississippi Valley-type Pb-Zn

ECONOMIC LIMITATIONS: Mining districts may extend over many hundreds of square kilometres, increasing mining costs (stripping, haulage to mill, etc.). One of the more favourable attributes of MVT deposits is the normally large grain size, resulting in good mineral separation and high metal recoveries (typical zinc recovery exceeds 90%). Recovery is especially high in deposits with little or no pyrite (Newfoundland Zinc, Gays River and the east and central Tennessee districts).

IMPORTANCE: Metal production from MVT districts can be similar to production from giant stratiform, sediment-hosted (SEDEX) deposits. The Tri-State district was one of the world's major producers of lead during the 20th century, yielding 500 Mt of ore. The Viburnum Trend produced over 123 Mt grading 5.8% Pb, 0.8% Zn, 0.14% Cu and 17 g/t Ag between 1960 and 1984.

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E13 - Irish-type Carbonate-hosted Zn-Pb

By Trygve Höy[1]

Höy, T., 1996. Irish-type carbonate-hosted Zn-Pb: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 21–24.

IDENTIFICATION

SYNONYMS: Kootenay Arc Pb-Zn, Remac type.

COMMODITIES (*BYPRODUCTS*): Zn, Pb, Ag; (*Cu, barite, Cd).*

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Reeves MacDonald (082FSW026), HB (082FSW004), Aspen (082FSW001), Jack Pot (082SW255), Jersey (082SW009), Duncan (082KSE020) , Wigwam (082KNW068); *Navan, Lisheen, Tynagh, Silvermines, Galmoy, Ballinalack, Allenwood West (Ireland); Troya (Spain).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Irish-type carbonate-hosted deposits are stratabound, massive sphalerite, galena, iron sulphide and barite lenses with associated calcite, dolomite and quartz gangue in dolomitized platformal limestones. Deposits are structurally controlled, commonly wedge shaped adjacent to normal faults. Deformed deposits are irregular in outline and commonly elongate parallel to the regional structural grain.

TECTONIC SETTING: Platformal sequences on continental margins which commonly overlie deformed and metamorphosed continental crustal rocks.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Adjacent to normal growth faults in transgressive, shallow marine platformal carbonates; also commonly localized near basin margins.

AGE OF MINERALIZATION: Known deposits are believed to be Paleozoic in age and younger than their host rocks; Irish deposits are hosted by Lower Carboniferous rocks; Kootenay Arc deposits are in the Lower Cambrian.

HOST/ASSOCIATED ROCK TYPES: Hosted by thick, non-argillaceous carbonate rocks; these are commonly the lowest pure carbonates in the stratigraphic succession. They comprise micritic and oolitic beds, and fine-grained calcarenites in a calcareous shale, sandstone, calcarenite succession. Underlying rocks include sandstones or argillaceous calcarenites and shales. Iron-formations, comprising interlayered hematite, chert and limestone, may occur as distal facies to some deposits. Deformed Kootenay Arc deposits are enveloped by fine-grained grey, siliceous dolomite that is generally massive or only poorly banded and locally brecciated.

DEPOSIT FORM: Deposits are typically wedge shaped, ranging from over 30 m thick adjacent to, or along growth faults, to 1-2 cm bands of massive sulphides at the periphery of lenses. Economic mineralization rarely extends more than 200 m from the faults. Large deposits comprise individual or stacked sulphide lenses that are roughly concordant with bedding. In detail, however, most lenses cut host stratigraphy at low angles. Contacts are sharp to gradational. Deformed deposits are typically elongate within and parallel to the hinges of tight folds. The Reeves MacDonald deposit forms a syncline with a plunge length of approximately 1500 m and widths up to 25 m. Others (HB) are elongate parallel to a strong mineral lineation. Individual sulphide lenses are irregular, but typically parallel to each other and host layering, and may interfinger or merge along plunge.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

E13 - Irish-type Carbonate-hosted Zn-Pb

TEXTURE/STRUCTURE: Sulphide lenses are massive to occassionally well layered. Typically massive sulphides adjacent to faults grade outward into veinlet-controlled or disseminated sulphides. Colloform sphalerite and pyrite textures occur locally. Breccias are common with sulphides forming the matrix to carbonate (or as clasts?). Sphalerite-galena veins, locally brecciated, commonly cut massive sulphides. Rarely (Navan), thin laminated, graded and crossbedded sulphides, with framboidal pyrite, occur above more massive sulphide lenses. Strongly deformed sulphide lenses comprise interlaminated sulphides and carbonates which, in some cases (Fyles and Hewlett, 1959), has been termed shear banding.

ORE MINERALOGY (Prinicipal and subordinate): Sphalerite, galena; *barite, chalcopyrite, pyrrhotite, tennantite, sulfosalts, tetrahedrite*.

GANGUE MINERALOGY (Prinicipal and subordinate): Dolomite, calcite, quartz, pyrite, marcasite; *siderite, barite, hematite, magnetite; at higher metamorphic grades, olivine, diopside, tremolite, wollastonite, garnet*.

ALTERATION MINERALOGY: Extensive early dolomitization forms an envelope around most deposits which extends tens of metres beyond the sulphides. Dolomitization associated with mineralization is generally fine grained, commonly iron-rich, and locally brecciated and less well banded than limestone. Mn halos occur around some deposits; silicification is local and uncommon. Fe in iron-formations is distal.

WEATHERING: Gossan minerals include limonite, cerussite, anglesite, smithsonite, hemimorphite, pyromorphite.

ORE CONTROLS: Deposits are restricted to relatively pure, shallow-marine carbonates. Regional basement structures and, locally, growth faults are important. Orebodies may be more common at fault intersections. Proximity to carbonate bank margins may be a regional control in some districts.

GENETIC MODEL: Two models are commonly proposed:

(1) syngenetic seafloor deposition: evidence inludes stratiform geometry of some deposits, occurrence together of bedded and clastic sulphides, sedimentary textures in sulphides, and, where determined, similar ages for mineralization and host rocks.

(2) diagenetic to epigenetic replacement: replacement and open-space filling textures, lack of laminated sulphides in most deposits, alteration and mineralization above sulphide lenses, and lack of seafloor oxidation.

ASSOCIATED DEPOSIT TYPES: Mississippi Valley type Pb-Zn (E12), sediment-hosted barite (E17), sedimentary exhalative Zn-Pb-Ag (E14), possibly carbonate-hosted disseminated Au-Ag (E03).

COMMENTS: Although deposits such as Tynagh and Silvermines have structures and textures similar to sedex deposits, and are associated with distal iron-formations, they are included in the Irish-type classification as recent work (e.g., Hizman, 1995) concludes they formed by replacement of lithified rocks. Deposits that can be demonstrated to have formed on the seafloor are not included in Irish-type deposits. It is possible that the same continental margin carbonates may host sedex (E14), Irish-type (E13) and Mississippi Valley-type (E12) deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated base metal, Ag and Mn values in both silt and soil samples; however, high carbonate content, and hence high pH may reduce effectiveness of stream silts.

GEOPHYSICAL SIGNATURE: Induced polarization surveys are effective and ground electromagnetic methods may work for deposits with iron sulphides. Deposits can show up as resistivity lows and gravity highs.

OTHER EXPLORATION GUIDES: The most important control is stratigraphic. All known deposits are in carbonate rocks, commonly the lowest relatively pure carbonate in a succession. Other guides are proximity to growth faults and intersection of faults, regional and local dolomitization and possibly laterally equivalent iron-formations.

E13 - Irish-type Carbonate-hosted Zn-Pb

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Irish deposits are typically less than 10 Mt with 5-6% Zn, 1-2% Pb and 30 g/t Ag. Individual deposits can contain up to 90 g/t Ag. The largest, Navan, produced 36 Mt and has remaining reserves of 41.8 Mt containing 8% Zn and 2% Pb. Mined deposits in the Kootenay Arc averaged between 6 and 7 Mt and contained 3-4 % Zn, 1-2 % Pb, and 3-4 g/t Ag. Duncan has reserves of 2.76 Mt with 3.3% Pb and 3.1% Zn; Wigwam contains 8.48 Mt with 2.14% Pb and 3.54% Zn.

ECONOMIC LIMITATIONS: These deposits are attractive because of their simple mineralogy and polymetallic nature, although significantly smaller than sedex deposits. In British Columbia the Kootenay Arc deposits are generally lower grade with up to only 6 % Pb+Zn. These deposits are also structurally complex making them more complicated to mine.

IMPORTANCE: Production from these deposits makes Ireland a major world zinc producer. Recent discovery of concealed deposits (Galmoy in 1986 and Lisheen in 1990) assures continued production. In British Columbia, a number of these deposits were mined intermittently until 1979 when H.B. finally closed. Some still have substantial lead and zinc reserves. However, their current potential for development is based largely on the precious metal content. The high carbonate content of the gangue minimizes acid-rock drainage problems.

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E14 - Sedimentary Exhalative Zn-Pb-Ag

by Don MacIntyre[1]

MacIntyre, D., 1995. Sedimentary exhalative Zn-Pb-Ag: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 37–39.

IDENTIFICATION

SYNONYMS: Shale-hosted Zn-Pb-Ag; sediment-hosted massive sulphide Zn-Pb-Ag; Sedex Zn-Pb.

COMMODITIES (*BYPRODUCTS*): Zn, Pb, Ag, (*minor Cu, barite*).

EXAMPLES (British Columbia - *Canada/International*): Cirque, Sullivan, Driftpile; *Faro, Grum, Dy, Vangorda, Swim, Tom and Jason (Yukon, Canada); Red Dog (Alaska, USA); McArthur River and Mt. Isa (Australia); Megen and Rammelsberg (Germany).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Beds and laminations of sphalerite, galena, pyrite, pyrrhotite and rare chalcopyrite, with or without barite, in euxinic clastic marine sedimentary strata. Deposits are typically tabular to lensoidal in shape and range from centimetres to tens of metres thick. Multiple horizons may occur over stratigraphic intervals of 1000 m or more.

TECTONIC SETTING: Intracratonic or continental margin environments in fault-controlled basins and troughs. Troughs are typically half grabens developed by extension along continental margins or within back-arc basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Restricted second and third order basins within linear, fault-controlled marine, epicratonic troughs and basins. There is often evidence of penecontemporaneous movement on faults bounding sites of sulphide deposition. The depositional environment varies from deep, starved marine to ? shallow water restricted shelf.

AGE OF MINERALIZATION: The major metallogenic events are Middle Proterozoic, Early Cambrian, Early Silurian and Middle to Late Devonian to Mississippian. The Middle Proterozoic and Devonian-Mississippian events are recognized worldwide. In the Canadian Cordillera, minor metallogenic events occur in the Middle Ordovician and Early Devonian.

HOST/ASSOCIATED ROCK TYPES: The most common hostrocks are those found in euxinic, starved basin environments, namely, carbonaceous black shale, siltstone, cherty argillite and chert. Thin interbeds of turbiditic sandstone, granule to pebble conglomerate, pelagic limestone and dolostone, although volumetrically minor, are common. Evaporites, calcareous siltstone and mudstone are common in shelf settings. Small volumes of volcanic rocks, typically tuff and submarine mafic flows, may be present within the host succession. Slump breccia, fan conglomerates and similar deposits occur near synsedimentary growth faults. Rapid facies and thickness changes are found near the margins of second and third order basins. In some basins high-level mafic sills with minor dikes are important.

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E14 - Sedimentary Exhalative Zn-Pb-Ag

DEPOSIT FORM: These deposits are stratabound, tabular to lens shaped and are typically comprised of many beds of laminae of sulphide and/or barite. Frequently the lenses are stacked and more than one horizon is economic. Ore lenses and mineralized beds often are part of a sedimentary succession up to hundreds of metres thick. Horizontal extent is usually much greater than vertical extent. Individual laminae or beds may persist over tens of kilometres within the depositional basin.

TEXTURE/STRUCTURE: Sulphide and barite laminae are usually very finely crystalline where deformation is minor. In intensely folded deposits, coarser grained, recrystallized zones are common. Sulphide laminae are typically monomineralic.

ORE MINERALOGY [Principal and *subordinate*]: The principal sulphide minerals are pyrite, pyrrhotite, sphalerite and galena. Some deposits contain significant amounts of *chalcopyrite*, but most do not. Barite may or may not be a major component of the ore zone. Trace amounts of *marcasite, arsenopyrite, bismuthinite, molybdenite, enargite, millerite, freibergite, cobaltite, cassiterite, valleriite and melnikovite* have been reported from these deposits. These minerals are usually present in very minor amounts.

ALTERATION MINERALOGY: Alteration varies from well developed to nonexistent. In some deposits a stockwork and disseminated feeder zone lies beneath, or adjacent to, the stratiform mineralization. Alteration minerals, if present, include silica, tourmaline, carbonate, albite, chlorite and dolomite. They formed in a relatively low temperature environment. Celsian, Ba-muscovite and ammonium clay minerals have also been reported but are probably not common.

ORE CONTROLS: Favourable sedimentary sequences, major structural breaks, basins.

GENETIC MODEL: The deposits accumulate in restricted second and third order basins or half grabens bounded by synsedimentary growth faults. Exhalative centres occur along these faults and the exhaled brines accumulate in adjacent seafloor depressions. Biogenic reduction of seawater sulphate within an anoxic brine pool is believed to control sulphide precipitation.

ASSOCIATED DEPOSIT TYPES: Associated deposit types include carbonate-hosted sedimentary exhalative, such as the Kootenay Arc and Irish deposits (E13), bedded barite (E17) and iron formation (F10).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: The deposits are typically zoned with Pb found closest to the vent grading outward and upward into more Zn-rich facies. Cu is usually found either within the feeder zone or close to the exhalative vent. Barite, exhalative chert and hematite-chert iron formation, if present, are usually found as a distal facies. Sediments such as pelagic limestone interbedded with the ore zone may be enriched in Mn. NH_3 anomalies have been documented at some deposits, as have Zn, Pb and Mn haloes. The host stratigraphic succession may also be enriched in Ba on a basin-wide scale.

GEOPHYSICAL SIGNATURE: Airborne and ground geophysical surveys, such as electromagnetics or magnetics should detect deposits that have massive sulphide zones, especially if these are steeply dipping. However, the presence of graphite-rich zones in the host sediments can complicate the interpretation of EM conductors. Also, if the deposits are flat lying and comprised of fine laminae distributed over a significant stratigraphic interval, the geophysical response is usually too weak to be definitive. Induced polarization can detect flat-lying deposits, especially if disseminated feeder zones are present.

OTHER EXPLORATION GUIDES: The principal exploration guidelines are appropriate sedimentary environment and stratigraphic age. Restricted marine sedimentary sequences deposited in an epicratonic extensional tectonic setting during the Middle Proterozoic, Early Cambrian, Early Silurian or Devono-Mississippian ages are the most favourable.

E14 - Sedimentary Exhalative Zn-Pb-Ag

ECONOMIC FACTORS

GRADE AND TONNAGE: The median tonnage for this type of deposit worldwide is 15 Mt, with 10 % of deposits in excess of 130 Mt (Briskey, 1986). The median grades worldwide are Zn - 5.6%, Pb - 2.8% and Ag - 30 g/t. The Sullivan deposit, one of the largest deposits of this type ever discovered, has a total size of more than 155 Mt grading 5.7% Zn, 6.6% Pb and 7 g/t Ag. Reserves at the Cirque are 32.2 Mt grading 7.9% Zn, 2.1% Pb and 48 g/t Ag.

ECONOMIC LIMITATIONS: The large, near-surface deposits are amenable to high-volume, open pit mining operations. Underground mining is used for some deposits.

IMPORTANCE: Sedimentary exhalative deposits currently produce a significant proportion of the world's Zn and Pb. Their large tonnage potential and associated Ag values make them an attractive exploration target.

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E15 - Blackbird Sediment-Hosted Cu-Co

by Trygve Höy[1]

Höy, T., 1995. Blackbird sediment-hosted Cu-Co: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 41–43.

IDENTIFICATION

SYNONYM: Sediment-hosted Cu-Co deposit.

COMMODITIES (BYPRODUCTS): Cu, Co, (Au, Bi, Ni, Ag; possibly Pb, Zn).

EXAMPLES (British Columbia - *Canada/International*): Canadian examples are not known; *Blackbird, Bonanza Copper and Tinker's Pride (Idaho, USA), possibly Sheep Creek deposits (Montana, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Pyrite and minor pyrrhotite, cobaltite, chalcopyrite, arsenopyrite and magnetite occur as disseminations, small veins and tabular to pod-like lenses in sedimentary rocks. Chloritic alteration and tourmaline breccias are locally associated with mineralization

TECTONIC SETTINGS: Near continental margins or in intracratonic basins. Within the Belt-Purcell basin, which may have formed in a large inland sea, extensional tectonics are suggested by possible turbidite deposition, growth faulting, gabbroic sills and (?)tuff deposition. Alternative setting is marine, in an incipient or failed rift along a continental margin.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: These deposits are not well understood. Possible turbidite deposition in marine or inland sea, associated with basaltic pyroclastic volcanics or mafic synsedimentary gabbroic sills; alternatively, tidal flat environment.

AGE OF MINERALIZATION: Can be of any age. The Blackbird deposits at the type locality are assumed to be approximately 1460 Ma, the age of the hostrocks.

HOST/ASSOCIATED ROCK TYPES: Fine-grained metasedimentary rocks; thin-bedded siltstone, fine-grained quartzite, black argillite and calcareous siltstone; garnet schist, phyllite, quartz-mica schist. In the Blackbird district synaeresis cracks (subaqueous shrinkage cracks) occur within immediate hostrocks, sedimentary structures indicative of shallow water, and locally subaerial exposure in overlying rocks, suggest shallow water environment. Numerous biotite-rich beds within the host succession may be mafic tuff units (or diorite sills?). Sheep Creek deposits are within correlative Newland Formation dolomitized shales and conglomerates.

DEPOSIT FORM: Irregular, tabular to pod-like deposits, from approximately 2 to 10 m thick.

TEXTURE/STRUCTURE: Fine to fairly coarse grained, massive to disseminated sulphides; pyrite locally has colloform textures. Locally sheared; vein sulphides in some deposits; quartz-tourmaline breccia pipes (?).

ORE MINERALOGY (Principal and *subordinate*) Cobaltite, chalcopyrite, pyrite, pyrrhotite, gold and silver in breccia pipes; *arsenopyrite, magnetite, cobaltian pyrite.* Sheep Creek: pyrite, marcasite, chalcopyrite, *tennantite* plus cobalt minerals; *covellite, bornite* in barite.

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E15 - Blackbird Sediment-Hosted Cu-Co

GANGUE MINERALOGY: quartz, biotite, barite; *tourmaline, hornblende, chlorite, muscovite, ankerite, dolomite, siderite, calcite and apatite*.

ALTERATION MINERALOGY: Silicification and intense chloritization; locally quartz-tourmaline breccias.

WEATHERING: Supergene enrichment with ludlamite and vivianite; erythrite (cobalt bloom); intense gossans at surface.

ORE CONTROLS: Regional controls include synsedimentary extensional fault structures, basin margin and growth faults. Local controls include association with mafic tuffs and stacked deposits at several stratigraphic intervals separated by barren rock.

GENETIC MODEL: Based on stratabound nature of deposits and similarity with unmetamorphosed Sheep Creek deposits, the Blackbird lenses are interpreted to be either syngenetic or diagenetic.

ASSOCIATED DEPOSIT TYPES: Possibly Besshi volcanogenic massive sulphide deposits (G04), Fe formations (F10), base metal veins, tourmaline breccias.

COMMENTS: Sheep Creek deposits are a relatively new exploration target in Belt rocks in Montana. They are in equivalent, lower metamorphic grade hostrocks to those of the Blackbird deposits, and have similar mineralogy and trace metal geochemistry. Lower Purcell Supergroup rocks and other structurally controlled sedimentary basins associated with variable mafic magmatism are prospective hosts in Canada.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Enriched in Fe, As, B, Co. Cu, Au, Ag and Mn; may be depleted in Ca and Na. Sheep Creek also contains high Ba.

GEOPHYSICAL SIGNATURE: Sulphide lenses usually show either an electromagnetic or induced polarization signature based on the style of mineralization and presence of conductive sulphides.

OTHER EXPLORATION GUIDES: Proximity to mafic tuffs or possibly early gabbroic sills, rapid sedimentary facies changes indicative of growth faults; regional pyrite development; may grade laterally to pyritic zones with anomalous Pb-Zn.

ECONOMIC FACTORS

GRADE AND TONNAGE: The Blackbird district deposits range from less than 100 000 t to 1.3 Mt containing 0.4 - 0.6 % Co and 1.3% Cu. Two zones of the Sheep Creek deposits contain respectively 4.5 Mt of 2.5% Cu and 0.12% Co, and 1.8 Mt with 6% Cu. Variable gold, up to 20 g/t in Blackbird lenses.

ECONOMIC LIMITATIONS: Generally lower copper grades favour open pit mining; Au and Ag are important byproducts.

IMPORTANCE: Small past producers of copper, cobalt and gold in Idaho.

E15 - Blackbird Sediment-Hosted Cu-Co

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E16 - Shale-Hosted Ni-Zn-Mo-PGE

by D.V. Lefebure[1] and R.M. Coveney, Jr. [2]

Lefebure, D.V., and Coveney Jr., R.M., 1995. Shale-hosted Ni-Zn-Mo-PGE: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 45–47.

IDENTIFICATION

SYNONYMS: Sediment-hosted Ni-Mo-PGE, Stratiform Ni-Zn-PGE.

COMMODITIES (BYPRODUCTS): Ni, Mo, (Zn, Pt, Pd, Au).

EXAMPLES (British Columbia - *Canada/International*): *Nick (Yukon, Canada); mining camps of Tianeshan, Xintuguo, Tuansabao and Jinzhuwoin and Zunyi Mo deposits, Dayong-Cili District (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Thin layers of pyrite, vaesite (NiS_2), jordisite (amorphous MoS_2) and sphalerite in black shale sub-basins with associated phosphatic chert and carbonate rocks.

TECTONIC SETTING(S): Continental platform sedimentary sequences and possibly successor basins. All known deposits associated with orogenic belts, however, strongly anomalous shales overlying the North American craton may point to as yet undiscovered deposits over the stable craton.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Anoxic basins within clastic sedimentary (flysch) sequences containing black shales.

AGE OF MINERALIZATION: Post Archean. Known deposits are Early Cambrian and Devonian, however, there is potential for deposits of other ages.

HOST/ASSOCIATED ROCK TYPES: Black shale is the host; associated limestones, dolomitic limestones, calcareous shale, cherts, siliceous shale, siliceous dolomite, muddy siltstone and tuffs. Commonly associated with phosphate horizons. In the Yukon at base of a 10 to 20 m thick phosphatic shale bed and in China the Ni-Mo beds are in black shales associated with phosphorite.

DEPOSIT FORM: Thin beds (0 to 15 cm thick, locally up to 30 cm) covering areas up to at least 100 ha and found as clusters and zones extending for tens of kilometres.

TEXTURE/STRUCTURE: Semimassive to massive sulphides as nodules, spheroids, framboids and streaks or segregations in a fine-grained matrix of sulphides, organic matter and nodular phosphorite or phosphatic carbonaceous chert. Mineralization can be rhythmically laminated; often has thin discontinuous laminae. Brecciated clasts and spheroids of pyrite, organic matter and phosphorite. In China nodular textures (~ 1 mm diameter) grade to coatings of sulphides on tiny 1-10 μm spherules of organic matter. Fragments and local folding reflect soft sediment deformation. Abundant plant fossils in Nick mineralization and abundant fossils of microorganisms (cyanobacteria) in the Chinese ores.

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E16 - Shale-Hosted Ni-Zn-Mo-PGE

ORE MINERALOGY (Principal and subordinate): Pyrite, vaesite (NiS_2), amorphous molybdenum minerals (jordisite, MoS_2), bravoite, *sphalerite, wurtzite, polydimite, gersdorffite, violarite, millerite, sulvanite, pentlandite, tennanite and as traces native gold, uranitite, tiemannite, arsenopyrite, chalcopyrite and covellite*. Discrete platinum group minerals may be unusual. Some ore samples are surprisingly light because of abundant organic matter and large amount of pores.

GANGUE MINERALOGY (Principal and *subordinate*): Chert, amorphous silica, phosphatic sediments and bitumen. Can be interbedded with pellets of solid organic matter (called stone coal in China). Barite laths are reported in two of the China deposits.

ALTERATION MINERALOGY: Siliceous stockworks and bitumen veins with silicified wallrock occur in the footwall units. Carbonate concretions up to 1.5 m in diameter occur immediately below the Nick mineralized horizon in the Yukon.

WEATHERING: Mineralized horizons readily oxidize to a black colour and are recessive. Phosphatic horizons can be resistant to weathering.

ORE CONTROLS: The deposits developed in restricted basins with anoxic conditions. Known deposits are found near the basal contact of major formations. Underlying regional unconformities and major basin faults are possible controls on mineralization. Chinese deposits occur discontinuously in a 1600 km long arcuate belt, possibly controlled by basement fractures.

GENETIC MODEL: Several genetic models have been suggested reflecting the limited data available and the unusual presence of PGEs without ultramafic rocks. Syngenetic deposition from seafloor springs with deposition of metals on or just beneath the seafloor is the most favoured model. Siliceous venting tubes and chert beds in the underlying beds in the Yukon suggest a hydrothermal source for metals.

ASSOCIATED DEPOSIT TYPES: Phosphorite layers (F07?), stone coal, SEDEX Pb-Zn (E14), Sediment-hosted barite (E17), vanadian shales, sediment-hosted Ag-V, uranium deposits.

COMMENTS: Ag-V and V deposits hosted by black shales have been described from the same region in China hosted by underlying late Precambrian rocks.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Ni, Mo, Au, PGE, C, P, Ba, Zn, Re, Se, As, U, V and S in rocks throughout large parts of basin and derived stream sediments. In China average regional values for host shales of 350 g/t Mo, 150 g/t Ni, several wt % P_2O_5 and 5 to 22% organic matter. Organic content correlates with metal contents for Ni, Mo and Zn.

GEOPHYSICAL SIGNATURE: Electromagnetic surveys should detect pyrite horizons.

OTHER EXPLORATION GUIDES: Anoxic black shales in sub-basins within marginal basins. Chert or phosphate-rich sediments associated with a pyritiferous horizon. Barren, 5 mm to 1.5 cm thick, pyrite layers (occasionally geochemically anomalous) up to tens of metres above mineralized horizon.

E16 - Shale-Hosted Ni-Zn-Mo-PGE

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The thin sedimentary horizons (not economic) represent hundreds of thousands of tonnes grading in per cent values for at least two of Ni-Mo-Zn with significant PGEs. In China, Zunyi Mo mines yield ~ 1000 t per year averaging ~4 % Mo and containing up to 4 % Ni, 2 % Zn, 0.7 g/t Au, 50 g/t Ag, 0.3 g/t Pt, 0.4 g/t Pd and 30 g/t Ir. The ore is recovered from a number of small adits using labour-intensive mining methods.

ECONOMIC LIMITATIONS: In China the Mo-bearing phase is recovered by roasting followed by caustic leaching to produce ammonium molybdate. Molybedenum-bearing phases are fine grained and dispersed, therefore all ore (cutoff grade 4.1% Mo) is direct shipped to the smelter after crushing.

IMPORTANCE: Current world production from shale-hosted Ni-Mo-PGE mines is approximately 1000 t of ore with grades of approximately 4 % Mo. Known deposits of this type are too thin to be economic at current metal prices, except in special conditions. However, these deposits contain enormous tonnages of relatively high grade Ni, Mo, Zn and PGE which may be exploited if thicker deposits can be found, or a relevant new technology is developed.

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ACKNOWLEDGEMENTS: Larry Hulbert of the Geological Survey of Canada introduced the senior author to this deposit type and provided many useful comments. Rob Carne of Archer, Cathro and Associates Limited reviewed a draft manuscript.

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E17 - Sedimentary-Hosted, Stratiform Barite

by S. Paradis[1], G.J. Simandl[2], D. MacIntyre[2] and G.J. Orris[3]

Paradis, S., Simandl, G.J., MacIntyre, D.G., and Orris, G.J., 1999. Sedimentary-hosted stratifrom barite: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 43–46.

IDENTIFICATION

SYNONYM: Bedded barite.

COMMODITIES (*BYPRODUCTS*): Barite (possibly Zn, Pb, ± Ag).

EXAMPLES (British Columbia (MINFILE #)- *Canada/International*): Kwadacha (094F 020), Gin (094F 017), Gnome (094F02E); *Tea, Tyrala, Hess, Walt and Cathy (Yukon, Canada); Walton (Nova Scotia, Canada); Fancy Hill (Arkansas, USA), Mountain Springs, Greystone (Nevada, USA); Jixi and Liulin (China); Fig Tree and Mabiligwe (South Africa).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sedimentary-hosted, stratiform or lens-shaped barite bodies, that may reach over ten metres in thickness and several kilometres in strike length. Barite-rich rocks (baritites) are commonly lateral distal equivalents of shale-hosted Pb-Zn (sedex) deposits. Some barite deposits are not associated with shale-hosted Zn-Pb deposits.

TECTONIC SETTINGS: Intracratonic or continental margin-type fault-controlled marine basins or half-grabens of second or third order and peripheral foreland (distal to the continental margin) basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Deep, starved marine basins to shallow water shelves. The barite-rich rocks (baritites) were deposited on the seafloor and commonly grade laterally into either shale-hosted Pb-Zn (sedex) deposits which formed closer to the submarine hydrothermal vents, or the more distal cherts, hematite-chert iron formations, silica and manganese-enriched sediments.

AGE OF MINERALIZATION: Deposits are hosted by rocks of Archean to Mesozoic ages but are most common in rocks of Phanerozoic, especially in the mid to late Paleozoic age.

HOST/ASSOCIATED ROCK TYPES: Major rock types hosting barite are carbonaceous and siliceous shales, siltstones, cherts, argillites, turbidites, sandstones, dolomites and limestones.

DEPOSIT FORM: Stratiform or lens-shaped deposits are commonly metres thick, but their thickness may exceed 50 metres. Their lateral extent may be over several square kilometres.

TEXTURE/STRUCTURE: The barite ore is commonly laminated, layered or massive. Barite may form rosettes, randomly oriented laths or nodules. Some of the barite deposits display breccias and slump structures. In metamorphosed areas, barite may be remobilized (forming veinlets) and/or recrystallized.

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E17 - Sedimentary-Hosted, Stratiform Barite

ORE MINERALOGY [Principal and *subordinate*]: Barite.

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, clay, organic material, celsian, hyalophane, cymrite, barytocalcite, calcite, dolomite, pyrite, *marcasite, sphalerite, galena, and in some cases witherite.*

ALTERATION MINERALOGY: None in most cases. Secondary barite veining. Weak to moderate sericitization reported in, or near, some deposits in Nevada.

WEATHERING: Barite-rich exposures sometimes create vegetation “kill zones”.

ORE CONTROLS: Sedimentary depositional environment is mainly half-grabens and basins of second or third order. While Zn-Pb-barite (sedex) deposits may require euxinic environment to stabilize sulphides, more oxidized depositional environment may be the key for deposition of high-grade (nearly sulphide-free) barite deposits. Syndepositional faults are extremely important for sedex deposits that are commonly proximal to the vents, but may not be essential for all sediment-hosted stratabound barite deposits.

GENETIC MODEL: Some stratiform barite deposits form from hydrothermal fluids that exhaled on the seafloor and precipitated barite and other minerals (sulphides, chert, etc.) as chemical sediments. The chemical sediments change composition with distance from the vent reflecting changes in temperature and other parameters of the hydrothermal fluid as it mixed with seawater. Barite-rich sediments can reflect hydrothermal fluids deficient in metals (lack of base metals in the source rock or insufficient temperature or unfavorable physical-chemical fluid conditions to carry base metals) or discharge of hydrothermal fluids in a shallow marine environment that does not favor precipitation of sulphides. Some of the sedimentary-hosted barite deposits are interpreted as chemical sediments related to inversion of stratified basin resulting in oxygenation of reduced waters. Others formed by erosion and reworking of sub-economic chemical sediments (Heinrichs and Reimer, 1977) or of semi-consolidated clays containing barite concretions (Reimer, 1986), resulting in selective concentration of barite.

ASSOCIATED DEPOSIT TYPES: Shale-hosted Zn-Pb deposits (E14), Irish-type massive sulphide deposits (E13), sedimentary manganese deposits (F01) and vein barite deposits (I10). In oxygen-starved basins, barite deposits may be stratigraphically associated with black shales enriched in phosphates (F08), vanadium, REE and uranium mineralization and possibly shale-hosted Ni-Mo-PGE (E16) deposits.

COMMENTS: There is a complete spectrum from sulphide-rich to barite-rich sedex deposits. The Cirque deposit in British Columbia, represents the middle of this spectrum and consists of interlaminated barite, sphalerite, galena and pyrite. Its reserves are in excess of 38.5 million tonnes averaging 8% Zn, 2.2% Pb, 47.2 g/tonne of Ag and 45-50% barite. Witherite, a barium carbonate, occurs as an accessory mineral in some barite deposits and rarely forms a deposit on its own. There has been no commercial witherite production in the western world since the mines in Northumberland, England closed. Recently, the Chengkou and Ziyang witherite deposits have been discovered in China (Wang and Chu, 1994). Witherite deposits may form due to severe depletion of seawater in SO^{-2}_4 and enrichment in Ba (Maynard and Okita, 1991). Alternatively, these deposits could have formed by high temperature replacement of barite by witherite (Turner and Goodfellow, 1990).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Barium enrichment on the scale of the basin and other indicators of shale-hosted Zn-Pb deposits, such as high values of Zn, Pb, Mn, Cu and Sr, in rock and stream sediment samples. Strongly anomalous Ba values in stream sediments and heavy sediments are only found in close proximity to barite mineralization because barite abrades rapidly during stream sediment transportation. The difference between $^{87}Sr/^{86}Sr$ ratios of barite and coeval seawater may be used to distinguish between cratonic rift (potentially sedex-related) barite occurrences and those of peripheral foreland basins (Maynard *et al.*,1995).

E17 - Sedimentary-Hosted, Stratiform Barite

GEOPHYSICAL SIGNATURE: Deposit may correspond to a gravity-high.

OTHER EXPLORATION GUIDES: Appropriate tectonic and depositional setting. Proximity to known occurrences of barite, shale-hosted sedex or Irish-type massive sulphide occurrences, exhalative chert, hematite-chert iron formations and regional Mn marker beds. Vegetation “kill zones” coincide with some barite occurrences.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits range from less than 1 to more than 25 million tonnes grading 30% to over 95% barite with a median size of 1.24 million tonnes containing 87.7 % $BaSO_4$ (Orris, 1992). Portions of some deposits may be direct shipping ore. The Magcobar mine in the Silvermines district of Ireland produced 4.6 Mt of 85% BaSO4 lump. Barite is produced at some metal mines, including the Ramelsburg and Meggen (8.9 Mt) mines in Germany.

ECONOMIC LIMITATIONS: Several modern applications require high brightness and whiteness values and high-purity products. There are different requirements for specific applications. Abrasivity, grade of concentrate, color, whiteness, density and type of impurities, oil index, water index, refractive index and base metal content are commonly reported for commercially available concentrates. Transportation cost, specific gravity and content of water-soluble alkaline earth metals, iron oxides and sulphides are important factors for barite used in drilling applications. Currently sulphide-free barite deposits are preferred by the barite producers. Some of the barite on the market is sold without complex upgrading. Selective mining and/or hand sorting, jigging, flotation and bleaching are commonly required. It is possible that in the future, due to technological progress, a substantial portion of barite on the market will originate as by-product of metal mining.

END USES: Barite is used mainly in drill muds, also as heavy aggregate, marine ballast, a source of chemicals, a component in ceramics, steel hardening, glass, fluxes, papers, specialized plastics and radiation shields, in sound proofing and in friction and pharmaceutical applications. Witherite is a desirable source of barium chemicals because it is soluble in acid, but it is not suitable for applications where inertness in acid environments is important.

IMPORTANCE: Competes for market with vein-type barite deposits. Celestite, ilmenite, iron oxides can replace barite in specific drilling applications. However the impact of these substitutes is minimized by relatively low barite prices.

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E18 - Carbonate-hosted, Nonsulphide Zn (hypogene)

by S. Paradis[1] and G.J. Simandl[2]

Paradis, S., and Simandl, G.J., 2012. Carbonate-hosted, nonsulphide Zn (hypogene) mineral deposit profile E18: In: Geological Fieldwork 2011, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey, Paper 2012-1, pp. 211–216.

IDENTIFICATION

SYNONYMS: Zinc-Oxides, Willemite-Dominant deposits.

COMMODITIES (BYPRODUCTS): Zn, Pb (Mn, Fe, Cu, V, Cd, Ag).

EXAMPLES: (British Columbia - *Canada/International*): Structurally-Controlled Replacement Deposits: *Abenab West, Berg Aukas (Namibia); Kabwe, Star Zinc (Zambia); Vazante, Ariense (Brazil); Beltana, Aroona, Reliance (Australia).*
Stratiform Deposits: *Abu Samar (Sudan), Desert View, Franklin/Sterling Hill (USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Zinc oxide minerals, such as willemite, franklinite or zincite, occur as massive to disseminated zones hosted primarily by carbonate rocks. The two subtypes of hypogene carbonate-hosted nonsulphide Zn-Pb deposits are: structurally-controlled replacement deposits in the form of podiform bodies, veins, and irregular pipes consisting mainly of willemite (±sphalerite, ±hematite, ±franklinite and ±zincite) and spatially associated with fractures and fault zones; and stratiform deposits forming lenses of franklinite-willemite-zincite (±gahnite) located in highly metamorphosed terrains.

TECTONIC SETTING(S): The structurally-controlled replacement deposits are located in intracratonic or continental margin environments in fault-controlled sedimentary basins within orogenic belts. The stratiform deposits are located in sedimentary or volcano-sedimentary basins within orogenic belts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Hostrocks to the structurally-controlled hypogene nonsulphide Zn-Pb deposits are carbonates deposited in platform successions. Shallowing-upward basins or proximity to major unconformities separating a reduced, carbonate-rich succession (below) from an oxidized sequence of terrestrial sedimentary rocks (above) are frequent settings (*e.g.*, Beltana and Vazante deposits; Groves *et al.*, 2003; Monteiro *et al.*, 2006). In case of stratiform deposits, metamorphic overprint obliterated all textural/structural indicators of depositional environment.

AGE OF MINERALIZATION: Ages of hypogene nonsulphide Zn deposits are poorly constrained between Proterozoic to Paleozoic time.

HOST / ASSOCIATED ROCK TYPES: Structurally-controlled deposits are commonly hosted by dolostone, limestone, dolomitized limestone, argillaceous carbonate, marble and slate. Stratiform deposits are typically hosted by metasedimentary rocks, such as calcitic and dolomitic marble, interlayered with metavolcanic and igneous intrusive rocks (Hague *et al.*, 1956; Hitzman *et al.*, 2003).

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DEPOSIT FORM: Structurally-controlled deposits are highly irregular, consisting of podiform bodies, veins within fault and shear zones, joint and fissure-fills, and open-space fills in breccia pipe-like karst structures. Individual podiform ore bodies range from a few tens to a few hundreds of metres in the two dimensions parallel with bedding. Perpendicular to bedding, dimensions are usually a few tens of metres. Stratiform nonsulphide deposits consist of a series of stratabound discontinuous tabular lenses that considerably varied in thickness and length from few tens of metres to few hundreds of metres.

TEXTURE / STRUCTURE: Mineralization in the structurally-controlled deposits is heterogeneous, resulting from various depositional mechanisms such as massive replacement of various hematitic and/or zincian dolomite wallrock facies, dissemination, internal sedimentation, fracture and vein fill, and brecciation. The massive ore is commonly granular and fine grained, and appears as finely porous to compact cryptocrystalline masses. The internal sediments consist of fine laminations of zinc oxide minerals in open cavities. Colloform or crustiform bands, rosettes and spherulites of willemite are deposited as vein and vug fill and in the matrix of breccias (Figures 1, 2). Mineralization in the stratiform tabular lenses consists of massive to disseminated equigranular, subrounded aggregates of Zn-rich minerals (Figures 3, 4, 5). The ores may have gneissic or disseminated textures, and minerals are generally coarse grained (>2-3 mm) and euhedral to subhedral (Hitzman *et al.*, 2003).

ORE MINERALOGY (Principal and *subordinate*):
Structurally-controlled replacement deposits: Willemite, *cerussite, coronadite, covellite, descloizite, franklinite, gahnite, galena, genthelvite, hedyphane, hemimorphite, hetaerolite, hydrozincite, mimetite, native silver, sauconite, scholzite, smithsonite, sphalerite, tarbuttite, vanadinite and zincite.*
Stratiform deposits: Franklinite, willemite, zincite, *adamite, anglesite, arsenopyrite, aurichalcite, azurite, chalcophanite, chalcopyrite, cuprite, gahnite, galena, hemimorphite, hetaerolite, hydrozincite, magnetite, malachite, melangerite, sauconite, smithsonite, sphalerite, tephroite and zincian fayalite (roepperite).*

Figure 1. Early dark red willemite covered by white willemite filling open spaces; Beltana mine, Australia. Pencil for scale. Photo used with permission of data metallogenica (www.datametallogenica.com).

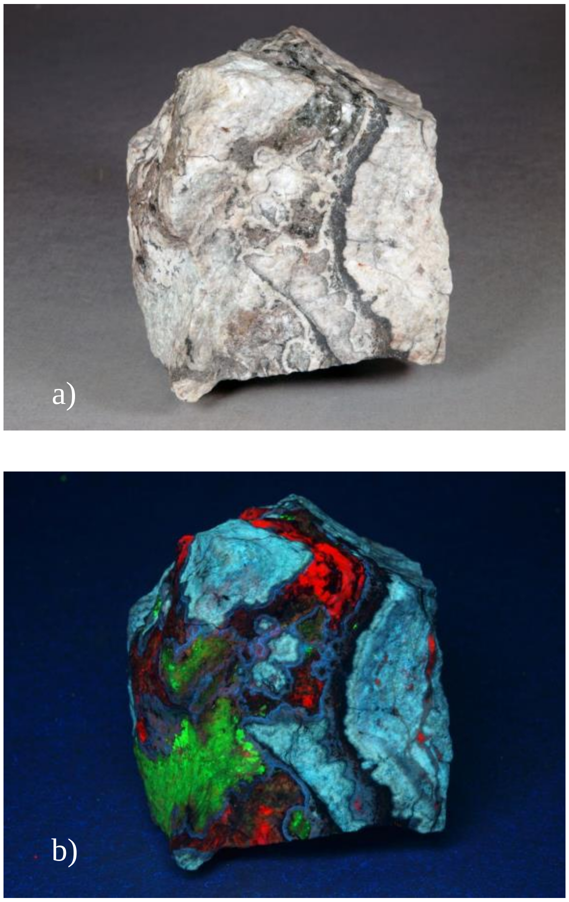

Figure 2. Zn-rich blocky ore from Beltana (Puttapa) consisting mostly of willemite. a) under daylight conditions. b) same photo under short wave ultraviolet light. Willemite fluoresces pale blue and shows green phosphorescence. calcite fluoresces red. Specimen measures 9 by 8 by 8 cm. Photo used with permission of Dr. Earl R. Verbeek, resident geologist, Sterling Hill Mining Museum, Ogdensburg, New Jersey, U.S.A.

E18 - Carbonate-hosted, Nonsulphide Zn (hypogene)

GANGUE MINERALOGY (Principal and *subordinate*): Structurally-controlled replacement deposits: Calcite, manganoan calcite, dolomite, ferroan dolomite, *apatite, barite, hematite, magnetite, quartz, siderite, Zn-rich chlorite.* Stratiform deposits: Calcite, manganoan calcite, dolomite, ferroan dolomite, *alleghanyite, apatite, aragonite, barite, fluorite, garnet, goethite, graphite, hematite, leucophoenicite, jacobsite, löllingite, phlogopite, quartz, siderite, sonolite and rhodonite.*

ALTERATION MINERALOGY: The structurally-controlled replacement deposits display pre to syn-mineralization alteration of the host carbonate rocks that is largely fracture-controlled and extends for about 50 m to 20 km from the major structures. Alteration consists of silicification and formation of a broad halo of net-veined breccia filled by dolomite, ankerite, siderite, hematite, jasper, and chlorite. Post-mineralization alteration locally consists of hematite, Zn-chlorite, and dolomite assemblage, and/or calcite replacing earlier dolomite and zinc minerals. No alteration mineralogy is reported for stratiform deposits.

In the case of stratiform deposits, any original pre-metamorphic alteration mineralogy was probably destroyed by metamorphic overprint. The exception may be Desert View deposit (United States), which could have a preserved manganese halo (Leavens and Patton, 2008). Sphalerite present in some structurally-controlled replacement and stratiform deposits is replaced by willemite under hydrothermal conditions (*i.e.*, at temperatures higher than 100˚C; Brugger *et al.*, 2003).

WEATHERING: Nonsulphides in both deposit types can be altered by supergene processes to minerals observed in supergene nonsulphide zinc deposits. Supergene mineral assemblages form a near-surface direct-replacement cap above many structurally-controlled replacement deposits. For example, an assemblage of hemimorphite, hydrozincite, and minrecordite form a cap above the willemite bodies of the Vazante deposit (Brazil). On the periphery of the Beltana deposit (Australia), hemimorphite and smithsonite formed by weathering of willemite. An assemblage of hemimorphite, cerussite, smithsonite, quartz, descloizite, pyromorphite, goethite, hematite, and iron-aluminum-manganese oxides replaces sulphides and willemite-bearing assemblages within the Kabwe (Zambia) and Berg Aukas (Namibia) deposits (Schneider *et al.*, 2008).

In the case of stratiform deposits, at least some goethite and hematite form by surface alteration of franklinite. Ferric oxide and hydroxide minerals are abundant within the Franklin and Sterling Hill deposits. Furthermore, under these conditions, hemimorphite, cerussite and hydrozincite commonly replace zincite.

ORE CONTROLS: For structurally-controlled deposits, the main controls are favourable sedimentary successions with proper redox states and potential structural zones for fluid ore mixing, *i.e.*, regional basement structural features, such as growth faults, normal and reverse faults, and shear zones.

Favorable sedimentary hosts are important for the localization of stratiform zinc oxides deposits. Faults may also have played a role in the localization of stratiform deposits but metamorphism and deformation have obliterated all evidences.

GENETIC MODEL: Structurally-controlled deposits formed where reduced, moderate to high temperature (100–330°C), Zn-rich, sulphur-poor fluid encountered a cooler, less saline, oxidized, sulphur-poor fluid of seawater, groundwater, or basinal origin (Hitzman *et al.*, 2003). The fundamental difference between the two deposit subtypes may be the site of fluid mixing (Hitzman *et al.*, 2003). The structurally-controlled deposits formed where fluids from a reduced sedimentary succession moved upwards along structures and encountered fluids that originated in oxidizing environment.

There is no consensus regarding the origin of the stratiform nonsulphide zinc deposits (*e.g.*, Franklin and Sterling Hill metamorphosed orebodies) because the nature of the primary mineralization is difficult to decipher. The stratiform deposits may have formed where Zn-rich hydrothermal fluids discharged into an oxidized, sulphur-poor body of water *(i.e.*, exhalative Zn carbonate-silicate oxide accumulations). Such mixing and accumulations of manganiferous sulphides and iron oxides may occur at the sediment/water interface or within sediments immediately beneath such body of water.

There is also a possibility that the current ore assemblages may be the post-metamorphic equivalent of hemimorphite and hydrous Mn and Fe-oxides derived from the oxidation of preexisting sulphides. In general, high fO_2/fS_2, oxidizing and alkaline conditions at neutral to basic pH, and elevated temperatures favor stability of willemite relative to sphalerite (Brugger *et al.*, 2003).

E18 - Carbonate-hosted, Nonsulphide Zn (hypogene)

Figure 3. “Classic” granular ore from Franklin deposit (U.S.A.) showing pronounced gneissic foliation with green willemite, black franklinite, and minor red zincite. The colour of much willemite at Franklin is some shade of green; at Sterling Hill, it is usually brown, tan or brownish red. Specimen measures 10 by 10 by 7 cm. Photo used with permission of Dr. Earl R. Verbeek, Resident Geologist, Sterling Hill Mining Museum, Ogdensburg, New Jersey, U.S.A.

nite and calcite are black and white, respectively. Photo used with permission of Dr. Earl R. Verbeek, Resident Geologist, Sterling Hill

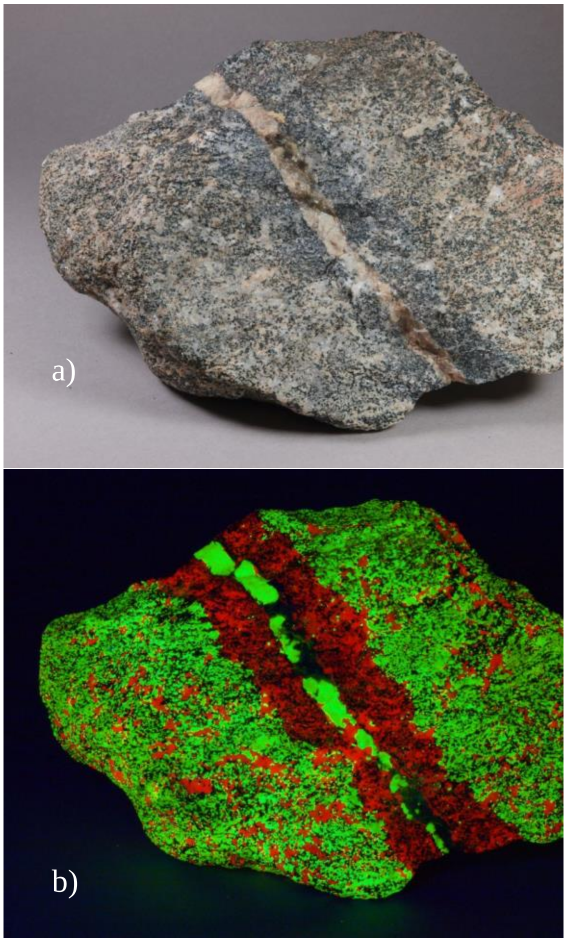

Figure 5. Sterling Hill franklinite-willemite-calcite ore. a) Daylight photograph of granular franklinite-willemite-calcite ore cut by a vein of willemite. The vein is enveloped by diffuse alteration zone. b) Same photograph under short wave ultraviolet light (colour-adjusted). Willemite fluoresces yellowish green and calcite fluoresces red. Specimen measures 17 cm in longest dimension. Photo used with permission of Dr. Earl R. Verbeek, Resident Geologist, Sterling Hill Mining Museum, Ogdensburg, New Jersey, U.S.A.

ASSOCIATED DEPOSIT TYPES: Carbonate-hosted, nonsulphide Zn-Pb (supergene, B09), Mississippi Valley-type (MVT, E12), and Irish-type (E13) are the most commonly associated deposits. Other potentially associated deposits are stratiform Zn sulphide and Fe (oxide or sulphide), Broken Hill-type (S01), magnetite *(i.e.*, iron oxide deposits), sedimentary manganese (F01), and carbonate-hosted Cu±Pb±Zn (E02) deposits.

E18 - Carbonate-hosted, Nonsulphide Zn (hypogene)

COMMENTS:These deposits are unusual in that they produce zinc, occasionally lead, and little else. The chemistry of the fluids responsible for the hypogene structurally-controlled nonsulphide deposits is similar to solutions produced in many continental sedimentary basins. Therefore these deposits could be found in the same districts as MVT, Irish-type and potentially sedimentary exhalative (SEDEX) deposits. British Columbia has prospective strata for these deposits in the miogeoclinal carbonate platform rocks of the Ancestral North America continental margin and in the pericratonic rocks of the Kootenay terrane.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Colorimetric field test for secondary zinc minerals (“Zinc Zap”) and hand-held x-ray fluorescence spectrometry are useful in exploration for nonsulphide Pb-Zn deposits in general (Paradis and Simandl, 2011; Simandl *et al.*, 2011). Positive Zn anomalies in residual soils and stream sediments and elevated concentrations of Pb, Mn, Fe, Cu, V, U, La, Cd, and As are also expected. Analysis of heavy mineral concentrates (identification of Zn-Pb nonsulphides) in stream and overburden may be effective in areas lacking deep weathering. Short wave ultraviolet light may help to detect an increase in the Mn content of calcite in proximity to deposit with these manganoan calcite fluorescing orange-red to red; however, calcite may also appear white, cream, yellow-orange, green or pink. If fluorescence of calcite is due to divalent Mn the colour of fluorescence will be orange-red to red. The other colours mentioned are due to different activators (quite diverse in calcite). Willemite may fluoresce green, yellow-orange or yellow under short wave ultraviolet light. Under long wave ultraviolet radiation, zincite may fluoresce yellow. Primary metamorphic zincite at Franklin and Sterling Hill does not fluoresce. Secondary zincite in veins or disseminated hydrothermal grains fluoresces in some specimens, but such zincite is uncommon and volumetrically insignificant. Willemite, ferroan dolomite, and supergene minerals such as hydrozincite and smithsonite, give distinct spectral responses in the short-wave near infrared portion of the spectrum (Hitzman *et al.*, 2003; McConachy *et al.*, 2009). Hyperspectral imaging holds promise as a useful tool for accurate mapping of structures, lithologies, and alteration.

GEOPHYSICAL SIGNATURE: Deposits may produce a gravity signature. Electrical methods will not be successful due to the absence or small amounts of sulphides. Deposits that contain magnetite and franklinite can produce a magnetic response; a larger response should be observed with stratiform nonsulphide deposits.

OTHER EXPLORATION GUIDES: Knowledge of the basin sedimentary succession with proper redox states and identification of potential zones for fluid mixing within major structures permits to focus exploration efforts. Discovery of outcropping hypogene Zn-Pb nonsulphide deposits depends on recognition and knowledge of the physical properties of common nonsulphide zinc minerals. The selection of grassroot exploration areas should target sedimentary rock sequences that have known nonsulphide (supergene and hypogene) zinc prospects, stratiform manganese deposits, Mississippi Valley-type deposits or Broken Hill-type deposits.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Most of the known deposits (except Vazante with 28.5 Mt at 18.3% Zn, and Franklin with 21.8 Mt at 19.5% Zn) fall in the range of <1 to 10 Mt and grade 5 to 38% Zn and 0 to 11% Pb. They may contain low concentrations of Mn, Fe, Cu, V, Cd, Ag, and Ba.

ECONOMIC LIMITATIONS: Some deposits (*e.g.*, Beltana and Aroona) are amenable to open pit mining operations; however, most hypogene nonsulphide deposits are exploited by underground mining.

IMPORTANCE: Nonsulphide deposits were the main source of zinc prior to the 1930s. Following the development of differential flotation and breakthroughs in smelting technology, the mining industry turned its attention almost entirely to sulphide ores. Today, most zinc is derived from sulphide ore. The nonsulphide deposits provided roughly 7% of the world’s zinc production in 2009. Hypogene nonsulphide deposits are relatively rare compared to supergene nonsulphide deposits, and they currently represent less than 2% of the zinc production.

E18 - Carbonate-hosted, Nonsulphide Zn (hypogene)

ACKNOWLEDGMENTS

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F - Chemical Sediment

Profile Title		Authors
F01	Sedimentary manganese	E.R. Force, S. Paradis and G.J. Simandl, 1999
F02	Bedded gypsum	Z.D. Hora, 2000
F03	Gypsum-hosted sulphur	Z.D. Hora, 2007
F04*	Bedded celestite	
F05*	Palygorskite	
F06*	Lacustrine diatomite	
F07	Sedimentary Phosphate	G.J. Simandl, S. Paradis and R. Fajber, 2012
F08*	Warm current-type phosphate	
F09*	Playa and Alkaline Lake Evaporites	
F10	Lake Superior & Rapitan types iron-formation	G.A. Gross, 2000
F11	Ironstone	G.A. Gross, 1999

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

F01 - Sedimentary Manganese

by E. R. Force[1], S. Paradis[2] and G.J. Simandl[3]

Force, E.R., Paradis, S., and Simandl, G.J., 1999, Sedimentary manganese: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, p. 47–50.

IDENTIFICATION

SYNONYMS: "Bathtub-ring manganese", “stratified basin margin manganese”, shallow-marine manganese deposits around black shale basins.

COMMODITY: Mn.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): *Molango (Mexico), Urcut (Hungary), Nikopol (Ukraine), Groote Eylandt (Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Laterally extensive beds of manganite, psilomelane, pyrolusite, rhodochrosite and other manganese minerals that occur within marine sediments, such as dolomite, limestone, chalk and black shale. The manganese sediments often display a variety of textures, including oolites and sedimentary pisolites, rhythmic laminations, slumped bedding, hard-ground fragments and abundant fossils. “Primary ore” is commonly further enriched by supergene process. These deposits are the main source of manganese on the world scale.

TECTONIC SETTING: Interior or marginal basin resting on stable craton.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: These deposits formed in shallow marine depositional environments (15-300 m), commonly in sheltered sites around islands along some areas of continental shelf and the interior basins. Most deposits overlie oxidized substrates, but basinward, carbonate deposits may be in reducing environments. Many are in within transgressive stratigraphic sequences near or at black shale pinchouts.

AGE OF MINERALIZATION: Most deposits formed during lower to middle Paleozoic, Jurassic, mid-Cretaceous and Proterozoic.

HOST/ASSOCIATED ROCK TYPES: Shallow marine sedimentary rocks, such as dolomites, limestone, chalk and black shales, in starved-basins and lithologies, such as sponge-spicule clays, are favourable hosts. Associated rock types are sandstones, quartzites, and a wide variety of fine-grained clastic rocks**.**

DEPOSIT FORM: Mn-enriched zones range from few to over 50 metres in thickness and extend from few to over 50 km laterally. They commonly have a “bathtub-ring" or “donut” shape. Some deposits may consist of a landward oxide facies and basinward reduced carbonate facies. Ore bodies represent discrete portions of these zones.

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[3] British Columbia Geological Survey, Victoria, British Columbia, Canada

F01 - Sedimentary Manganese

TEXTURE/STRUCTURE: Oolites and sedimentary pisolites, rhythmic laminations, slumped bedding, hard-ground fragments, abundant fossils, fossil replacements, and siliceous microfossils are some of commonly observed textures.

ORE MINERALOGY [Principal and *subordinate*]: Manganese oxides: mainly manganite, psilomelane, pyrolusite; carbonates: mainly rhodochrosite, kutnohorite, calcio-rhodochrosite.

TEXTURE/STRUCTURE: Oolites and sedimentary pisolites, rhythmic laminations, slumped bedding, hard-ground fragments, abundant fossils, fossil replacements, and siliceous microfossils are some of commonly observed textures.

ORE MINERALOGY [Principal and *subordinate*]: Manganese oxides: mainly manganite, psilomelane, pyrolusite; carbonates: mainly rhodochrosite, kutnohorite, calcio-rhodochrosite.

GANGUE MINERALOGY [Principal and subordinate]: Kaolinite, goethite, smectite, glauconite, quartz, biogenic silica; *magnetite or other iron oxides, pyrite, marcasite, phosphate, ± barite, carbonaceous material, ± chlorite, ± siderite, manganocalcite*.

ALTERATION MINERALOGY: N/A.

WEATHERING: Grades of primary ore are relatively uniform; however, supergene enrichment may result in a two or three-fold grade increase. The contacts between primary ore and supergene-enriched zones are typically sharp. Mn carbonates may weather to brown, nondescript rock. Black secondary oxides are common.

ORE CONTROLS: Sedimentary manganese deposits formed along the margins of stratified basins where the shallow oxygenated water and deeper anoxic water interface impinged on shelf sediments. They were deposited at the intersection of an oxidation-reduction interface with platformal sediments. Sites protected from clastic sedimentation within transgressive sequences are most favourable for accumulation of high grade primary deposits.

GENETIC MODELS: Traditionally these deposits are regarded as shallow, marine Mn sediments which form rims around paleo-islands and anoxic basins. Manganese precipitation is believed to take place in stratified water masses at the interface between anoxic seawater and near surface oxygenated waters.. The Black Sea and stratified fjords, such as Saanich Inlet or Jervis inlet, British Columbia (Emerson 1982; Grill, 1982) are believed to represent modern analogues. Extreme Fe fractionation is caused by a low solubility of iron in low Eh environments where Fe precipitates as iron sulfide. A subsequent increase in Eh and/or pH of Mn-rich water may produce Mn-rich, Fe-depleted chemical sediments. The manganese oxide facies is preserved on oxidized substrates. Carbonate facies may be preserved either in oxidized or reduced substrates in slightly deeper waters.

ASSOCIATED DEPOSIT TYPES: Black shale hosted deposits, such as upwelling-type phosphates (F07), sediment-hosted barite deposits (E17), shale-hosted silver-vanadium and similar deposits (E16) and sedimentary-hosted Cu (E04), may be located basinward from the manganese deposits. Bauxite and other laterite-type deposits (B04), may be located landward from these manganese deposits. No direct genetic link is implied between sedimentary manganese deposits and any of these associated deposits.

COMMENTS: A slightly different model was proposed to explain the origin of Mn-bearing black shales occurring in the deepest areas of anoxic basins by Huckriede and Meischner (1996).

Calvert and Pedersen (1996) suggest an alternative hypothesis, where high accumulation rate of organic matter in sediments will promote the development of anoxic conditions below the sediment surface causing surface sediments to be enriched in Mn oxyhydroxides. When buried they will release diagenetic fluids, supersaturated with respect to Mn carbonates, that will precipitate Ca-Mn carbonates.

F01 - Sedimentary Manganese

Sedimentary manganese deposits may be transformed into Mn-silicates during metamorphism. The metamorphic process could be schematically represented by the reaction:

Rhodochrosite + SiO_2 = Rhodonite + CO_2

Mn-silicates may be valuable as ornamental stones, but they are not considered as manganese metal ores under present market conditions.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mn-enriched beds. Mn/Fe ratio is a local indicator of the basin morphology that may be reflecting separation of Mn from Fe by precipitation of pyrite. Some of the large manganese deposits, including Groote Eylandt, coincide with, or slightly postdate, $\delta^{13}C$ positive excursions. These $\delta^{13}C$ anomalies may therefore indicate favorable stratigraphic horizons for manganese exploration.

GEOPHYSICAL SIGNATURE: Geophysical exploration is generally not effective. Supergene cappings may be suitable targets for the self potential method.

OTHER EXPLORATION GUIDES: These deposits occur within shallow, marine stratigraphic sequences. Black shale pinchouts or sedimentary rocks deposited near onset of marine regression are particularly favourable for exploration. High Mn concentrations are further enhanced in depositional environments characterized by weak clastic sedimentation. Manganese carbonates occur basinward from the manganese oxide ore. Many sedimentary manganese deposits formed during periods of high sea levels that are contemporaneous with adjacent anoxic basin. If Mn oxides are the main target, sequences containing shellbed-biogenic silica-glauconite are favorable. Evidence of the severe weathering of the land mass adjacent to, and contemporaneous with the favourable sedimentary setting, is also considered as a positive factor. In Precambrian terrains sequences containing both black shales and oxide-facies iron formations are the most favorable.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The average deposit contains 6.3 Mt at 30% MnO, but many deposits exceed 100 million tonnes. There is a trend in recent years to mine high-grade ores (37 to 52% Mn) to maximize the output of existing plants. The countries with large, high-grade ore reserves are South Africa, Australia, Brazil and Gabon.

ECONOMIC LIMITATIONS: On the global scale the demand for manganese ore, siliconmanganese, and ferromanganese depends largely on the steel industry. The 1996 world supply of manganese alloys was estimated at 6.6 Mt. Partly in response to highly competitive markets, in the western world much of the manganese ore mining is being integrated with alloy production. As a result, the bulk of manganese units for the steel production is now being supplied in form of alloys. There is also a new tendency to have the ore processed in China and CIS countries. The high cost of constructing new, environment-friendly plants and lower costs of energy are some of the reasons.

END USES: Used in pig iron-making, in upgrading of ferroalloys, in dry cell batteries, animal feed, fertilizers, preparation of certain aluminum alloys, pigments and colorants. Steel and iron making accounts for 85 to 90% of demand for manganese in the United States. Increasing use of electric-arc furnaces in steel-making has resulted in gradual shift from high-carbon ferromanganese to siliconmanganese. Natural manganese dioxide is gradually being displaced by synthetic (mainly electrolitic variety). There is no satisfactory substitute for manganese in major applications.

F01 - Sedimentary Manganese

IMPORTANCE: Sedimentary marine deposits are the main source of manganese on the world scale. Some of these deposits were substantially upgraded by supergene enrichment (Dammer, Chivas and McDougall, 1996). Volcanogenic manganese deposits (G02) are of lesser importance. Progress is being made in the technology needed for mining of marine nodules and crusts (Chung, 1996); however, this large seabed resource is subeconomic under present market conditions.

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F02 - Bedded Gypsum

Z.D. Hora[1]

Hora, Z.D., 2000. Bedded gypsum: mineral deposit profile F02, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 4 pp.

IDENTIFICATION

SYNONYM(S): Evaporite gypsum.

COMMODITIES (BYPRODUCTS): Gypsum/anhydrite.

EXAMPLES (British Columbia – *Canada/International*): Windermere Creek (082JSW021, 028), Coyote Creek (082JSW009, 017, 022) (082GNW071), Forget-Me-Not Creek (083E 001); *Harcus (Manitoba), Hagersville (Ontario), Hillsborough (New Brunswick), Little Narrows, Windsor (Nova Scotia), Oakfield, New York (USA), Sandusky Bay, Ohio (USA), Shoals, Indiana (USA), Saltville, Virginia (USA), Medicine Lodge, Kansas (USA), Clark County, Nevada (USA), Plaster City, California (USA), Germany, France, Spain.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Massive beds of laminated gypsum in low-energy sedimentary sequences. Gypsum may replace anhydrite, which forms the deeper parts of the deposits. Gypsum beds are typically tabular to lensoidal in shape and range from a few metres to several hundreds of metres thick. Gypsum is part of an evaporate sequence that may include thick beds of rock salt and potash.

TECTONIC SETTING: Recent and Ancient continental shelf and slowly subsiding marginal marine basins. Passive margin setting.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Coastal hypersaline basins, peritidal environment, shallow inner shelf hypersaline lagoons in high evaporation/low precipitation climates. Coastal and continental sabkha environment. Sedimentation often in repetitive cycles.

AGE of MINERALIZATON: Paleozoic to Tertiary (in some tropical areas similar Recent accumulations are known to exist).

HOST/ASSOCIATED ROCK TYPES: Redbed sandstone, siltstone, claystone, dolomite. Sometimes sandstone and fine-grained siliciclastics/carbonate reefs, platform carbonates, sometimes halite, celestite, magnesium and potash chlorides and sulphates. In deeply buried deposits, original gypsum becomes dehydrated into anhydrite, which when uplifted and exposed by erosion may rehydrate back into gypsum.

DEPOSIT FORM: Gypsum deposits are strata bound, tabular to lens shaped and are typically comprised of many bands of highly deformed gypsum resulting from high plasticity of the calcium sulphate under the pressure. Individual beds may persist over tens of kilometres in length within the depositional basin. In a platform environment, gypsum forms flat or low-angle dipping massive beds, in orogenic belts like Canadian Cordillera, for example, highly deformed, discontinuous,lenticular bodies. In BC’s Stanford Range, the stratigraphic thickness is from 100 metres at Windermere to 50–60 metres further south at Coyote Creek.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

F02 - Bedded Gypsum

TEXTURE/STRUCTURE: Mostly granoblastic texture of anhedral to subhedral crystals, sometimes grading into mosaics of ill-defined anhedral crystals. Thinly laminated, fine-grained masses, with ocal veining and aggregates of secondary selenite crystals. In highly deformed with plastic flow features with intimate folding, original laminations can be stretched and pulled apart, with deposits secondary veining of fine-grained and crystalline gypsum. Laminations are generally from a fraction of a millimeter to 4 millimetres thick, and are frequently crenulated. If interbedded with more competent rocks, like dolomite in thin layers, they may exhibit boudinage features. Large scale, concentric, open and chevron folds are common.

ORE MINERALOGY (Principal and *Subordinate*): Gypsum is the principal mineral, in some deposits where there is a demand, anhydrite may be a co-product.

GANGUE MINERALOGY (Principal and *Subordinate*): Clay, shale, dolomite; anhydrite in some deposits, soluble salts – chloride, carbonate and sulphate of sodium and potassium.

ALTERATION MINERALOGY: Secondary gypsum in veins and crystal aggregates, native sulphur.

WEATHERING: In many deposits, particularly in old orogenic belts, gypsum is the weathering product of anhydrite beds exposed by erosion on the surface. Gypsum deposits may be subject to karst type of weathering, including sinkholes and other types of underground cavities. The hydrated zone for BC deposits near Invermere is 30 to 40 metres deep in the Windermere area and 20 and 25 metres in the Coyote Creek area.

ORE CONTROLS: Depth of weathering (rehydration) in anhydrite deposits. Facies change into clastic, chloride or carbonate sedimentation in the original basin. Contamination by clay and carbonate gangue, presence of soluble salts.

GENETIC MODELS: Chemical precipitation of calcium sulphate from saturated brines. Gypsum will begin to precipitate when normal sea water salinity is concentrated to approximately 3.35 times the original salinity. Such concentration will take place when the evaporation exceeds the influx of normal seawater or fresh water into the basin. There are three depositional models currently accepted for evaporite gypsum formation – deep water/deep basin, shallow water/deep basin, and shallow water/shallow basin. Deep water evaporates are believed to result from crystals generated at the air-water interface gradually settling to the bottom. The depth of water in these deposits may be as much as 40 metres. Shallow water evaporates form in water about 5 metres in depth or less as coastal sabkha deposits. Deep basin/shallow water environment is associated with deposits of halite and magnesium/potash salts. With burial diagenesis, gypsum is converted into anhydrite. Later uplift, removal of covering rocks and presence of meteoric waters reverses the reaction and anhydrite is converted back to gypsum.

ASSOCIATED DEPOSIT TYPES: Rock salt and potash deposits, celestite, frasch sulphur.

COMMENTS: The classical deep basin/shallow water accumulations of anhydrite/gypsum with rock salt with or without potash might be expected to have sabkha deposits along the margin of the basin.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Heavy concentrations of sulphate in groundwater.

GEOPHYSICAL SIGNATURE: In heavy overburden areas, karst features and outline of gypsum and shale host rock may be identified with resistivity methods.

OTHER EXPLORATION GUIDES: Karst features, such as sinkholes.

F02 - Bedded Gypsum

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The low price of gypsum generally does not permit any beneficiation. Mine production ranges between 85 to 95% pure gypsum. Only traces of soluble salts and up to 2% of hydrous clays may be tolerated. The median tonnage depends on the size of local markets and abundance of other gypsum deposits in the region, but mostly is in the tens of millions of tonnes range. In regions with limited surface resources, some deposits are mined underground.

ECONOMIC LIMITATIONS: Transportation cost is the main limiting factor for many gypsum deposits. Synthetic gypsum produced by desulphurization of flue gases in smelters, coal burning power stations and similar operations is replacing natural gypsum in some industrial applications.

END USES: Cement retarder, wallboard, plaster; low-grade gypsum has been used as soil conditioner in agriculture.

IMPORTANCE: In the year 2000, Canada produced 8.5 million tonnes of gypsum and anhydrite, the USA produced 19.5 million tonnes of gypsum. Canada had 11 production centres, and the USA had 56 active mines. Approximately 75 % of gypsum in the USA and Canada is used to manufacture wallboard and related construction products, and the remaining 25 % is used in cement industry.

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F03 - Gypsum-Hosted Sulphur

by Z.D. Hora[1]

Hora, Z.D., 2007. Gypsum-hosted sulphur: mineral deposit profile F03, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 5 pages.

IDENTIFICATION

SYNONYM: Frasch sulphur (Frasch is process of pumping hot water underground to melt the sulphur and pump it up to the surface for recovery).

COMMODITIES (BYPRODUCTS): Sulphur.

EXAMPLES (British Columbia - *Canada/International*): Trutch (094G 023, 024), Prophet River (094I 002, 003),Windermere Creek (082JSW021,028), Branch F (082GNW071); *Coronation prospect(Alberta)*; *Kennetcook, Hilden, Pictou Harbor (Nova Scotia); Main Pass, Lake Washington, Jefferson Island (Louisiana); Wharton Co., Culberson Co., Hoskins Mound, Boling, (Texas);Texistepec, Jaltipan (Mexico); Tarnobrzeg (Poland).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Elemental sulphur occurring in economic quantities as replacements along beds, as the matrix and clasts in breccias and disseminated through porous carbonate rocks or sandstones. The sulphur is often associated with anhydrite or gypsum interbedded with dolomites or limestones and below impermeable mudstones or shales. The elemental sulphur is found in zones that are metres to tens of metres thick, often quite extensive laterally and frequently occurs with hydrogene sulphide.

TECTONIC SETTINGS: Ancient continental shelf and slowly subsiding marginal marine basins. Passive margin setting.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The host sedimentary rocks were deposited in a restricted basin along with evaporitic beds of anhydrite, barite and sometimes celestite. In some cases the evaporitic rocks formed diapiric salt domes. Presence of hydrocarbons in surrounding rocks, together with sulphate reducing bacteria and migrating meteoric water.

AGE OF MINERALIZATION: Most deposits are considered to be Tertiary or younger, but they are hosted mostly in Devonian, Mississippian, Triassic and Miocene rocks.

HOST / ASSOCIATED ROCK TYPES: Anhydrite or gypsum with porous dolomite/limestone, sandstone and siltstone beds / mudstones, siltstones, bioepigenetic calcite, locally barite and celestite.

DEPOSIT FORM: Strata controlled replacement mineralized bodies, collapsed cave fill heterolithic breccias, porous carbonate reef structures, replacement orebodies in roofs of diapiric salt domes.

TEXTURE/STRUCTURE: In sedimentary deposits the ore textures frequently mimic sedimentary textures of original gypsum or anhydrite. In collapsed cave fill deposits sulphur occurs as microcrystalline disseminations in biogenic calcite, crystals lining limestone cavities and crystalline masses, crusts and clasts in collapse breccia. In diapiric structures, sulfur is usually massive in the lower part of the so called “caprock”.

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F03 - Gypsum-Hosted Sulphur

ORE MINERALOGY [Principal and *subordinate*]: Elementary sulphur, secondary calcite, hydrocarbons and hydrogene sulphide / *barite, celestite, galena, sphalerite, marcasite, pyrite.*

GANGUE MINERALOGY [Principal and *subordinate*]: Anhydrite, gypsum, limestone / *siltstone, sandstone.*

ALTERATION MINERALOGY: Secondary, white calcite. Celestite and barite are probably also products of the calcium sulphate reduction process.

WEATHERING: While native sulphur is resistant to chemical weathering and can be found in outcrop, it is brittle and easy to disintegrate mechanically.

ORE CONTROLS: Critical to the generation of a significant sulphur deposit is the confinement of the hydrogene sulphide to a restricted area where elemental sulphur may be deposited and preserved. Overlying impermeable strata of clays or shales may trap the hydrogene sulphide and prevent subsequent oxidation. Structural controls are often important for the migration of hydrocarbons and groundwater, for the development of collapse breccias, and as well for development of diapiric salt domes.

GENETIC MODELS: The origin of sulphur deposits is widely accepted to be associated with the actions of sulphate reducing bacteria in the presence of gypsum or anhydrite and hydrocarbons. At relatively shallow depths (generally less than 750 metres, but locally deeper) and at temperatures below about 60 degrees Celsius, the bacteria can thrive in the subsurface given an adequate energy source. The host anhydrite must be exposed to migrating meteoric waters to be hydrated to gypsum. Into this system, petroleum or natural gas is introduced from depth, along faults, joints or permeable strata. Bacteria are introduced by meteoric water which oxidize the hydrocarbons and reduce the sulphate to hydrogene sulphide. The latter is then oxidized by molecular oxygen derived usually from meteoric water or ferric iron to produce elemental sulphur and calcium carbonate. Under some circumstances, hydrogene sulphide may oxidize into native sulphur without the presence of meteoric water. In high temperature/ high pressure environments, hydrogene sulphide may also form as a product of thermal maturation of crude oil and thermochemical sulphate reduction. A variety of sulphur forms are dissolved in the sour gas phase and precipitate with lowering the pressure and/or temperature, which can happen by natural processes during uplift and erosion, or during natural gas production. Some deposits may be the result of combination of the two processes.

ASSOCIATED DEPOSIT TYPES: Gypsum (F02), halite, potash salts, oil and natural gas, hydrogene sulphide pools, possibly celestite (F04).

COMMENTS: At present, natural gas processing plants provide considerable amounts of North America’s sulphur from sour gas.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Presence of H_2S in oil and natural gas. Light carbon isotope survey anomalies may detect biogenic calcium carbonate. Detrital native sulphur in soil.

GEOPHYSICAL SIGNATURE: Gravity methods can outline diapiric structures, porous limestone host rocks and collapse features.

OTHER EXPLORATION GUIDES: For subsurface deposits favourable lithologies with evaporite sequence. Biogenic calcite may form weathered out small buttes in otherwise flat topography.

F03 - Gypsum-Hosted Sulphur

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Production of Frash sulphur from individual North American deposits has varied from less than one hundred thousand to more than 80 million tonnes. Boiling Dome, Texas produced over 90 million tonnes of sulphur between 1928-1994, Main Pass dome in Louisiana was reported to have 67 million long tons reserves in 1989, the Culberson orebody in Texas reported pre-production reserves of 81.5 long tons of sulphur. In Poland, sulphur-bearing rocks are from few metres to over 40 metres thick, sulphur content is quite variable from few % to over 50 %, the average varies from 22 to 33%. Rocks containing less than 5% of sulphur are considered barren. Total measured reserves in 1992 in Poland were reported at about 600 million tonnes and another 500 million tonnes inferred, in two separate mining districts.

ECONOMIC LIMITATIONS: For the Frasch method, the maximum depth of the orebody is up to approximately 1000 metres below surface. Since the year 2000, all sulphur in Canada and USA comes from involuntary production to remove it from natural gas and other hydrocarbons, and a variety of base metal smelting operations.

END USES: Sulphuric acid for industrial applications, one of the main uses is for production of phosphate fertilizers.

IMPORTANCE: Sulphur mining from outcrops of this deposit type is known to have taken place as early as 2000 BC in Egypt; archeological work indicates its use by man thousands of years earlier. A major world source of sulphur from the discovery and development of Frasch mining in 1895 until the last U.S. operation was closed in August 2000.

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F03 - Gypsum-Hosted Sulphur

Rogers, M.C., Thurston, P.C., Fyon, J.A., Kelly, R.I., and Breaks, F.W. (1995): Descriptive Mineral Deposit Models of Metallic and Industrial Deposits Types and Related Mineral Potential Assessment Criteria; *Ontario Geological Survey*, Open File Report 5916, 241 pages.

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F07 - Sedimentary Phosphate

by G.J. Simandl[1,2], S. Paradis[2,3] and R. Fajber[1]

Simandl, G.J., Paradis, S., and Fajber, R., 2012. Sedimentary phosphate deposits mineral deposit profile F07: In: Geological Fieldwork 2011, Ministry of Energy and Mines, British Columbia Geological Survey, Paper 2012-1, p. 217–222.

IDENTIFICATION

SYNONYMS: Upwelling phosphate deposits, phosphorite or stratiform phosphate deposits

COMMODITIES (BYPRODUCTS): Phosphate ± F, ± rare earth elements (REE including Y), ± V, ± U, ± gypsum (phosphogypsum)

EXAMPLES (British Columbia (MINFILE #) – *Canada/International*): Crow (082GNE025), Cabin Creek (CS) (082GSE055), Bighorn (082GSE060), Ram 1 (082GSE056), Wapiti (093I 008) and Wapiti East (093I 022); *Athabaska Basin (Saskatchewan, Canada), Bone Valley and Hawthorn Formations (Florida, U.S.A.), Phosphoria Formation (Idaho, Montana and Wyoming, U.S.A.); Ganntour deposit (Morocco).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sedimentary phosphate deposits are stratiform or lens-shaped, measuring from less than 1 metre to tens of metres in thickness. They extend for tens to hundreds of kilometres in their longest dimension. Mineralized zones consist of phosphorites (≥18% P_2O_5) or phosphate rocks (<18% P_2O_5). These rocks are bedded. They may be primary or reworked (secondary). The main ore mineral is microcrystalline francolite, commonly in form of laminae, pellets, oolites, nodules and fragments of bones or shells (Figure 1). This mineral may be also present within the rock matrix.

Figure 1. Typical appearance of phosphate rock containing a fragment of a crinoid (Fernie Formation, southeastern British Columbia).

TECTONIC SETTING(S): The most favourable tectonic settings for larger deposits are passive continental shelves and adjacent sag basins; some sedimentary phosphate deposits formed at active continental margins, intracontinental basins and even lacustrine environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Deposition usually occurred in areas of warm paleoclimate, mostly between the 40th parallels. The most common depositional environment for sedimentary phosphate deposits is a marine sedimentary basin with a good connection to the open sea (commonly west-facing at the time of phosphate deposition), and upwelling areas with high plankton productivity.

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F07 - Sedimentary Phosphate

AGE OF MINERALIZATION: Deposits range in age from Proterozoic to Holocene. Phosphate deposits are particularly abundant in Cambrian, Permian, Jurassic, Cretaceous, Eocene and Miocene times (Cook and McElhinny, 1979). In terms of inferred resources (tonnage), the Eocene, Miocene and Permian are the most important time intervals. In British Columbia, the majority of phosphate occurrences are located in rocks of Jurassic and Triassic age.

HOST / ASSOCIATED ROCK TYPES: Hostrocks are phosphorites ($\geq$18% P_2O_5) and phosphate rocks (<18% P_2O_5). Associated rock types are typically sedimentary rocks including marl, black shale, chert, limestone, dolostone, and in some cases lava flows, tuffs and diatomite-bearing rocks. Figure 2 shows conceptual vertical section of the platform perpendicular to the shoreline.

DEPOSIT FORM: Phosphate-bearing rocks are generally stratiform; bed thicknesses range from less than 1 metre to tens of metres and may extend for distances up to several hundreds of kilometres in their longest dimension. The thickest deposits are amalgamated/condensed beds (tabular units) reflecting variations in upwelling intensity and storm frequency through time. Individual phosphorite deposits delimited by drilling may measure from a few hundreds of metres to tens of kilometres in their longest dimension. Phosphorite deposits commonly occur in belts.

TEXTURE / STRUCTURE: Phosphorite deposits commonly contain phosphate pellets and nodules as well as phosphatized shells and bones; ooids (Figure 3), intraformational rip-up breccias, clasts, concretions, phosphatic stromatolite mounds (or their fragments), crossbeds, hardgrounds and burrows. Phosphatic minerals may also form the matrix. Gangue mineralogy and textures in phosphorites are determined partially by the depositional environment at the time of phosphogenesis and partially by the environment that prevailed during reworking and winnowing (natural P_2O_5 upgrading) of the original phosphate rocks and during diagenesis. Phosphorites formed by replacement (during diagenesis) may be paler buff, tan and/or macroscopically featureless.

"Pristine" phosphate accumulations (one cycle of phosphogenesis) are characterized by phosphatised laminae and lenses, coated grains, coprolites, peloids and fossils. Allochthonous phosphate accumulations show sharp and erosive lower boundary, assemblages of phosphatic and non-phosphatic particles and internal grading, accreted grains, minor unconformities, scour marks and bed truncations, and heterogeneous phosphate particles. Condensed phosphates represent an intermediate stage between pristine and allochthonous phosphate deposits (Föllmi, 1996).

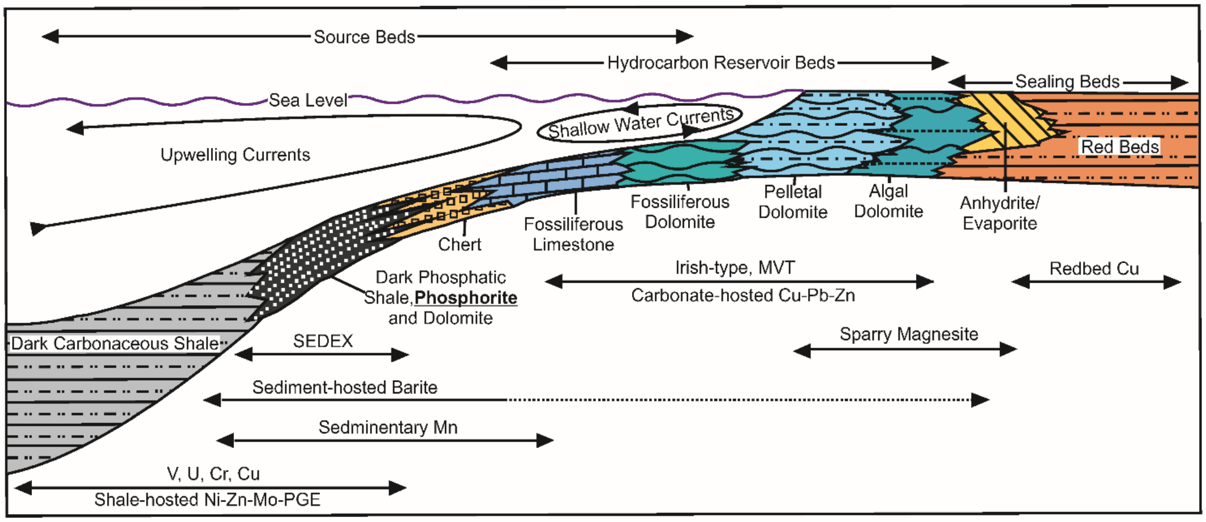

Figure 2. Schematic vertical section across continental platform, showing key lithologies and spatial relationship between phosphorites and other deposit types and hydrocarbons (modified from Sheldon, 1963; Hein *et al.*, 2004).

F07 - Sedimentary Phosphate

ORE MINERALOGY (Principal and *subordinate*): Francolite (carbonate-rich fluorapatite), secondary minerals derived by the weathering of francolite: millisite, Fe-pallite, crandalite, wavellite and other Al-phosphates. Secondary minerals are not desirable from the metallurgical point of view.

GANGUE MINERALOGY (Principal and *subordinate*): Dolomite, calcite, quartz, montmorillonite or illite ±*chert, ±halite, ±gypsum, ±iron oxides, ±siderite, ±pyrite, ±carnotite*, ±glauconite,±sphalerite, ±zeolites.*

ALTERATION MINERALOGY: Dahllite is believed to form during late diagenesis (Trappe, 1998).

WEATHERING: Lateritic alteration of francolite results in the formation of millisite, Fe-pallite, crandalite, wavellite and other aluminum-phosphates. Turquoise may form if copper is present. Weathering decreases concentrations of pyrite and sphalerite and may result in the release of selenium.

ORE CONTROLS: Phosphorites are stratigraphically and spatially linked to paleodepositional environments favourable for phosphogenesis (high bio-productivity and phosphorus flux, stratification within water/unconsolidated sediment column, and a moderate to low supply of allogenic sediment). Phosphorite deposits are spatially related to multiple cycles of regression-transgression. Phosphate facies commonly rest on, or are associated with, erosional surfaces (unconformities) and/or start with phosphatic lag concentrates. Entrapment basins (zones) characterized by a low influx of continent-derived sediments are required for the deposition of phosphorites.

GENETIC MODEL: Seawater averages 0.071 ppm phosphorous (Redfield, 1958) and may contain as much as 0.372 ppm phosphorus (Gulbradsen and Robertson, 1973). Warm surface waters typically contain less than 0.0033 ppm phosphorus (McKelvey, 1973). Phosphate rocks and primary phosphorites form in or laterally adjacent to organic-rich sediments beneath regions where upwelling, nutrient-rich, cold waters interact with a warm sunlit surface seawater layer, creating favourable conditions for intense algal bloom. Algae die, or are eaten by other life forms, then accumulate on the seafloor as fecal pellets and/or organic debris beneath sites of active coastal upwelling. Decomposition of organic debris in an oxygen-deprived environment by bacteria and dissolution of fish bones and scales are linked to precipitation of phosphate minerals (phosphogenesis) near the sediment-water interface. Precipitation of apatite within intergranular spaces during diagenesis and through non-biological chemical processes may also contribute to formation of phosphate rocks.
Most phosphorites were enriched by the reworking, winnowing (concentration) and accumulation of the above described phosphorus-bearing sediments.

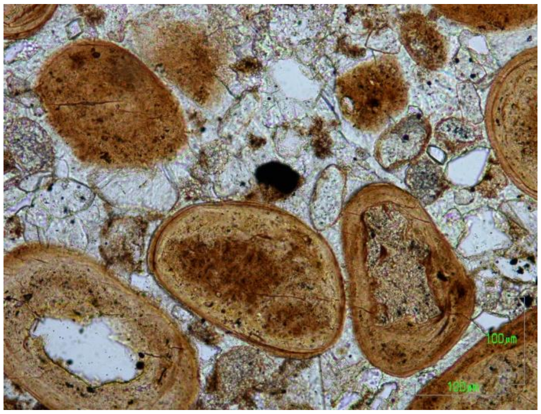

Figure 3. Phosphorite of Sulphur Mountain Formation, northeast British Columbia. Phosphate ooids in carbonate matrix (plane-polarized light; shorter margin of the photograph equals 500 microns). This phosphorite contains 23.6% P_2O_5, 1167.4 ppm of rare earth elements (including 227 ppm La, 122.5 ppm Ce, 45.4 ppm Pr, 186 ppm Nd, 35.7 ppm Sm, 8.75 ppm Eu, 43.5 ppm Gd, 8.4 ppm Ho, 23.7 ppm Er, 3.0 ppm Tm, 15.2 ppm Yb, 2.1 Lu and 399 ppm Y).

ASSOCIATED DEPOSIT TYPES: Sedimentary manganese deposits (F01), evaporites (gypsum-anhydrite, F02), SEDEX deposits (E14), coal deposits (A03 and A04), hydrocarbon reservoirs, Mississippi Valley-type Pb-Zn deposits (E12), sparry magnesite deposits (E09) and red bed Cu deposits (E04) are spatially associated with the phosphate deposits. See Figure 2.

* Carnotite is a potassium uranium vanadate radioactive mineral with chemical formula: $K_2(UO_2)_2(VO_4)_2{\bullet}3H_2O$. It is commonly considered as a gangue mineral; however, if present in high concentrations it becomes an ore mineral.

F07 - Sedimentary Phosphate

COMMENTS: The high trace element content of some phosphorites may limit their suitability for agricultural applications. Repetitive fertilizing of agricultural fields over several decades may result in unacceptable concentrations of potentially harmful elements in soils. For example, elevated concentrations of uranium, thorium, lead, cadmium, selenium and chromium in fertilizer are not desirable.

Phosphorite deposits can supply several byproducts, such as fluorine (Simandl, 2009). Uranium and vanadium were extracted from phosphate deposits in United States. Phosphate deposits also have the potential to produce yttrium (Pell, 1991) and other rare earth elements as byproducts (Simandl *et al.*, 2011a, b). Synthetic gypsum (phosphogypsum) can also be a byproduct of phosphoric acid production; however, its use is typically limited because it incorporates unwanted trace elements.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Phosphorous and in some cases rare earth elements, fluorine, and uranium can be used as pathfinders. Since phosphogenesis is commonly associated with organic-rich sediments, nitrogen and carbon may be considered as part of the signature; however, in practice these elements are not part of standard analytical packages used in exploration. Rapid ammonium molybdate – nitric acid field method can be used for field identification of phosphate (Swanson, 1981); however, this method is generally considered as over sensitive. A portable, hand-held XRF is an effective tool in determining the concentrations of phosphorus, light rare earth elements, yttrium, and a number of other trace elements commonly contained in phosphate rocks (Fajber and Simandl, 2012).

GEOPHYSICAL SIGNATURE: Radiometric surveys could be an effective exploration tool if the deposit contains above background concentrations of radioactive elements.

OTHER EXPLORATION GUIDES: Phosphate deposits are expected to occur mostly in favourable paleolatitudes (between the 40th parallels). Remote sensing (spectral analysis) is also showing some promise. Conceptual vertical section showing spatial distribution of the associated deposit types (Figure 2) may be used as a guide in early stages of exploration. Phosphatic and glauconitic facies are commonly spatially related (Odin and Letolle, 1980). In those settings, glauconite, characterized by its green colour (easily recognizable by prospector), may be used as an indirect guide to mineralization.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: According to the United States Geological Survey grade and tonnage model, 90% of the sedimentary phosphate deposits contain more than 26 million tonnes, 50% of them contain 330 million tonnes or more, and less than 10% of these deposits contain more than 4200 million tonnes (Mosier, 1992). According to the same model, 90% of these deposits grade more than 15% P_2O_5, 50% of them grade more than 25% P_2O_5 and less than 10% grade more than 32% P_2O_5 (Mosier, 1992).

Historically only deposits with grades exceeding 25% P_2O_5 were considered of economic interest. As these deposits are being depleted, lower ore grades are becoming acceptable and upgrading has become common practice. For example, in Idaho companies use high-grade ore (or acid grade >31% P_2O_5) directly in fertilizer plants, while medium grade (or furnace grade) rock (24 to 31% P_2O_5) can be used as feed for elemental phosphorus plants. Lower grade rocks (15 to 24% P_2O_5) are also mined but they have to beneficiated to meet the above requirements.

Under favourable conditions (*i.e.* near existing flotation plants, as in Florida), even phosphate rocks grading as low as 3% P_2O_5 may be of economic interest (Zhang *et al.*, 2006). Furthermore, a small proportion of mined phosphate rock is simply ground and sold to growers of organic products as “natural rock phosphate”. Such products work reasonably well in acidic soils; however, most of the phosphorus contained in these products is not readily available for plant use in neutral or alkaline soils (pH ≥7).

F07 - Sedimentary Phosphate

ECONOMIC LIMITATIONS: Most of the deposits are being mined using open-pit methods or drag lines; however, under exceptional circumstances, high-grade deposits may be mined by underground methods.

Phosphatic rocks may be enriched in REE, V, U, F, Ag, Cd, Cr, Mo, As, Se, Sr, Te, Zn and other elements. Elements such as U, Th and their decay products, Cd, Tl, Se and Hg are closely monitored. If found in excessive concentrations these elements are recovered to mitigate environmental risks linked to fertilizer use or phosphate tailings disposal (Laznicka, 1985; Northolt, 1994; Trappe, 1998).

High concentrations of certain elements other than P can cause problems during processing. High CaO/P_2O_5 ratios result in an increase in sulfuric acid consumption during phosphoric acid production; high concentrations of Mg and SiO_2 cause filtration problems; high concentrations of Na and K results in scaling; organic matter causes foaming during production of phosphoric acid; high Cl concentrations cause premature corrosion. High levels of relatively toxic elements (*e.g.* Cd, Se and As) may make a phosphorite unsuitable for fertilizer production.

IMPORTANCE: World phosphate production for 2011 is estimated at 176 million tonnes. Sedimentary phosphate deposits account for 80% of the world phosphate production. Morocco and the Western Sahara (administered by Morocco) accounted for 50 million tonnes. Other North African countries, China, U.S.A. and Russia are also major producers (Jasinski, 2011). Other sources of phosphorus include apatite concentrate produced from some carbonatite deposits (N01) and peralkaline intrusions (Brazil, Canada, Russia and South Africa), guano deposits (small and only of local importance) and also apatite produced as a by-product of iron extraction from some of iron oxide copper gold (IOCG) deposits (D07).

Phosphorus is an essential element for plant and animal life. There are no substitutes for phosphorus in agricultural applications. Elemental phosphorus is used in production of variety of intermediate products that are consumed in the manufacturing of detergents, matches, fireworks, pesticides, toothpastes and explosives. Phosphorus compounds may also be used as gasoline additives, in some plastics, fire retardants, *etc.*

The recovery of phosphate from waste waters is technically possible; however, the economics of the process remain challenging at current prices of phosphate fertilisers (Parson and Smith, 2008).

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F10 - Iron-Formation
Lake Superior and Rapitan-Types

by G.A. Gross[1]

Gross, G.A., 2000. Iron formation - Lake Superior and Rapitan types:, Ministry of Energy, Mines and Petroleum Resources British Columbia Geological Survey mineral deposit profile, website, 5 p.

IDENTIFICATION

SYNONYMS: Taconite, metataconite, itabirite, banded iron-formation (BIF), jaspilite, hematite or magnetite quartzite, banded chert hematite lithofacies.

COMMODITIES (BYPRODUCTS): Fe (Mn).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Lake Superior type: Humphrey, Wabush, Smallwood (Labrador, Canada), Mount Wright (Quebec, Canada); *Mesabi Range (Minnesota, USA)*. Rapitan-type: Crest, Mackenzie Mountains (Yukon and Northwest Territories, Canada); *Jacadigo (Brazil)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Lake Superior-type iron-formations are chemically and biochemically precipitated, banded sedimentary rocks composed of hematite and magnetite, containing 15% or more Fe, interbedded with chert and other sedimentary rocks, such as quartz arenite, dolostone, black shale and argillite. Manganiferous lithofacies contain pyrolusite, manganite and hollandite.

Rapitan-type iron-formations have distinctive lithological features which reflect different environments of formation. Microbanded hematite interbedded with mud and siltstone, chert nodules and lenses associated with diamictites (tillite) and mudflows, including dropstones, sandstone, conglomerate, and argillites

TECTONIC SETTING(S): Lake Superior-type: Deposited along craton margins, in marine continental shelf and shallow rift basins; directly related to and form a part of the tectonic belts developed along the margins of cratons or plates. Rapitan-type: Deposited in grabens and fault scarp basins along rifted margins of continents or ancient cratons in sequences of Late Proterozoic and Early Paleozoic rocks.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Lake Superior-type iron-formations occur in the fold belts along craton margins, often within gently dipping homoclines of quartz arenite, dolomite and shale or lie unconformably on Archean gneisses, granulites, and granitoid cratonic rocks near the original basin shorelines. Outward from the craton to its faulted margins, these homocline structures are succeeded by broad open folds that are intensely deformed by complex isoclinal folds and faults, imbricate thrust sheets and nappe structures that developed by tectonic transport directed toward the craton. Structural deformation of the marginal basins appears to be related to the initial stages of plate subduction that took place along the craton margins. As the tectonic systems and volcanic arcs developed along the margins of the Superior-Ungava craton, iron-formation units were deposited in the marginal basins in association with clastic and chemical sediments, including thick sequences of shale, argillite, dolostone, stromatolitic dolostone, chert, chert breccia, black carbon-rich shale, quartz arenite, conglomerate, siltstone, redbeds, tuff and other volcanic rocks. Lateral transitions occur in many basins from stratigraphic sequences of iron-formation and typical mature clastic sediments that were deposited in near shore environments on the platform to sequences of greywacke, turbidites, and shale interbedded with iron-formation, tuff and volcanic rocks deposited near volcanic centres offshore from the craton margins.

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F10 - Iron-Formation: Lake Superior and Rapitan-Types

Rapitan-type iron-formations commonly formed in grabens and fault scarp basins along rifted margins of land areas of high relief and in the type area were associated with glaciation. Oxide (hematite) lithofacies of iron-formation are associated with relatively coarse-grained clastic sediments, diamictite and minor carbonate rocks in thick stratigraphic sequences that include sandstone, conglomerate, mudstone, argillite, diamictite (tillite), and thin beds of dolomite and carbonate.

AGE OF MINERALIZATION: Most Lake Superior-type iron-formations formed in the Early Proterozoic, some in Middle to Late Proterozoic. Rapitan-type iron-formations strata were deposited in Late Proterozoic to Early Paleozoic.

HOST/ASSOCIATED ROCK TYPES: Lake Superior-type commonly interbedded with thick sequences of sedimentary rocks, including shale, argillite, dolostone, stromatolitic dolostone, chert, chert breccia, black carbon-rich shale, quartz arenite, conglomerate, siltstone, redbeds, and with tuff and other volcanic rocks. Deposition of Rapitan-type with a predominance of relatively immature clastic sediment, occasional mudflow, conglomerate and diamictite (tillite), sandstone, conglomerate, mudstone, argillite, diamictite (tillite), and thin beds of dolomite and carbonate.

DEPOSIT FORM: Individual beds are from 1mm to more than 1m thick and multiple beds have cumulative stratigraphic thicknesses ranging from 30 to 300 m and strike lengths of several kilometres. Repetition of iron-formation beds by complex folds and thrust faults may produce very large deposits of ore.

TEXTURE/STRUCTURE: Lake Superior-type deposits commonly have primary sedimentary features such as granules and oolites in a chert or carbonate matrix, interlayered beds of chert or quartz and iron oxide minerals, crossbedding, intraformational breccia, slump folds, compaction and desiccation structures, and stromatolite-like forms. Macro bands commonly range in thickness from 1 to 10 cm, and exceed 1 m in a few places; micro bands (< 1 mm thick) are rare. Iron is uniformly distributed in discrete grains or grain-clusters of hematite, magnetite and goethite in a cherty or granular quartz matrix.
Rapitan-type typically has interbedding of thick and thin layers of red to blue hematite, mudstone and fine grained clastic components intermixed with jasper chert in lenses, large (5mm) nodules and thin bands.

ORE MINERALOGY (Principal and *subordinate*): Lake Superior-type: Hematite, magnetite, goethite, and pyrolusite, manganite and hollandite in manganiferrous iron oxide lithofacies.
Rapitan-type: Predominance of red to blue and grey fine grained hematite, magnetite content is minor to absent, goethite minor, uncommon or inconspicuous, manganese oxide minerals in some lithofacies.

GANGUE MINERALOGY (Principal and *subordinate*): Lake Superior-type: Quartz in granular and chert form, iron silicates, iron carbonates and iron sulphides.
Rapitan-type: Quartz in various forms of chert, fine grained clastic silicate minerals, iron carbonates, fine grained clastic quartz and mudstone.

METAMORPHISM: The grain size of iron oxide minerals generally increases with the grade or rank of metamorphism. Iron silicate minerals are recrystallized to form higher rank metamorphic minerals, such as minnesotaite, grunerite, cummingtonite and hypersthene or forsterite. Iron silicate minerals also form under special conditions by the reaction of quartz and iron oxide and carbonate minerals. As the rank of metamorphism increases, siderite, ankerite and dolostone break down and magnetite, actinolite, cummingtonite, grunerite, minnesotaite and various other silicate minerals are formed. Grain size enlargement of iron oxide minerals which increases with rank of metamorphism is the most critical factor in controlling the beneficiation characteristics of iron-formation and thus determines whether an iron-formation can be processed to provide an iron ore concentrate and considered as an iron ore resource. No highly metamorphosed examples of Rapitan-type iron-formation are known.

WEATHERING: Surface weathering causes the oxidation of iron minerals, removal by leaching of the chert-quartz and gangue minerals and the development of aluminous clay minerals. Residually enriched types of iron ore deposits formed by deep weathering processes can overly all types of iron-formation; probably the best known residual deposits are related to Lake Superior-type iron-formation.

F10 - Iron-Formation: Lake Superior and Rapitan-Types

ORE CONTROLS: The most desirable deposits have been highly metamorphosed and have granular, medium to coarse-grained textures that developed during metamorphism. Metamorphism is the most important factor in forming iron ore in iron-formation as it controls grain size enlargement and the beneficiation qualities of an iron-formation for processing and production of iron ore concentrate. Basin architecture and many physical, chemical and biochemical factors controlled the deposition and the kinds of primary lithofacies of iron-formations that formed, and the kinds of clastic sediments associated with them. Discrete beds and oxide lithofacies are desirable for the metamorphosed iron deposits, many large “residually enriched” iron ore deposits were derived from thick sequences of oxide and carbonate lithofacies of iron-formation. Deposition of the successions of clastic sediments and iron-formation was related to basin architecture and the many factors controlling their depositional environments.

GENETIC MODEL: Two principal genetic models have been considered for the origin of iron-formations. One emphasizes hydrothermal effusive or exhalative and biochemical processes and the other a combination of hydrogenous and sedimentary processes with derivation of the iron, silica and other constituents by deep weathering of a land mass. Biogenic processes evidently played an essential part in the deposition of iron-formations of all types and ages. The specific biochemical processes that formed the older metamorphosed sedimentary beds cannot be clearly defined because many primary features of the sediments have been destroyed. Contemporary glaciation may not have been an essential factor in the genesis of all Rapitan-type iron-formations although striated boulders indicate glaciation in the type area. High relief in the land areas adjacent to the basins and troughs in which they formed appears to have been a consistent feature in their geological settings.

ASSOCIATED DEPOSIT TYPES: Lake Superior-type iron-formations are the source rocks or protore for the large, direct-shipping iron ore deposits formed by secondary enrichment processes. They also may grade laterally into volcanogenic deposits, including Algoma-type iron-formation (G01), volcanogenic massive sulphide deposits (G04, G05, G06) and sedimentary manganese (F01). Manganiferous facies of iron-formation may contain more than 3% manganese and Mn to Fe ratios range up to 40 to 1 in some manganese lithofacies. Ornamental stones (“tiger's eye” quartz, blue asbestos, crocidolite and riebeckite) are recovered from some metamorphosed iron-formations. Chert rocks and especially jasper cherts have had many decorative and ornamental uses. Rapitan-type iron-formation is the source of the distinctive “Alaska black diamond” ornamental stone.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Fe and Mn-rich sediments. Rapitan-type: The iron-formation in the type area has high P and low Al and Mn contents.

GEOPHYSICAL SIGNATURE: Aeromagnetic surveys can identify linear anomalies that clearly outline the magnetite-bearing iron-formations. Gravity surveys have been used in conjunction with surveys that measure magnetic properties to trace iron-formation beds and the residual-enriched iron ore deposits in them.

OTHER EXPLORATION GUIDES: Granular, medium- to coarse-grained textures with well-defined sharp grain boundaries are desirable to enable liberation and beneficiation of the crude ore. Oxide facies iron-formation deposited in highly oxidizing environments normally has a lower content of minor elements, especially sodium, potassium, sulphur, and arsenic, which have deleterious effects in the processing of the ore and quality of steel produced from it. Most iron-formations are regional-scale stratigraphic units that are relatively easy to define by mapping. Basin analysis and sedimentation modeling enable definition of factors that controlled the development, location and distribution of different iron-formation lithofacies. Iron-formations may be marker-beds for other stratafer deposits, such as bedded manganese, stratiform base-metal sulphide, Sedex, and gold-bearing iron-formations.

F10 - Iron-Formation: Lake Superior and Rapitan-Types

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Economic grades range from 25% to over 45% Fe. Deposits range from <10 to > 1,000 Mt. Rapitan-type: Crest deposit contains a resource of 5,600 Mt averaging 47.2% Fe.

ECONOMIC LIMITATIONS: Discrete well-defined magnetite and hematite lithofacies of iron-formation are preferred. Metamorphism, especially amphibolite and higher grades, enlarges the grain size of magnetite, hematite and quartz, greatly improving its amenability to concentration and beneficiation.

END USES: Iron ore consisting of mineral concentrates is usually processed further by pelletizing and sintering, and blended with other types of ore to improve the overall grade and structural quality of the furnace burden, the blended mixture of iron ore, coke, coal or carbon fuel, and carbonate rock charged to blast furnaces.

IMPORTANCE: Lake Superior-type deposits include the thickest and most extensive stratigraphic units of iron-formation. They provide the largest iron deposits and are the source rocks for more than 60 % of the iron ore resources of the world. The remote location of Rapitan-type iron-formations in Canada has distracted from their development as sources of iron ore or for other industrial applications.

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F10 - Iron-Formation: Lake Superior and Rapitan-Types

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F11 - Ironstone

by G. A. Gross[1]

Gross, G.A., 1999, Ironstone: Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey mineral deposit profile, website, 4 pp.

IDENTIFICATION

SYNONYMS: Two types of ironstone, Minette and Clinton.

COMMODITIES (BYPRODUCTS): Fe.

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Minette-type: Moberly? (094A006); *Clear Hills and Swift Creek, Peace River area (Alberta, Canada), Jurassic Lorraine Basin (France, Luxembourg), Midlands (England), Lisakov, southern Ural Mountains (Russia), Kerch near the Black Sea and Sea of Azov (Ukraine).* Clinton-type: *Wabana Mine (Newfoundland, Canada); Alabama and Appalachian areas (United States)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Ironstone ore of Clinton-type is typically layered to massive, deep red to purplish red or brown, and composed of oolites or spherules consisting of hematite and goethite. Minette-type ironstone is mainly dark brown to green-brown or grey-green with similar texture and is thin bedded to massive.

TECTONIC SETTINGS: Shallow euxinic marine basins along continental margins, in river beds and estuarine basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Neritic oxygenated and euxinic environments in continental shelf and estuarine basins. Some appear to have been sand bars that were formed parallel to ancient shorelines.

AGE OF MINERALIZATION: Late Precambrian to Recent.

HOST/ASSOCIATED ROCK TYPES: Ore is iron-oxide beds and lenses which are separated by lenses of clastic sediment which grade laterally over a distance of tens to hundreds of metres into leaner siliceous material. They are associated with black shale, siltstone, sandstone, shale, limestone, and manganiferous, phosphatic or pyritic shale.

DEPOSIT FORM: Ironstone beds are commonly less than 10 m thick and extend along strike for more than one kilometre.

TEXTURE/STRUCTURE: Oolites and ooids in the ironstone consist of alternating concentric rings of siderite or mixtures of siderite, hematite and chamosite surrounding nuclei of fossil fragments, sand grains, or granules distributed in a matrix of hematite or siderite. The spherules, oolites, and granules in the beds range in size from 0.1 to 0.5 mm. Isolated iron-rich granules or oolites may also occur in associated sediments. The oolitic beds show many sedimentary features that form in shallow water, such as crossbedding, ripple-marks, scour-and-fill structures, worm burrows, and abraded fossil fragments.

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[1] Emeritus Scientist, Geological Survey of Canada, Ottawa, Ontario, Canada

F11 - Ironstone

ORE MINERALOGY: Goethite and hematite are the principal iron oxide minerals in the Minette-type and Clinton-type ironstones respectively. Chamosite and siderite are common in both types of ironstone but are abundant in Minette-type.

GANGUE MINERALOGY: Clay minerals, fine grained detritus, mud and organic debris consisting of chamosite, montmorillonite, nontronite, glauconite, ankerite, pyrite and marcasite, apatite, fluorapatite, quartz, and complex phosphatic, manganiferous and sulphide minerals.

ALTERATION MINERALOGY: Delicate, well-preserved textures in some deposits show that there has been little alteration of the oolites, ooids or spherules after lithification, except for induration, faulting, and the addition of small amounts of secondary calcite and quartz in joints and fractures.

WEATHERING: Oxidation of iron minerals and development of hydrated iron oxide and clay minerals, leaching of carbonate and silicate minerals.

ORE CONTROLS: Ironstone acceptable for iron ore must have a minimum of shale and clay intermixed with the iron-rich oolites and spherules, a high proportion of iron in hematite, goethite and hydrated iron oxide minerals, and iron distributed in discrete mineral grains, oolites and spherules, rather than intermixed in clay-sized or amorphous aggregates, a minimum of complex iron silicates and carbonate minerals. Key factors controlling the sedimentation of ironstone ore beds were the composition and chemistry of the basin water (including Eh and pH), water depth and distribution of clastic material.

GENETIC MODEL: Beds of oolitic hematite and goethite were deposited in shallow water at the sediment-water interface during normal deposition of mud, silt, sand, black shale and limey sediment. Delicate adjustment of the Eh and pH and composition of the basin water, water depth, and the distribution of clastic material were required for the formation of ironstone. The oolites indicate agitation and disturbance of the water during deposition, probably by wave or tidal action, in a shallow bay or shelf. Evidently hematite and chamosite formed on the surface of the sediment, while siderite formed contemporaneously during early diagenesis of the underlying sediments where concentrations of ammonia and carbon dioxide were produced from decaying organic matter. Chamosite appears to have formed in advance of the other iron-rich minerals. Ferrous iron in solution may have reacted with complexes of clay and colloidal clay particles to form chamosite on the surface of convenient nuclei. The conspicuous increase in hematite in the outer parts of oolites suggests that part of it may have formed by oxidation of chamosite or during a later stage of precipitation. Fossilized algae are found in ore beds and evidently algae were very abundant in the marine plant life growing on the sea bottom. Tubules of algae preserved in the siderite are usually coated on the exterior with hematite. The source of the iron could be onshore weathering processes followed by transport in solution as inorganic and organic acid compounds. The iron in some of the ironstones may have come from submarine volcanic emanations and could have been transported by currents to the sedimentary basin where it was oxidized and precipitated in shallow water near the shore.

ASSOCIATED DEPOSIT TYPES: The typically high content of phosphorus in ironstones suggests that some facies of ironstone might be used as metallogenic markers for locating beds and nodules rich in phosphate and likewise for associated manganiferous beds.

COMMENTS: The term ironstone refers to lithofacies of hydrolithic sediments composed of yellow to brown or blood-red iron oxide and clay minerals and fine-grained clastic and fossil detritus that commonly have well developed oolitic and granular textures (Gross, 1965). Fossilized algae are found in ore beds and evidently algae were very abundant in the marine plant life growing on the sea bottom.

F11 - Ironstone

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalously high Fe, Mn and/or P contents in sediments.

GEOPHYSICAL SIGNATURE: None.

OTHER EXPLORATION GUIDES: Most of the ironstone facies selected for ore should be sought in strata which record neritic to estuarian environments, have a predominance of chemically precipitated material, a minimum of clastic material, and distinctive mineral assemblages and textures that are conducive to beneficiation and smelting.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The iron content ranges from 20 to more than 60%, although ore grades are usually more than 30%. Grade and quality are of special concern in the use of ironstone iron ore. The total thickness of ironstone units rarely exceeds 10 m, but estimates of iron resources in single basins often exceed one billion tons. The Wabana mine ore ranged from 45 to 59.6% Fe and from 6.5 to 20% silica.

ECONOMIC LIMITATIONS: The most desirable ironstone beds have a minimum of intermixed shale and clay, a high proportion of iron as hematite, goethite and hydrated iron oxide minerals, and iron distributed in discrete mineral grains, oolites and spherules, rather than intermixed in clay-sized or amorphous aggregates, a minimum of complex iron silicates and carbonate minerals. Ironstone ores commonly have significantly high contents of alumina, phosphorus, calcium and magnesium. Iron ore should have the highest content of iron and the lowest possible content of slag-forming constituents (alumina, silica, and calcium and magnesium silicates), and meet the grade and quality specifications of a particular iron and steel industry. The content of deleterious constituents, such as sulphur and arsenic, must be kept low and controlled to very rigid specifications. Phosphate minerals, associated with organic debris, and other constituents, such as sulphide minerals, should be kept to a minimum in iron ore as large volumes of slag are required in furnaces for their removal.

END USES: Ironstone is a source of ferrous iron in fertilizer products prepared for use in tropical areas where iron is oxidized by weathering processes and the soils become depleted in essential ferrous iron compounds. Ironstone ores are more acceptable in areas where phosphorus-rich slag can be used in the production of fertilizers. The slag produced in processing ironstone ore has been used in the production of cement, light-weight aggregate, building materials, etc.

IMPORTANCE: Ironstone has provided a relatively small amount of iron ore in Canada, although ore from Wabana Mine in Newfoundland was used in Canada and Europe for more than 50 years. Large resources of Minette-type ironstone have been explored in the Peace River area of Alberta, and small deposits are known in northern Yukon and Nova Scotia. Limonite gossans and bog-iron occurrences overlying Lower Cretaceous shales and siltstones in the Fort St. John region of British Columbia are probably related to ironstone occurrences. Important production of iron ore has been mined from ironstone deposits in Alabama (Clinton Formation). Minette ironstone deposits in England, France, Luxembourg and Germany were one of the principal sources of iron ore in western Europe until production was phased out in recent years.

F11 - Ironstone

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G - Marine Volcanic Association

	Profile Title	Authors
G01	Algoma-type iron-formation	G.A. Gross, 1996
G02*	Volcanogenic Mn	
G03*	Volcanogenic anhydrite / gypsum	
G04	Besshi massive sulphide Cu-Zn	T. Höy, 1995
G05	Cyprus massive sulphide Cu (Zn)	T. Höy, 1995
G06	Noranda/Kuroko massive sulphide Cu-Pb-Zn	T. Höy, 1995
G07	Subaqueous hot spring Ag-Au	D.J. Alldrick, 1999

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

G01 - Algoma-Type Iron-Formation

by G.A. Gross[1]

Gross, G.A., 1996. Algoma-type iron-formation: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 25–27.

IDENTIFICATION

SYNONYMS: Taconite, itabirite, banded iron-formation.

COMMODITIES (BYPRODUCTS): Fe (Mn).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Falcon (093O016), Lady A (092B029); *McLeod (Helen), Sherman, Adams, Griffith (Ontario, Canada), Woodstock, Austin Brook (New Brunswick, Canada), Kudremuk (India), Cerro Bolivar (Venezuela), Carajas (Brazil), part of Krivoy Rog (Russia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Iron ore deposits in Algoma-type iron-formations consist mainly of oxide and carbonate lithofacies that contain 20 to 40 % Fe as alternating layers and beds of micro- to macro-banded chert or quartz, magnetite, hematite, pyrite, pyrrhotite, iron carbonates, iron silicates and manganese oxide and carbonate minerals. The deposits are interbedded with volcanic rocks, greywacke, turbidite and pelitic sediments; the sequences are commonly metamorphosed.

TECTONIC SETTINGS: Algoma-type iron-formations are deposited in volcanic arcs and at spreading ridges.

AGE OF MINERALIZATION: They range in age from 3.2 Ga to modern protolithic facies on the seafloor and are most widely distributed and achieve the greatest thickness in Archean terranes (2.9 to 2.5 Ga).

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: They formed both near and distal from extrusive centres along volcanic belts, deep fault systems and rift zones and may be present at any stage in a volcanic succession. The proportions of volcanic and clastic sedimentary rocks vary and are rarely mutually exclusive.

HOST/ASSOCIATED ROCKS: Rocks associated with Algoma-type iron-formations vary greatly in composition, even within local basins, and range from felsic to mafic and ultramafic volcanic rocks, and from greywacke, black shale, argillite, and chert interlayered with pyroclastic and other volcaniclastic beds or their metamorphic equivalents. Algoma-type iron-formations and associated stratafer sediments commonly show a prolific development of different facies types within a single stratigraphic sequence. Oxide lithofacies are usually the thickest and most widely distributed units of iron-formation in a region and serve as excellent metallogenetic markers.

DEPOSIT FORM: Iron ore deposits are sedimentary sequences commonly from 30 to 100 m thick, and several kilometres in strike length. In most economic deposits, isoclinal folding or thrust faulting have produced thickened sequences of iron-formation.

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G01 - Algoma-Type Iron-Formation

STRUCTURE/TEXTURE: Micro-banding, bedding and penecontemporaneous deformation features of the hydroplastic sediment, such as slump folds and faults, are common, and can be recognized in many cases in strongly metamorphosed oxide lithofacies. Ore mineral distribution closely reflects primary sedimentary facies. The quality of oxide facies crude ore is greatly enhanced by metamorphism which leads to the development of coarse granular textures and discrete grain enlargement.

ORE MINERALOGY: Oxide lithofacies are composed of magnetite and hematite. Some deposits consist of siderite interbedded with pyrite and pyrrhotite.

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, siderite or ferruginous ankerite and dolomite, manganoan siderite and silicate minerals. *Silicate lithofacies are characterized by iron silicate minerals including grunerite, minnesotaite, hypersthene, reibeckite and stilpnomelane, associated with chlorite, sericite, amphibole, and garnet.*

WEATHERING: Minor oxidation of metal oxide minerals and leaching of silica, silicate and carbonate gangue. Algoma-type iron-formations are protore for high-grade, direct shipping types of residual-enriched iron ore deposits.

GENETIC MODEL: Algoma-type iron deposits were formed by the deposition of iron and silica in colloidal size particles by chemical and biogenic precipitation processes. Their main constituents evidently came from hydrothermal-effusive sources and were deposited in euxinic to oxidizing basin environments, in association with clastic and pelagic sediment, tuff, volcanic rocks and a variety of clay minerals. The variety of metal constituents consistently present as minor or trace elements evidently were derived from the hydrothermal plumes and basin water and adsorbed by amorphous iron and manganese oxides and smectite clay components in the protolithic sediment. Their development and distribution along volcanic belts and deep-seated faults and rift systems was controlled mainly by tectonic rather than by biogenic or atmospheric factors. Sulphide facies were deposited close to the higher temperature effusive centres; iron oxide and silicate facies were intermediate, and manganese-iron facies were deposited from cooler hydrothermal vents and in areas distal from active hydrothermal discharge. Overlapping and lateral transitions of one kind of lithofacies to another appear to be common and are to be expected.

ORE CONTROLS: The primary control is favourable iron-rich stratigraphic horizons with little clastic sedimentation, often near volcanic centres. Some Algoma-type iron-formations contain ore deposits due to metamorphic enhancement of grain size or structural thickening of the mineralized horizon.

ASSOCIATED DEPOSITS: Algoma-type iron-formations can be protore for residual-enriched iron ore deposits (B01?). Transitions from Lake Superior to Algoma-type iron-formations occur in areas where sediments extend from continental shelf to deep-water environments along craton margins as reported in the Krivoy Rog iron ranges. Oxide lithofacies of iron-formation grade laterally and vertically into manganese-rich lithofacies (G02), and iron sulphide, polymetallic volcanic-hosted and sedex massive sulphide (G04, G05, G06, E14).

COMMENTS: Lithofacies selected for iron and manganese ore are part of the complex assemblage of stratiform units formed by volcanogenic-sedimentary processes that are referred to collectively as stratafer sedimentary deposits, and includes iron-formation (more than 15% Fe) and various other metalliferous lithofacies.

G01 - Algoma-Type Iron-Formation

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values for Fe and Mn; at times elevated values for Ni, Au, Ag, Cu, Zn Pb, Sn, W, REE and other minor elements.

GEOPHYSICAL SIGNATURE: Electromagnetic, magnetic, and electrical conductance and resistivity survey methods are used effectively in tracing and defining the distribution of Algoma-type beds, either in exploring for iron and manganese ore, or for using these beds as metallogenetic markers.

OTHER EXPLORATION GUIDES: Discrete, well defined magnetite and hematite lithofacies of iron-formation are preferred with a minimum of other lithofacies and clastic sediment interbedded in the crude ore. Iron-formations are usually large regional geological features that are relatively easy to define. Detailed stratigraphic information is an essential part of the database required for defining grade, physical and chemical quality, and beneficiation and concentration characteristics of the ore. Basin analysis and sedimentation modeling enable definition of factors that controlled the development, location and distribution of different iron-formation lithofacies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Orebodies range in size from about 1000 to less than 100 Mt with grades ranging from 15 to 45% Fe, averaging 25% Fe. Precambrian deposits usually contain less than 2% Mn, but many Paleozoic iron-formations, such as those near Woodstock, New Brunswick, contain 10 to 40 % Mn and have Fe/Mn ratios of 40:1 to 1:50. The largest B.C. deposit, the Falcon, contains inferred reserves of 5.28 Mt grading 37.8% Fe.

ECONOMIC LIMITATIONS: Usually large-tonnage open pit operations. Granular, medium to coarse-grained textures with well defined, sharp grain boundaries are desirable for the concentration and beneficiation of the crude ore. Strongly metamorphosed iron-formation and magnetite lithofacies are usually preferred. Oxide facies iron-formation normally has a low content of minor elements, especially Na, K, S and As, which have deleterious effects in the processing of the ore and quality of steel produced from it.

IMPORTANCE: In Canada, Algoma-type iron-formations are the second most important source of iron ore after the taconite and enriched deposits in Lake Superior-type iron-formations. Algoma-type iron-formations are widely distributed and may provide a convenient local source of iron ore.

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G01 - Algoma-Type Iron-Formation

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G04 - Besshi Massive Sulphide

by Trygve Höy[1]

Höy, T., 1995. Besshi massive sulphide: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 49–50.

IDENTIFICATION

SYNONYMS: Besshi type, Kieslager.

COMMODITIES (*BYPRODUCTS*): Cu, Zn, Pb, Ag, (*Au, Co, Sn, Mo, Cd*).

EXAMPLES (British Columbia - *Canada/International*): Goldstream (082M 141), Standard (082M 090), Montgomery (082M 085), True Blue (082F 002), Granduc(?) (104B 021), Windy Craggy (?) (114P 020); *Greens Creek (Alaska, USA), Besshi (Japan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits typically comprise thin sheets of massive to well layered pyrrhotite, chalcopyrite, sphalerite, pyrite and minor galena within interlayered, terrigenous clastic rocks and calcalkaline basaltic to andesitic tuffs and flows.

TECTONIC SETTINGS: Oceanic extensional environments, such as back-arc basins, oceanic ridges close to continental margins, or rift basins in the early stages of continental separation.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Terrigenous clastic rocks associated with marine volcanic rocks and sometimes carbonate rocks; these may overlie platformal carbonate or clastic rocks.

AGE OF MINERALIZATION: Any age. In British Columbia, most deposits are Cambrian, Late Triassic and less commonly Mississippian-Permian in age.

HOST/ASSOCIATED ROCK TYPES: Clastic sediments and marine volcanic rocks; basaltic tuffs and flows, shale and siltstone, commonly calcareous; less commonly chert and Fe formations. Possibly ultramafics and metagabbro in sequence.

DEPOSIT FORM: Typically a concordant sheet of massive sulphides up to a few metres thick and up to kilometres in strike length and down dip; can be stacked lenses.

TEXTURE/STRUCTURE: Massive to well-layered, fine to medium-grained sulphides; gneissic sulphide textures common in metamorphosed and deformed deposits; durchbewegung textures; associated stringer ore is uncommon. Crosscutting pyrite, chalcopyrite and/or sphalerite veins with chlorite, quartz and carbonate are common.

ORE MINERALOGY [Principal and *subordinate*]: Pyrite, pyrrhotite, chalcopyrite, sphalerite, *cobaltite, magnetite, galena, bornite, tetrahedrite, cubanite, stannite, molybdenite, arsenopyrite, marcasite*.

GANGUE MINERALOGY (Principal and *subordinate*): Quartz, calcite, ankerite, siderite, albite, tourmaline, *graphite, biotite.*

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G04 - Besshi Massive Sulphide

ALTERATION MINERALOGY: Similar to gangue mineralogy - quartz, chlorite, calcite, siderite, ankerite, pyrite, sericite, graphite.

ORE CONTROLS: Difficult to recognize; early (syndepositional) faults and mafic volcanic centres.

GENETIC MODEL: Seafloor deposition of sulphide mounds in back-arc basins, or several other tectonic settings, contemporaneous with volcanism.

ASSOCIATED DEPOSIT TYPES: Cu, Zn veins.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Cu, Zn, Ag, Co/Ni>1; Mn halos, Mg enrichment.

GEOPHYSICAL SIGNATURE: Sulphide lenses usually show either an electromagnetic or induced polarization signature depending on the style of mineralization and presence of conductive sulphides.

OTHER EXPLORATION GUIDES: Mafic volcanic rocks (tholeiitic, less commonly alkalic) associated with clastic rocks; Mn-rich garnets in metamorphosed exhalative horizons, possible structures, such as faults; possible association with ultramafic rocks.

ECONOMIC FACTORS

GRADE AND TONNAGE: Highly variable in size. B.C. deposits range in size from less than 1 Mt to more than 113 Mt. For example, Goldstream has a total resource (reserves and production) of 1.8 Mt containing 4.81 % Cu, 3.08 % Zn and 20.6 g/t Ag and Windy Craggy has reserves in excess of 113.0 Mt containing 1.9 % Cu, 3.9 g/t Ag and 0.08% Co. The type-locality Besshi deposits average 0.22 Mt, containing 1.5% Cu, 2-9 g/t Ag, and 0.4-2% Zn (Cox and Singer, 1986).

IMPORTANCE: Significant sources of Cu, Zn and Ag that can be found in sedimentary sequences that have not been thoroughly explored for this type of target.

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G05 - Cyprus Massive Sulphide Cu (Zn)

by Trygve Höy[1]

Höy, T., 1995. Cyprus massive sulphide Cu (Zn): In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 51–52.

IDENTIFICATION

SYNONYMS: Cyprus massive sulphide, cuprous pyrite.

COMMODITY (BYPRODUCTS): Cu, (Au, Ag, Zn, Co, Cd).

EXAMPLES (British Columbia - *Canada/International*): Chu Chua (092F 140), Lang Creek (104P 008), Hidden Creek (103P 021), Bonanza (103P 023), Double Ed (103P 025) ; *Cyprus; York Harbour and Betts Cove (Newfoundland, Canada); Turner-Albright (USA); Lokken (Norway).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits typically comprise one or more lenses of massive pyrite and chalcopyrite hosted by mafic volcanic rocks and underlain by a well developed pipe-shaped stockwork zone.

TECTONIC SETTINGS: Within ophiolitic complexes formed at oceanic or back-arc spreading ridges; possibly within marginal basins above subduction zones or near volcanic islands within an intraplate environment.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Lenses commonly are in tholeiitic or calcalkaline marine basalts, commonly pillowed, near a transition with overlying argillaceous sediments. Many lenses appear to be structurally controlled, aligned near steep normal faults.

AGE OF MINERALIZATION: Any age. Deposits in British Columbia are primarily Mississippian-Permian or Late Triassic.

HOST/ASSOCIATED ROCK TYPES: Tholeiitic or calcalkaline pillow and flow basalts, basaltic tuff, chert, argillite. Overlying “umbers” consist of ochre [Mn-poor, Fe-rich bedded mudstone containing goethite, maghemite (Fe_3O_4-Fe_2O_3 mixture) and quartz] or chert.

DEPOSIT FORM: Concordant massive sulphide lens overlying cross-cutting zone of intense alteration and stockwork mineralization and hydrothermally altered wallrock, and overlain by chert.

TEXTURE/STRUCTURE: Massive, fine-grained pyrite and chalcopyrite, sometimes brecciated or banded?; massive magnetite, magnetite-talc and talc with variable sulphide content; associated chert layers, locally brecciated, contain disseminated sulphides; disseminated, vein and stockwork mineralization beneath lenses.

ORE MINERALOGY (Principal and *subordinate*): Pyrite, chalcopyrite, magnetite, sphalerite, *marcasite, galena, pyrrhotite, cubanite, stannite-besterite, hematite*. Sometimes goethite alteration of top of sulphide layer.

GANGUE MINERALOGY: Talc, chert, magnetite, chlorite.

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G05 - Cyprus Massive Sulphide Cu (Zn)

ALTERATION MINERALOGY: Chlorite, talc, carbonate, sericite and quartz veins in the core of the stringer zone, sometimes with an envelope of weak albite with illite alteration.

ORE CONTROLS: Prominent structural control with clustering or alignment of sulphide lenses along early normal faults, near transition from mafic pillow basalts; less commonly mafic tuff; to overlying fine pelagic material.

GENETIC MODEL: Seafloor deposition of sulphide mounds contemporaneous with mafic volcanism, such as spreading ridges.

ASSOCIATED DEPOSIT TYPES: Vein and stockwork Cu (-Au) mineralization; Mn and Fe-rich cherts; massive magnetite (-talc) deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Cu, Zn; common depletion of Ca and Na; less common, local minor Na enrichment; possible local K enrichment; prominent Fe and Mn enrichment in footwall stringer zone.

GEOPHYSICAL SIGNATURE: Sulphide lenses usually show either an electromagnetic or induced polarization signature depending on the style of mineralization and presence of conductive sulphides.

OTHER EXPLORATION GUIDES: Mafic ophiolitic volcanic rocks; transition to argillite; clustering or alignment of deposits indicative of fault control; ochre and exhalite (chert) horizons; regional pyritic horizons.

ECONOMIC FACTORS

GRADE AND TONNAGE: Published average is 1.6 Mt containing 1.7 % Cu, 0-33 g/t Ag; 0-1.9 g/t Au, 0-2.1 % Zn (Cox and Singer, 1986). B.C. examples: Chu Chua reserves - 1.043 Mt, 2.97 % Cu, 0.4 % Zn, 8.0 g/t Ag, 1.0 g/t Au; Anyox deposits - 0.2 to 23.7 Mt, approx. 1.5% Cu, 9.9 g/t Ag and 0.17 g/t Au.

IMPORTANCE: Deposits at Anyox produced 335,846 tonnes copper, 215,057 kg silver and 3,859 kg gold. Worldwide these deposits are generally significant more for their higher grades and polymetallic nature, than their size.

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G06 - Noranda/Kuroko Massive Sulphide Cu-Pb-Zn

by Trygve Höy[1]

Höy, T., 1995. Noranda/Kuroko massive sulphide Cu-Pb-Zn: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 53–54.

IDENTIFICATION

SYNONYM: Polymetallic volcanogenic massive sulphide.

COMMODITIES (BYPRODUCTS): Cu, Pb, Zn, Ag, Au (Cd, S, Se, Sn, barite, gypsum).

EXAMPLES (British Columbia - *Canada/International*): Homestake (082M 025), Lara (092B 001), Lynx (092B 129), Myra (092F 072), Price (092F 073), H-W (092F 330), Ecstall (103H 011), Tulsequah Chief (104K 011), Big Bull (104K 008), Kutcho Creek (104J 060), Britannia (092G 003); *Kidd Creek (Ontario, Canada), Buchans (Newfoundland, Canada), Bathurst-Newcastle district (New Brunswick, Canada), Horne-Quemont (Québec, Canada), Kuroko district (Japan), Mount Lyell (Australia), Rio Tinto (Spain), Shasta King (California, USA), Lockwood (Washington, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: One or more lenses of massive pyrite, sphalerite, galena and chalcopyrite commonly within felsic volcanic rocks in a calcalkaline bimodal arc succession. The lenses may be zoned, with a Cu-rich base and a Pb-Zn-rich top; low-grade stockwork zones commonly underlie lenses and barite or chert layers may overlie them.

TECTONIC SETTING: Island arc; typically in a local extensional setting or rift environment within, or perhaps behind, an oceanic or continental margin arc.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Marine volcanism; commonly during a period of more felsic volcanism in an andesite (or basalt) dominated succession; locally associated with fine-grained marine sediments; also associated with faults or prominent fractures.

AGE OF MINERALIZATION: Any age. In British Columbia typically Devonian; less commonly Permian-Mississippian, Late Triassic, Early (and Middle) Jurassic, and Cretaceous.

HOST/ASSOCIATED ROCK TYPES: Submarine volcanic arc rocks: rhyolite, dacite associated with andesite or basalt; less commonly, in mafic alkaline arc successions; associated epiclastic deposits and minor shale or sandstone; commonly in close proximity to felsic intrusive rocks. Ore horizon grades laterally and vertically into thin chert or sediment layers called informally “exhalites”.

DEPOSIT FORM: Concordant massive to banded sulphide lens which is typically metres to tens of metres thick and tens to hundreds of metres in horizontal dimension; sometimes there is a peripheral apron of "clastic" massive sulphides; underlying crosscutting “stringer” zone of intense alteration and stockwork veining.

TEXTURE/STRUCTURE: Massive to well layered sulphides, typically zoned vertically and laterally; sulphides with a quartz, chert or barite gangue (more common near top of deposit); disseminated, stockwork and vein sulphides (footwall).

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G06 - Noranda/Kuroko Massive Sulphide Cu-Pb-Zn

ORE MINERALOGY (Principal and *subordinate*): Upper massive zone: pyrite, sphalerite, galena, chalcopyrite, *pyrrhotite, tetrahedrite-tennantite, bornite, arsenopyrite*. Lower massive zone: pyrite, chalcopyrite, *sphalerite, pyrrhotite, magnetite*.

GANGUE MINERALOGY (Principal and *subordinate*): Barite, chert, *gypsum, anhydrite and carbonate* near top of lens, carbonate quartz, chlorite and sericite near the base.

ALTERATION MINERALOGY: Footwall alteration pipes are commonly zoned from the core with quartz, sericite or chlorite to an outer zone of clay minerals, albite and carbonate (siderite or ankerite).

ORE CONTROLS: More felsic component of mafic to intermediate volcanic arc succession; near centre of felsic volcanism (marked by coarse pyroclastic breccias or felsic dome); extensional faults.

ASSOCIATED DEPOSIT TYPES: Stockwork Cu deposits; vein Cu, Pb, Zn, Ag, Au.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Zn, Hg and Mg halos, K addition and Na and Ca depletion of footwall rocks; closer proximity to deposit - Cu, Ag, As, Pb; within deposit - Cu, Zn, Pb, Ba, As, Ag, Au, Se, Sn, Bi, As.

GEOPHYSICAL SIGNATURE: Sulphide lenses usually show either an electromagnetic or induced polarization signature depending on the style of mineralization and presence of conductive sulphides. In recent years borehole electromagnetic methods have proven successful.

OTHER EXPLORATION GUIDES: Explosive felsic volcanics, volcanic centres, extensional faults, exhalite (chert) horizons, pyritic horizons.

ECONOMIC FACTORS

GRADE AND TONNAGE: Average deposit size is 1.5 Mt containing 1.3% Cu, 1.9 % Pb, 2.0 % Zn, 0.16 g/t Au and 13 g/T Ag (Cox and Singer, 1986). British Columbia deposits range from less than 1 to 2 Mt to more than 10 Mt. The largest are the H-W (10.1 Mt with 2.0 % Cu, 3.5 % Zn, 0.3 % Pb, 30.4 g/t Ag and 2.1 g/t Au) and Kutcho (combined tonnage of 17 Mt, 1.6 % Cu, 2.3 % Zn, 0.06 % Pb, 29 g/t Ag and 0.3 g/t Au).

IMPORTANCE: Noranda/Kuroko massive sulphide deposits are major producers of Cu, Zn, Ag, Au and Pb in Canada. Their high grade and commonly high precious metal content continue to make them attractive exploration targets.

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G06 - Noranda/Kuroko Massive Sulphide Cu-Pb-Zn

Ohmoto, H. and Skinner, B.J., Editors (1983): The Kuroko and Related Volcanogenic Massive Sulfide Deposits; *Economic Geology*, Monograph 5, 604 pages.

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G07 - Subaqueous Hot Spring Au-Ag

Dani J. Alldrick[1]

Alldrick, D.J., 1999. Subaqueous hot spring Au-Ag: In: Massey, N.W.D., Alldrick, D.J. and Lefebure, D.V., Potential for subaqueous hot-spring (Eskay Creek) deposits in British Columba, British Columbia Ministry of Mines, British Columbia Geological Survey Open File 1999-14, Appendix 1, pp. 10-14.

IDENTIFICATION

SYNONYMS: Eskay Creek-type deposit; epithermal massive sulphide; subaqueous hydrothermal deposit.

COMMODITIES (BYPRODUCTS): Ag, Au (Cu, Pb, Zn, As, Sb, Hg).

EXAMPLES (British Columbia - *Canada/International*): Eskay Creek (104B 008), Lulu (104B 376); *Osorezan, Vulcano Islands and Jade hydrothermal field (Japan), Mendeleev Volcano (Kurile Islands, Russia), Rabaul (Papua New Guinea), White Island (New Zealand), Bacon-Manito and Surigao del Norte (Philippines).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Synsedimentary bedded sulphides, replacement sulphides and associated veins are deposited in volcanic rocks and derived sediments in shallow water (<1000 metres depth).

TECTONIC SETTING: Active volcanic arcs (both oceanic island arcs and continental margin arcs), mid-ocean ridges, intraplate hot spot volcanoes, ridge subduction, near-trench volcanoes, rifted fore-arcs, rifted continental margins, oceanic backarcs, intracontinental oceanic rifts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: 1) Summits of seamounts; 2) Collapsed calderas; 3) Sea-flooded, breached calderas; 4) Unconsolidated shallow marine sediments on the flanks of emergent volcanic islands; 5) Intra-arc rifts; 6) Water-filled reservoirs in active continental volcanic areas (crater lakes, playa lakes, stream flood plains, glacier subfloors).

AGE OF MINERALIZATION: Examples range from Holocene to Archean. More than 50 modern (active) sites have been identified.

HOST / ASSOCIATED ROCK TYPES: Mineralization hosted by intermediate to felsic flows and tuffs and minor intercalated sedimentary rocks. Pillow lavas, coarse epiclastic debris flows, and assorted subvolcanic feeder dikes are all part of the local stratigraphic package.

DEPOSIT FORM: Highly variable. Large, textureless massive sulphide pods, finely laminated stratiform sulphide layers and lenses, reworked clastic sulphide sedimentary beds. Footwall stockwork or stringer-style vein networks. Epithermal-style breccia veins with large vugs, coarse sulphides and chalcedonic silica. All types may coexist in a single deposit.

TEXTURE / STRUCTURE: Range from fine clastic sulphides and framboid-like chemical precipitates to very coarse grained sulphide aggregates in breccia veins. Structural styles include: stratabound and stratiform sulphide lenses and layers, vein stockworks, major breccia veins.

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G07 - Subaqueous Hot Spring Au-Ag

ORE MINERALOGY (Principal and *subordinate*): Sphalerite, tetrahedrite, boulangerite, bournonite, native gold, native silver, amalgam, galena, chalcopyrite, enargite, pyrite, stibnite, realgar, arsenopyrite, orpiment; *metallic arsenic, Hg-wurtzite, cinnabar, aktashite, unnamed Ag-Pb-As-S minerals, jordanite, wurtzite, krennerite, coloradoite, marcasite, magnetite, scorodite, jarosite, limonite, anglesite, native sulphur*.

GANGUE MINERALOGY (Principal and *subordinate*): Magnesian chlorite, muscovite (sericite), chalcedonic silica, amorphous silica, calcite, dolomite, pyrobitumen, gypsum, barite, potassium feldspar, alunite; *carbon, graphite, halite and cristobalite.*

ALTERATION MINERALOGY: Massive chlorite (clinochlore)-illite-quartz-gypsum-barite rock or quartz-muscovite-pyrite rock are associated with the near-footwall stockwork zones. Chlorite and pyrite alteration is associated with the deep-footwall stockwork zones where alteration minerals are restricted to fractures. Stratabound mineralization is accompanied by magnesian chlorite, muscovite, chalcedonic silica, calcite, dolomite and pyrobitumen. At the Osorezan hot spring deposits, pervasive silica and alunite microveinlets are the dominant alteration phases.

GENETIC MODEL: Deposits are formed where "hot spring" (i.e. epithermal) fluids vent into a shallow water environment. Fluids are magmatic in character, rather than meteoric. This concept contrasts with some characteristics of the process model for volcanogenic massive sulphides. Lateral and vertical zoning has been recognized within a single lens. Lateral zoning varies from Sb, As and Hg-rich mineral suites outward to Zn, Pb and Cu-rich assemblages. Vertical zoning is expressed as a systematic increase in Au, Ag and base metal content up-section. Fluid conduits are fissures generated by: seismic shock, inflating of the volcano over an expanding magma chamber, or fracturing in response to regional compressional tectonics. A near-surface subvolcanic magma body is the likely source of metals, fluids and heat, but shallow subaqueous hot springs may be distal to the main eruptive centres or subvolcanic heat sources.

ASSOCIATED DEPOSIT TYPES: Hot spring Hg (H02), hot spring Au-Ag (H03), epithermal veins (H04, H05), volcanogenic exhalative massive sulphides (G06).

COMMENTS: This deposit type is the shallow subaqueous analogue of hot spring Au-Ag deposits. The brief discussion by Laznicka (1985, p. 907) seems especially prophetic in light of the subsequent discoveries at Osorezan (1987) and Eskay Creek (1988).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ag, Au, Cu, Pb, Zn, As, Sb, Hg (Mo?).

GEOPHYSICAL SIGNATURE: The pyrite associated with the stockwork mineralization and with the widespread alteration should produce a broad induced polarization anomaly. The best drill targets would be local anomalous `peaks’ within this anomalous 'plateau'. Airborne magnetometer surveys may help delineate favourable strata and fault offsets.

OTHER EXPLORATION GUIDES: The geological deposit model and its regional setting, coupled with regional stream sediment geochemistry are the best exploration tools. Additional exploration guides include: 1. Broad hydrothermal systems marked by widespread sericite-pyrite alteration; 2. Evidence of a volcanic crater or caldera setting; 3. Accumulations of felsic volcanic strata in a local subaqueous setting in a regionally subaerial environment or along the near shore zone of a regional subaerial/subaqueous volcanic facies transition. Focus on the sedimentary intervals within the volcanic pile (these favourable sedimentary rocks may be recessive).

G07 - Subaqueous Hot Spring Au-Ag

ECONOMIC FACTORS

GRADE AND TONNAGE: Eskay Creek began production with mineable reserves of 1.08 Mt grading 65.5 g/t Au, 2930 g/t Ag, 5.7 % Zn, 0.77 % Cu and 2.89% Pb and a geological resource of 4.3 Mt grading 28.8 g/t Au and 1 027 g/t Ag. On January 1, 1999 total production reached 460,160 tonnes grading 64.28 g/t Au, 3108 g/t Ag, plus minor lead and zinc, while mineable reserves stood at 1.45 Mt grading 57.7 g/t Au and 2493 g/t Ag.

IMPORTANCE: These deposits are attractive because of their bonanza precious metal grades, polymetallic character, tendency to occur in clusters of deposits and well-constrained geologic settings.

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H – Epithermal

	Profile Title	Authors
H01	Travertine	Z.D. Hora, 1996
H02	Hot spring Hg	A. Panteleyev, 1996
H03	Hot spring Au-Ag	A. Panteleyev, 1996
H04	Epithermal Au-Ag-Cu; high sulphidation	A. Panteleyev, 1996
H05	Epithermal Au-Ag; low sulphidation	A. Panteleyev, 1996
H06*	Epithermal Mn	
H07	Sn-Ag veins	A. Panteleyev, 1996
H08	Alkalic intrusion-associated Au-Ag	T. Schroeter and R. Cameron, 1996
H09	Hydrothermal clays	Z.D. Hora, 2007

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

H01 - Travertine

by Z.D. Hora[1]

Hora, Z. D., 1996. Travertine: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 29–30.

IDENTIFICATION

SYNONYMS: Tufa, calcareous sinter; certain varieties also referred to as onyx marble or Mexican onyx.

COMMODITIES (*BYPRODUCTS*): Decorative stone, building stone products, soil conditioner, agriculture lime; *onyx marble*.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Clinton (O92P 079), Slocan (82KSW074,075), Wishing Well (Deep River, 094N 001); *Gardiner (Montana, USA), Salida (Colorado, USA), Bridgeport (California, USA); Lazio, Tuscany (Italy); Pamukkale (Turkey); Mexico, Spain, Iran*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Mounds, sheets, sometimes terraced, shallow lake in-fills, valley in-fill.

TECTONIC SETTING: Young orogenic belts with carbonate sediments in the subsurface; thrusts and faults with deep water circulation. Also intercontinental rift zones with strike-slip faulting, with or without associated volcanic activity.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Subaerial precipitation of calcium carbonate from mineral springs; also in shallow lacustrine basins with influx of mineralized CO_2-rich water. Hot spring waters which give rise to travertine deposits usually do not originate at temperatures in excess of 100^{o}C. Circulating ground waters are channeled by thrusts, faults and fractured rocks and mineralized by dissolution of subsurface carbonate rocks.

AGE OF MINERALIZATION: Tertiary to recent.

HOST/ASSOCIATED ROCK TYPES: Carbonate rocks in the subsurface; hydrothermal breccia and siliceous sinters, lacustrine sediments, carbonate veins (usually aragonite) in form of “Mexican onyx”.

DEPOSIT FORM: Conical mounds, sheets, basin in-fills. As it is deposited by precipitation from warm spring waters, it shows successive layers with sometimes different colours and textures. May be elongated above underlying feeder zones following faults and breccia zones.

TEXTURE: Banded, porous, brecciated; may be pisolitic. Generally fine-grained carbonate matrix with numerous irregular cavities ranging in size from a pin head to 1 cm or more across. The cavities are usually oriented in lines giving the rock parallel texture. Lacustrine varieties are more massive. The mounds may be criss-crossed by veins of “Mexican onyx”, a varicoloured banded aragonite.

ORE MINERALOGY [Principal and *Subordinate*]: Calcite, aragonite, *silica, fluorspar, barite, native sulphur.*

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[1] Retired, British Columbia Geological Survey, Victoria, B.C., Canada

H01 - Travertine

WEATHERING: Clay/iron stains filling the voids, joints and bedding planes.

ORE CONTROLS: Commonly developed along high-angle faults and shear zones in young orogenic belts.

GENETIC MODEL: Travertine forms as surface deposits from geothermal systems of generally less than 100°C in temperature. The carbonate deposition results from the loss of some of the carbon dioxide by cooling, evaporation or presence of algae.

ASSOCIATED DEPOSIT TYPES: Hot springs Au-Ag (H03), Hot spring Hg (H02), marl, solfatara sulphur, geyserite silica.

COMMENTS: To be economically of interest, the size must be suitable to open a quarry face, the carbonate must be recrystallized and cemented to be strong and hard for ornamental stone applications. Sediments of similar texture and composition may occur in karst regions, where the carbonate precipitated from cold water.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mineral springs with carbon dioxide.

OTHER EXPLORATION GUIDES: Precipitation of tufa from small streams on moss and other organic matter, presence of thermal spring and solfatara exhalations.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Large deposits may reach 1-2 Mt, but even the small deposits of several tens to a hundred thousand tonnes may be of importance for local and custom type work. The travertine has to meet the minimum physical test requirements for intended use.

END USES: Interior and exterior facing, tile, ashlar, custom-made shapes as steps and sills, lapidary work and precious stone applications.

ECONOMIC LIMITATIONS: Even small occurrences can be exploited for local and custom markets.

IMPORTANCE: Locally important facing stone, however the usage does not match marble or granite. Mexican onyx is an important decorative stone.

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H02 - Hot Spring Hg

by A. Panteleyev[1]

Pantelyev, A., 1996. Hot spring Hg: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 31–32.

IDENTIFICATION

SYNONYMS: (Epithermal) hot spring, subaerial siliceous sinter.

COMMODITIES (*BYPRODUCTS*): Hg (*Au*).

EXAMPLES (British Columbia - *Canada/International*): Ucluelet; *Knoxville district, Sulphur Bank (California, USA), McDermitt and Steamboat Springs (Nevada, USA), Abuta mine (Japan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Uppermost portions of epithermal systems develop clay altered zones and siliceous caps a few metres to hundreds of metres below surface and silica sinter deposits above the groundwater table as hot spring deposits. Travertine ledges and other silica-carbonate accumulations may be present nearby as peripheral or deeper deposits.

TECTONIC SETTING: Continental margin rifting and strike-slip faulting associated with small volume mafic to intermediate volcanism.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Modern and fossil hot spring settings with silica and silica-carbonate deposition near the paleo groundwater table and as subaerial silica sinter precipitates.

AGE OF MINERALIZATION: Tertiary and younger; some currently active hot springs.

HOST/ASSOCIATED ROCK TYPES: Intermediate to basic volcanic flows, tuffs and breccias, minor diabasic dykes; hydrothermal breccias, travertine and siliceous sinters, lacustrine sediments. Country rocks commonly include greywacke, shale and fault-related serpentinized ultramafic bodies.

DEPOSIT FORM: Lensoid hot spring deposits and tabular lithologic replacement zones; commonly with cone- or wedge-like underlying feeder zones centered on regional-scale fault and fracture zones. Commonly less than 300 metres in vertical extent from paleosurface. Locally phreatic explosion pits.

TEXTURE: Disseminated sulphides in country rocks and hydrothermal breccias, quartz stockworks of banded to vuggy, multiple-generation quartz-chalcedony veins. Hydrofracturing textures are common. Less frequently cinnabar occurs as grains, lenses and fracture coatings in opaline silica sinter deposits. In some deposits cinnabar is concentrated on surfaces of wood and other organic matter.

ORE MINERALOGY [Principal and *Subordinate*]: Cinnabar, pyrite, *native sulphur and mercury, stibnite, gold, marcasite*.

GANGUE MINERALOGY [Principal and *Subordinate*]: Quartz, chalcedony; *opal, carbonate, iron oxides, manganese oxides*.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

H02 - Hot Spring Hg

ALTERATION MINERALOGY [Principal and *Subordinate*]: Kaolinite, alunite, Fe-Mn oxides and sulphur above water table (minor amounts of cinnabar). Opaline quartz deposited at the water table, with cinnabar. Quartz, pyrite, zeolites, chlorite and minor *adularia* below the water table; silica-carbonate-magnesite assemblages in mafic, commonly serpentinized, rocks.

GENETIC MODEL: Deposits form in geothermal systems from near surface hot waters at less than 150°C, and generally cooler. Organic materials in solution and high CO_2 vapour concentration may be important in the transporting of elevated amounts of Hg.

ORE CONTROLS: Located just below the paleo groundwater table within hot spring systems. Commonly developed along high-angle faults and generally in young volcanic terranes.

ASSOCIATED DEPOSIT TYPES: Hot spring Au-Ag (H03), epithermal Au-Ag (H04, H05), placer Au (C01, C02).

COMMENTS: There has been little work in recent years on this deposit type other than to examine their potential for related gold deposits, for example, McLaughlin mine in California (Gustafson, 1991). The significant Hg deposits typically contain no other recoverable constituents.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Hg, Sb, As. Generally <5 ppb Au but rare deposits with elevated gold are known.

GEOPHYSICAL SIGNATURE: VLF to identify favourable structures; magnetic lows in mafic volcanic hosts due to alteration envelope.

OTHER EXPLORATION GUIDES: Can be overlain by native sulphur occurrences or hot spring deposits with siliceous sinters and clay-altered rocks. Recent deposits are commonly associated with modern hot springs or geothermal fields. Silica-carbonate alteration with distinctive orange-coloured, amorphous limonite in weathered zones, typically in mafic and serpentizized hostrocks.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Commercially exploited deposits tend to be very small; the largest deposits rarely exceed 1 mt in size. The median production from 20 Cordilleran USA mines is <1000 tonnes with 0.35% Hg. Typical mineable reserves contain ores ranging from 0.2 to 0.6% Hg. Productive deposits are Sulphur Bank and 5 small mines in the Knoxville District in California which produced 4,700 tonnes of Hg and 5,520 tonnes Hg respectively.

ECONOMIC LIMITATIONS: There probably is no operating mine of this type in the world today.

IMPORTANCE: These are relatively small deposits from near surface geological environments that are easily eroded and therefore rarely preserved. They currently are not important sources of mercury but can be associated with auriferous epithermal deposits.

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H02 - Hot Spring Hg

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H03 - Hot Spring Au-Ag

by Andre Panteleyev[1]

Pantelyev, A., 1996. Hot spring Au-Ag: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 33–35.

IDENTIFICATION

SYNONYMS: (Epithermal) hot spring, subaerial siliceous sinter.

COMMODITIES (BYPRODUCTS): Au, (Ag, Hg).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Cinola (uppermost part, 103F 034), Clisbako (093C 016), Wolf? (093F 045), Trout? (093F 044); *McLaughlin (California, USA), Round Mountain (Nevada, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Auriferous chalcedonic or opaline silica and fine-grained quartz form veins, stockworks and matrix filling in breccias hosted by volcanic and, less commonly, sedimentary rocks. These are the uppermost parts of epithermal systems which develop mineralized siliceous caps a few metres to hundreds of metres below surface with subaerial siliceous sinter deposits at the water table and explosion breccias above.

TECTONIC SETTINGS: Continental margin rifting and district-scale fracture systems with associated bimodal or low volume mafic to intermediate volcanism. Commonly in regions of strike-slip faulting with transform faults and transtensional basin margins. Also extensional tectonism with related caldera development and resurgence, flow-dome complexes and high-level subvolcanic intrusive activity.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Shallow parts of fossil geothermal systems. Hot springs deposit silica near the paleo groundwater table and as subaerial, ponded precipitates. Deeper fluids are channeled by permeable stratigraphic units, hydrothermal breccia bodies and faulted/fractured rocks. Subaerial volcanic centres including flow-dome or caldera complexes and related radial and ring fracture systems.

AGE OF MINERALIZATION: Tertiary and Quaternary are most common; some currently active hot springs. Hot spring sinters as old as Late Devonian have been described (Cunneen and Sillitoe, 1989).

HOST/ASSOCIATED ROCK TYPES: Intermediate or bimodal basaltic-rhyolitic volcanics including volcanic flows, flow domes, tuffs and breccias; hydrothermal breccias and siliceous sinters. Any type of permeable or structurally prepared country rock can be mineralized, most commonly ash flow units and caldera-fill sediments. In some cases, serpentinized ultramafic and mafic rocks in major fault zones in areas of post-faulting volcanic activity are mineralized. Sedimentary rocks occur at Cinola and many other deposits.

DEPOSIT FORM: Near-surface, lensoid hot spring deposits and planar lithologic replacement zones. Individual zones are up to hundreds of metres in two dimensions and tens of metres in the third. Underlying these are cone or wedge-like hydrothermal feeder systems with quartz stockworks and veins centred on regional-scale fault and fracture zones, or their splays. Locally phreatic and phreatomagmatic explosion pits formed at the paleosurface.

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H03 - Hot Spring Au-Ag

TEXTURE/STRUCTURE: Generally very fine grained disseminated sulphides in silicified (opalized and chalcedonic) country rocks and silica sinter; hydrothermal breccias, quartz stockworks and banded to vuggy, sheeted, multiple-generation quartz-chalcedony veins. Hydrofracturing textures are common.

ORE MINERALOGY [Principal and *Subordinate*]: Pyrite, marcasite, gold, electrum; *stibnite, sulphosalt minerals, realgar, cinnabar* (cinnibar only near tops of deposits).

GANGUE MINERALOGY [Principal and *Subordinate*]: Quartz, chalcedony; *opal, calcite, dolomite, barite.* Strong silicification with quartz, chalcedony and opal in crustified, banded veins, sheeted veins and stockworks is characteristic in ores. Silica in some deposits contains abundant hydrocarbons that impart a characteristic brownish colour to the quartz.

ALTERATION MINERALOGY [Principal and *Subordinate*]: Multiple episodes of silicification to form veins and stockworks, and pervasive silicified hostrocks adjacent to them, is typical. Country rocks containing the silicified zones have argillic and, less commonly, advanced argillic assemblages with quartz-kaolinite and rarely *alunite*. They are flanked, or underlain, by propylitic rocks with chlorite, Fe oxides, zeolites and minor *adularia*. Selenite, alunite and other sulphate minerals and native sulphur can be abundant locally near surface.

WEATHERING: Limonite (jarosite, hematite, goethite) is locally prominent near surface in strongly oxidized deposits.

ORE CONTROLS: A key element at the McLaughlin deposit was the superposition of multiple generations of auriferous veinlets each carrying a small amount of gold (Lehrman, 1986).

GENETIC MODEL: Hydrothermal breccias and multiple generations of veins with calcite replacement by silica attest to boiling of hydrothermal fluids as an important ore-depositing mechanism. The boiling levels are related to the paleosurface and commonly have a surficial expression as active or paleo-hot springs. The deeper hydrothermal fluid systems, generaly within 500 m of surface (paleosurface for older deposits), can be developed along active, regional high-angle faults and other volcanic and subvolcanic intrusion-related structures. The structures commonly cut or flank domes in flow-dome complexes.

ASSOCIATED DEPOSIT TYPES: Hot spring Hg (H02), solfatara sulphur; epithermal Au-Ag (H04, H05), placer Au (C01, C02).

COMMENTS: Many deposits currently being exploited throughout the world have grades between 1 and 2 g/t Au and range from a few to tens of millions of tonnes in size. They are viable generally because the rocks are commonly strongly oxidized and the gold can be recovered by heap leaching methods. The siliceous sinters formed at or very near to the surface rarely contain economic mineralization These deposits have a greater depth extent then hot spring mercury deposits. In their deeper parts they may grade into precious metal bearing and base metal epithermal veins.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, Sb, As, Hg, Tl near surface, increasing Ag, Ba at depth; locally Ni, B, Li and W. The Ag/Au ratio varies from 1:1 at surface to 30:1 at a depth of a few hundred metres. Mineralized rocks can be strongly leached at surface. Notably absent are: Se, Te, F, Mo, Sn and Mn. Base metal content is relatively low, for example, common amounts are Cu <60 ppm, Pb <5 ppm and Zn <450 ppm.

GEOPHYSICAL SIGNATURE: Resistivity, VLF to identify faults.

OTHER EXPLORATION GUIDES: Siliceous sinter can be used to identify the paleosurface; Hg mineralization may overlie deeper gold ores.

H03 - Hot-Spring Au-Ag

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Mineralization tends to be low grade. Economically attractive bulk-mineable deposits contain >10 Mt of 1 to 2 g/t Au, or greater. High-grade veins and stockworks within the larger mineralized zones can be exploited by underground methods. The McLaughlin deposit, a superior discovery, contained initial reserves of 17.5 Mt with 5.2 g/t Au and about 16 g/t Ag, including a sheeted vein zone with 2.45 Mt with 9.15 g/t Au. Reserves for Cinola are about 31 Mt with 2.19 g/t Au; the deposit has a feeder zone at depth that contains material containing in excess of 100 g/t Au.

ECONOMIC LIMITATIONS: Refractory primary ore in deposits that lack significant oxidation renders many of the lower grade deposits uneconomic.

IMPORTANCE: Individual deposits are attractive economically, for example, the McLaughlin mine in California.

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White, D. (1981): Active Geothermal Systems and Hydrothermal Ore Deposits; *Economic Geology,* 75th Anniversary Volume, pages 392-423.

H04 - Epithermal Au-Ag-Cu: High Sulphidation

by Andre Panteleyev[1]

Pantelyev, A., 1996. Epithermal Au-Ag-Cu: high sulphidation: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 37–39.

IDENTIFICATION

SYNONYMS: (Epithermal) acid-sulphate, quartz-alunite Au, alunite-kaolinite ± pyrophyllite, advanced argillic, Nansatsu-type, enargite gold. The deposits are commonly referred to as *acid-sulphate* type after the chemistry of the hydrothermal fluids, *quartz-alunite* or *kaolinite-alunite* type after their alteration mineralogy, or *high-sulphidation* type in reference to the oxidation state of the acid fluids responsible for alteration and mineralization.

COMMODITIES (BYPRODUCTS): Au, Ag, Cu (*As*, *Sb*).

EXAMPLES (British Columbia (MINFILE #) - *International*): Mt. McIntosh/Hushamu (EXPO, 92L 240), Taseko River deposits - Westpine (Empress) (92O 033), Taylor-Windfall (92O 028) and Battlement Creek (92O 005); *Goldfield and Paradise Peak (Nevada, USA), Summitville (Colorado, USA); Nansatsu (Japan), El Indio (Chile); Temora (New South Wales, Australia), Pueblo Viejo (Dominica), Chinkuashih (Taiwan), Rodalquilar (Spain), Lepanto and Nalesbitan (Philippines).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Veins, vuggy breccias and sulphide replacements ranging from pods to massive lenses occur in volcanic sequences associated with high level hydrothermal systems marked by acid-leached, advanced argillic, siliceous alteration.

TECTONIC SETTING: Extensional and transtensional settings, commonly in volcano-plutonic continent-margin and oceanic arcs and back-arcs. In zones with high-level magmatic emplacements where stratovolcanoes and other volcanic edifices are constructed above plutons.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Subvolcanic to volcanic in calderas, flow-dome complexes, rarely maars and other volcanic structures; often associated with subvolcanic stocks and dikes, breccias. Postulated to overlie, and be genetically related to, porphyry copper systems in deeper mineralized intrusions that underlie the stratovolcanoes.

AGE OF MINERALIZATION: Tertiary to Quaternary; less commonly Mesozoic and rarely Paleozoic volcanic belts. The rare preservation of older deposits reflects rapid rates of erosion before burial of subaerial volcanoes in tectonically active arcs.

HOST/ASSOCIATED ROCK TYPES: Volcanic pyroclastic and flow rocks, commonly subaerial andesite to dacite and rhyodacite, and their subvolcanic intrusive equivalents. Permeable sedimentary intervolcanic units can be sites of mineralization.

DEPOSIT FORM: Veins and massive sulphide replacement pods and lenses, stockworks and breccias. Commonly irregular deposit shapes are determined by hostrock permeability and the geometry of ore-controlling structures. Multiple, crosscutting composite veins are common.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

H04 - Epithermal Au-Ag-Cu: High Sulphidation

TEXTURE/STRUCTURE: Vuggy 'slaggy' silica derived as a residual product of acid leaching is characteristic. Drusy cavities, banded veins, hydrothermal breccias, massive wallrock replacements with fine-grained quartz.

ORE MINERALOGY (Principal and *Subordinate*): pyrite, enargite/luzonite, chalcocite, covellite, bornite, gold, electrum; *chalcopyrite, sphalerite, tetrahedrite/tennantite, galena, marcasite, arsenopyrite, silver sulphosalts, tellurides including goldfieldite*. Two types of ore are commonly present: massive enargite-pyrite and/or quartz-alunite-gold.

GANGUE MINERALOGY (Principal and *Subordinate*): Pyrite and quartz predominate. Barite may also occur; carbonate minerals are absent.

ALTERATION MINERALOGY (Principal and *Subordinate)*: Quartz, kaolinite/dickite, alunite, barite, hematite; sericite/illite, amorphous clays and silica, pyrophyllite, andalusite, diaspore, corundum, tourmaline, *dumortierite, topaz, zunyite, jarosite, Al-P sulphates (hinsdalite, woodhouseite, crandalite, etc*.) and native sulphur. Advanced argillic alteration is characteristic and can be areally extensive and visually prominent. Quartz occurs as fine-grained replacements and, characteristically, as vuggy, residual silica in acid-leached rocks.

WEATHERING: Weathered rocks may contain abundant limonite (jarosite-goethite-hematite), generally in a groundmass of kaolinite and quartz. Fine-grained supergene alunite veins and nodules are common.

ORE CONTROLS: In volcanic edifices - caldera ring and radial fractures; fracture sets in resurgent domes and flow-dome complexes, hydrothermal breccia pipes and diatremes. Faults and breccias in and around intrusive centres. Permeable lithologies, in some cases with less permeable cappings of hydrothermally altered or other cap rocks. The deposits occur over considerable depths, ranging from high-temperature solfataras at paleosurface down into cupolas of intrusive bodies at depth.

GENETIC MODEL: Recent research, mainly in the southwest Pacific and Andes, has shown that these deposits form in subaerial volcanic complexes or composite island arc volcanoes above degassing magma chambers. The deposits can commonly be genetically related to high-level intrusions. Multiple stages of mineralization are common, presumably related to periodic tectonism with associated intrusive activity and magmatic hydrothermal fluid generation.

ASSOCIATED DEPOSIT TYPES: Porphyry Cu±Mo±Au deposits (L04), subvolcanic Cu-Ag-Au (As-Sb) (L01), epithermal Au-Ag deposits: low sulphidation type (H05), silica-clay-pyrophyllite deposits (Roseki deposits) (H09), hot spring Au-Ag (H03), placer Au deposits (C01,C02).

COMMENTS: High-sulphidation epithermal Au-Ag deposits are much less common in the Canadian Cordillera than low-sulphidation epithermal veins. However, they are the dominant type of epithermal deposit in the Andes.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, Cu, As dominate; also Ag, Zn, Pb, Sb, Mo, Bi, Sn, Te, W, B and Hg.

GEOPHYSICAL SIGNATURE: Magnetic lows in hydrothermally altered (acid-leached) rocks; gravity contrasts may mark boundaries of structural blocks.

OTHER EXPLORATION GUIDES: These deposits are found in second order structures adjacent to crustal-scale fault zones, both normal and strike-slip, as well as local structures associated with subvolcanic intrusions. The deposits tend to overlie and flank porphyry copper-gold deposits and underlie acid-leached siliceous, clay and alunite-bearing ‘lithocaps’.

H04 - Epithermal Au-Ag-Cu: High Sulphidation

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: There is wide variation in deposit types ranging from bulk-mineable, low-grade to selectively mined, high-grade deposits. Underground mines range in size from 2 to 25 Mt with grades from 178 g/t Au, 109 g/t Ag and 3.87% Cu in direct smelting ores (El Indio) to 2.8 g/t Au and 11.3 g/t Ag and 1.8% Cu (Lepanto). Open pit mines with reserves of <100 Mt to >200 Mt range from Au-Ag mines with 3.8 g/t Au and 20 g/t Ag (Pueblo Viejo, Dominica) to orebodies such as the Nansatsu deposits, Japan that contain a few million tonnes ore grading between 3 and 6 g/t Au. Porphyry Au (Cu) deposits can be overprinted with late-stage acid sulphate alteration zones which can contain in the order of ~1.5 g/t Au with 0.05 to 0.1% Cu in stockworks (Marte and Lobo) or high-grade Cu-Ag-Au veins (La Grande veins, Collahausi). More typically these late stage alteration zones carry <0.4 to 0.9 g/t Au and >0.4 to 2% Cu (Butte, Montana; Dizon, Philippines).

ECONOMIC LIMITATIONS: Oxidation of primary ores is commonly neccessary for desireable metallurgy; primary ores may be refractory and can render low-grade mineralization noneconomic.

IMPORTANCE: This class of deposits has recently become a focus for exploration throughout the circum-Pacific region because of the very attractive Au and Cu grades in some deposits. Silica-rich gold ores (3-4 g/t Au) from the Nansatsu deposits in Japan are used as flux in copper smelters.

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H05 - Epithermal Au-Ag: Low Sulphidation

by Andre Panteleyev[1]

Pantelyev, A., 1996. Epithermal Au-Ag: low sulphidation: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 41–43.

IDENTIFICATION

SYNONYMS: (Epithermal) adularia-sericite; quartz-adularia, Comstock, Sado-type; bonanza Au-Ag; alkali chloride (hydrothermal).

COMMODITIES (BYPRODUCTS): Au, Ag (*Pb, Zn, Cu*).

EXAMPLES (British Columbia (MINFILE #) - *International*): Toodoggone district deposits - Lawyers (94E 066), Baker (94E 026), Shas (94E 050); Blackdome (92O 050-053); Premier Gold (Silbak Premier), (104B 054); Cinola (103F 034); *Comstock, Aurora (Nevada, USA), Bodie (California, USA), Creede (Colorado, USA), Republic (Washington, USA), El Bronce (Chile), Guanajuato (Mexico), Sado, Hishikari (Japan), Colqui (Peru), Baguio (Philippines) Ladolam (Lihir, Papua-New Guinea).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Quartz veins, stockworks and breccias carrying gold, silver, electrum, argentite and pyrite with lesser and variable amounts of sphalerite, chalcopyrite, galena, rare tetrahedrite and sulphosalt minerals form in high-level (epizonal) to near-surface environments. The ore commonly exhibits open-space filling textures and is associated with volcanic-related hydrothermal to geothermal systems.

TECTONIC SETTING: Volcanic island and continent-margin magmatic arcs and continental volcanic fields with extensional structures.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level hydrothermal systems from depths of ~1 km to surficial hot spring settings. Regional-scale fracture systems related to grabens, (resurgent) calderas, flow-dome complexes and rarely, maar diatremes. Extensional structures in volcanic fields (normal faults, fault splays, ladder veins and cymoid loops, etc.) are common; locally graben or caldera-fill clastic rocks are present. High-level (subvolcanic) stocks and/or dikes and pebble breccia diatremes occur in some areas. Locally resurgent or domal structures are related to underlying intrusive bodies.

AGE OF MINERALIZATION: Any age. Tertiary deposits are most abundant; in B.C. Jurassic deposits are important. Deposits of Paleozoic age are described in Australia. Closely related to the host volcanic rocks but invariably slightly younger in age (0.5 to 1 Ma, more or less).

HOST/ASSOCIATED ROCK TYPES: Most types of volcanic rocks; calcalkaline andesitic compositions predominate. Some deposits occur in areas with bimodal volcanism and extensive subaerial ashflow deposits. A less common association is with alkalic intrusive rocks and shoshonitic volcanics. Clastic and epiclastic sediments in intra-volcanic basins and structural depressions.

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H05 - Epithermal Au-Ag: Low Sulphidation

DEPOSIT FORM: Ore zones are typically localized in structures, but may occur in permeable lithologies. Upward-flaring ore zones centred on structurally controlled hydrothermal conduits are typical. Large (> 1 m wide and hundreds of metres in strike length) to small veins and stockworks are common with lesser disseminations and replacements. Vein systems can be laterally extensive but ore shoots have relatively restricted vertical extent. High-grade ores are commonly found in dilational zones in faults at flexures, splays and in cymoid loops.

TEXTURE/STRUCTURE: Open-space filling, symmetrical and other layering, crustification, comb structure, colloform banding and multiple brecciation.

ORE MINERALOGY (Principal and *Subordinate*): Pyrite, electrum, gold, silver, argentite; *chalcopyrite, sphalerite, galena, tetrahedrite, silver sulphosalt and/or selenide minerals.* Deposits can be strongly zoned along strike and vertically. Deposits are commonly zoned vertically over 250 to 350 m from a base metal poor, Au-Ag-rich top to a relatively Ag-rich base metal zone and an underlying base metal rich zone grading at depth into a sparse base metal, pyritic zone. From surface to depth, metal zones contain: Au-Ag-As-Sb-Hg, Au-Ag-Pb-Zn-Cu, Ag-Pb-Zn. In alkalic hostrocks tellurides, V mica (roscoelite) and fluorite may be abundant, with lesser *molybdenite*.

GANGUE MINERALOGY (Principal and *Subordinate*): Quartz, amethyst, chalcedony, quartz pseudomorphs after calcite, calcite; *adularia, sericite, barite, fluorite, Ca-Mg-Mn-Fe carbonate minerals such as rhodochrosite, hematite and chlorite*.

ALTERATION MINERALOGY: Silicification is extensive in ores as multiple generations of quartz and chalcedony are commonly accompanied by adularia and calcite. Pervasive silicification in vein envelopes is flanked by sericite-illite-kaolinite assemblages. Intermediate argillic alteration [kaolinite-illite-montmorillonite (smectite)] formed adjacent to some veins; advanced argillic alteration (kaolinite-alunite) may form along the tops of mineralized zones. Propylitic alteration dominates at depth and peripherally.

WEATHERING: Weathered outcrops are often characterized by resistant quartz ± alunite 'ledges' and extensive flanking bleached, clay-altered zones with supergene alunite, jarosite and other limonite minerals.

ORE CONTROLS: In some districts the epithermal mineralization is tied to a specific metallogenetic event, either structural, magmatic, or both. The veins are emplaced within a restricted stratigraphic interval generally within 1 km of the paleosurface. Mineralization near surface takes place in hot spring systems, or the deeper underlying hydrothermal conduits. At greater depth it can be postulated to occur above, or peripheral to, porphyry and possibly skarn mineralization. Normal faults, margins of grabens, coarse clastic caldera moat-fill units, radial and ring dike fracture sets and both hydrothermal and tectonic breccias are all ore fluid channeling structures. Through-going, branching, bifurcating, anastamosing and intersecting fracture systems are commonly mineralized. Ore shoots form where dilational openings and cymoid loops develop, typically where the strike or dip of veins change. Hangingwall fractures in mineralized structures are particularly favourable for high-grade ore.

GENETIC MODEL: These deposits form in both subaerial, predominantly felsic, volcanic fields in extensional and strike-slip structural regimes and island arc or continental andesitic stratovolcanoes above active subduction zones. Near-surface hydrothermal systems, ranging from hot spring at surface to deeper, structurally and permeability focused fluid flow zones are the sites of mineralization. The ore fluids are relatively dilute and cool solutions that are mixtures of magmatic and meteoric fluids. Mineral deposition takes place as the solutions undergo cooling and degassing by fluid mixing, boiling and decompression.

ASSOCIATED DEPOSIT TYPES: Epithermal Au-Ag: high sulphidation (H04); hot spring Au-Ag (H03); porphyry Cu±Mo±Au (L04) and related polymetallic veins (I05); placer gold (C01, C02).

H05 - Epithermal Au-Ag: Low Sulphidation

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values in rocks of Au, Ag, Zn, Pb, Cu and As, Sb, Ba, F, Mn; locally Te, Se and Hg.

GEOPHYSICAL SIGNATURE: VLF has been used to trace structures; radiometric surveys may outline strong potassic alteration of wallrocks. Detailed gravity surveys may delineate boundaries of structural blocks with large density contrasts.

OTHER EXPLORATION GUIDES: Silver deposits generally have higher base metal contents than Au and Au-Ag deposits. Drilling feeder zones to hot springs and siliceous sinters may lead to identification of buried deposits. Prospecting for mineralized siliceous and silica-carbonate float or vein material with diagnostic open-space textures is effective.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The following data describe the median deposits based on worldwide mines and U.S.A. models:

- Au-Ag deposits (41 Comstock-type 'bonanza' deposits) - 0.77 Mt with 7.5 g/t Au, 110 g/t Ag and minor Cu, Zn and Pb. The highest base metal contents in the top decile of deposits all contain <0.1% Cu, Zn and 0.1% Pb
- Au-Cu deposits (20 Sado-type deposits) - 0.3 Mt with 1.3% g/t Au, 38 g/t Ag and >0.3% Cu; 10 % of the deposits contain, on average, about 0.75% Cu with one having >3.2% Cu.

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H07 - Sn-Ag Veins

by Andre Panteleyev[1]

Pantelyev, A., 1996. Sn-Ag veins: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 45–47.

IDENTIFICATION

SYNONYMS: Polymetallic Sn veins, Bolivian polymetallic veins, polymetallic tin-silver deposits, polymetallic xenothermal.

COMMODITIES (BYPRODUCTS): Ag, Sn (Zn, Cu, Au, Pb, Cd, In, Bi, W).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): D zone (104P 044, 080,081) and Lang Creek veins ('Pant', 104P 082), Cassiar district; *Cerro Rico de Potosi, Oruro, Chocaya, (Bolivia), Pirquitas (Argentina), Ashio, Akenobe and Ikuno (Japan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sulphide and quartz-sulphide veins carrying cassiterite, a wide variety of other base metals and zones with silver minerals. They are associated with epizonal (subvolcanic) quartz-bearing intrusions, or their immediate hostrocks. In some places the ore is in volcanic rocks within dacitic to quartz latitic flow-dome complexes.

TECTONIC SETTING: Continental margin; synorogenic to late orogenic belts with high-level plutonism in intermediate to felsic volcanoplutonic arcs. In British Columbia the only significant Sn-bearing deposits occur with S or A-type granites in eastern tectonic assemblages underlain by continental rocks of North American origin.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: In faults, shears and fractures that cut or are proximal to high-level felsic intrusions and in flow-dome complexes, namely domes and their surrounding tuff rings and explosive breccias.

AGE OF MINERALIZATION: Tertiary in the type area of Bolivia; Cretaceous and Tertiary in Japan; Tertiary and older in British Columbia.

HOST/ASSOCIATED ROCK TYPES: Hostrocks for veins can be of any type and do not appear to be an important control on the occurrence of the deposits; they include sedimentary, volcanic and intrusive rocks and sometimes, metasedimentary rocks at depth. Intrusive rocks with which the mineralization is associated are quartz bearing and peraluminous, but seem to be restricted to intermediate compositions between 60 and 70% SiO_2 (dacite to rhyodacite); more felsic rocks are present, but are less common.

DEPOSIT FORM: Veins, commonly with swarms of closely spaced, splaying smaller veins in sheeted zones. Veins vary in width from microveinlets to a few metres, and commonly are less than a metre wide. The ore shoots in veins are commonly 200-300 m along strike and dip but the veins may extend to more than 1000 m in depth and strike length. Vein systems and related stockworks cover areas up to a square kilometre along the tops of conical domes or intrusions 1-2 km wide.

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H07 - Sn-Ag Veins

TEXTURE/STRUCTURE: Multistage composite banded veins with abundant ore minerals pass at depth into crystalline quartz veins and upwards into vuggy quartz-bearing veins and stockworks.

ORE MINERALOGY [Principal and *Subordinate*]: Pyrite, cassiterite; *pyrrhotite, marcasite; sphalerite, galena, chalcopyrite, stannite, arsenopyrite, tetrahedrite, scheelite, wolframite, andorite, jamesonite, boulangerite, ruby silver (pyrargyrite), stibnite, bismuthinite, native bismuth, molybdenite, argentite, gold and complex sulphosalt minerals*. These deposits are characterized by their mineralogical complexity. There is no consistency between deposits in vertical or lateral zoning, but individual deposits are markedly spatially and temporally zoned. In some deposits, notably intrusion or dome-hosted examples, core zones are denoted by the high-temperature minerals cassiterite, wolframite, bismuthinite and arsenopyrite. Surrounding ores have varying amounts of stannite and chalcopyrite with, most significantly, sphalerite, galena and various Pb sulphosalt and Ag minerals. Silver in the upper parts of the vein systems occurs in argentite, ruby silver and native silver and at depth is mainly present in tetrahedrite.

GANGUE MINERALOGY [Principal and *Subordinate*]: Quartz, sericite, pyrite; *tourmaline at depth, kaolinite and chalcedony near surface; rare barite, siderite, calcite, Mn carbonate and fluorite*.

ALTERATION MINERALOGY: Quartz-sericite-pyrite is characteristic; elsewhere quartz-sericite-chlorite occurs in envelopes on veins. Near-surface argillic and advanced argillic alteration overprinting is present in some deposits.

WEATHERING: Prominent limonite cappings are derived from the oxidation of pyrite.

ORE CONTROLS: Sets of closely spaced veins, commonly in sheeted zones, fractures and joints within and surrounding plutons are related to the emplacement and cooling of the host intrusions. The open space filling and shear-replacement veins are associated with stockworks, breccia veins and breccia pipes. A few deposits occur in faults, shears, fold axes and cleavage or fracture zones related to regional tectonism. Some early wallrock replacement along narrow fissures is generally followed and dominated by open-space filling in many deposits.

GENETIC MODEL: Dacitic magma and the metal-bearing hydrothermal solutions represent the uppermost products of large magmatic/hydrothermal systems. The Sn is probably a remobilized component of sialic rocks derived from recycled continental crust.

ASSOCIATED DEPOSIT TYPES: Polymetallic veins Ag-Pb-Zn (I05); epithermal Au-Ag: low sulphidation (H05), mantos (J01, J02), porphyry Sn (L06), placers (C01, C02). This deposit type grades with depth into Sn veins and greissens (I13) associated with mesozonal granitic intrusions into sediments. Cassiterite in colluvium can be recovered by placer mining. Mexican-type rhyolite Sn or “wood tin” deposits represent a separate class of deposit (Reed *et al*., 1986).

COMMENTS: Many Sn-bearing base metal vein systems are known to occur in eastern British Columbia, but there is poor documentation of whether the Sn is present as cassiterite or stannite. The former can be efficiently recovered by simple metallurgy, the latter cannot.

H07 - Sn-Ag Veins

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ag, Cu, Zn, Pb, Sn, W, As, Bi.

OTHER EXPLORATION GUIDES: The vein systems may display impressive vertical and horizontal continuity with marked metal zoning. Bolivian polymetallic vein deposits have formed at depths of 0.5 to 2 km below the paleosurface. Deeper veins of mainly massive sulphide minerals contain Sn, W and Bi; the shallower veins with quartz-barite and chalcedony-barite carry Ag and rarely Au. Metal zoning from depth to surface and from centres outward shows: Sn + W, Cu + Zn, Pb + Zn, Pb + Ag and Ag ± Au; commonly there is considerable ‘telescoping’ of zones. Oxidized zones may have secondary Ag minerals, such as Ag chlorides.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Considerable variation in metal contents of ores is evident between deposits. Potentially bulk-mineable bedrock deposits contain in the order of 0.2% Sn with 70-179 g/t Ag (Cerro Rico, Potosi, Bolivia).

ECONOMIC LIMITATIONS: These veins tend to be narrow.

IMPORTANCE: These veins are an important source of cassiterite for economic placer deposits around the world and the lodes have been mined in South America. They are currently attractive only when they carry appreciable Ag. In some deposits Au content is economically significant and Au-rich zones might have been overlooked during past work. Future Sn production from these veins will probably be as a byproduct commodity, and only if cassiterite is the main Sn mineral.

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H08 - Alkalic Intrusion-Associated Au-Ag

by Tom G. Schroeter[1] and Robert Cameron[2]

Schroeter, T., and Cameron, R., 1996. Alkalic intrusion-associated Au-ag: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 49–51.

IDENTIFICATION

SYNONYMS: Alkalic epithermal, Au-Ag-Te veins

COMMODITIES (BYPRODUCTS): Au, Ag (*Zn, Pb*)

EXAMPLES (British Columbia - *Canada/International*): Flathead (082GSE070), Howell (082GSE037), Howe (082GSE048); *Cripple Creek (Colorado, USA), Zartman, Landusky, Golden Sunlight (Montana, USA), Golden Reward (South Dakota, USA)*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: These deposits include quartz veins with pyrite, sphalerite and galena in structural zones and stockworks within alkalic intrusions and/or disseminated pyritic zones in alkalic intrusions, diatremes, coeval volcanics (Cripple Creek) and surrounding sediments. Argillic alteration, +/- silicification, carbonatization, and barite and fluorite veins are common.

TECTONIC SETTINGS: Associated with alkalic intrusive rocks in sedimentary cover rocks above continental crust, generally associated with extensional faulting. Tertiary examples in the USA are related to continental rifting; Rio Grande rift for Cripple Creek, Great Falls tectonic zone for the Montana deposits. Flathead area of British Columbia is in a continental setting but the extensional component is not as apparent.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Diatreme-intrusive complexes, high-level alkalic plugs, and dikes that intrude Proterozoic to Mesozoic continental clastic and carbonate rocks. Cripple Creek is within a large maar diatreme complex. Flathead intrusions are coeval with chemically similar volcanic rocks, the Crowsnest volcanics, in southern Alberta.

AGE OF MINERALIZATION: Any age; Flathead intrusions are early Cretaceous (98.5 Ma)

HOST/ASSOCIATED ROCK TYPES: (Flathead area): Intrusions include alkali feldspar syenite, foid-bearing syenite (nepheline, leucite, nosean, analcite), mela-syenite and related diatreme breccias with 10 % to 100 % intrusive component. Textures include coarse porphyritic sanidine, micro-syenite, tinguaite. Host sedimentary rocks include clastic rocks, shales and argillites to sandstones, and impure fine-grained carbonaceoous limestone and massive calcarenitic limestone. Gold may be present in all rock types.

DEPOSIT FORM: Deposits may be in the form of sheeted veins in structural zones within intrusions (*e.g*, Zortman, Cripple Creek) with dimensions of 50 m to 100 m in width and hundreds of metres in length to, less commonly, large disseminated, diffuse zones within diatremes (*e.g*., Montana Tunnels, Cripple Creek), volcanic rocks (*e.g*., Cripple Creek) or stratabound within favourable sedimentary lithologies.

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H08 - Alkalic Intrusion-Associated Au-Ag

DEPOSIT FORM: Deposits may be in the form of sheeted veins in structural zones within intrusions (*e.g*, Zortman, Cripple Creek) with dimensions of 50 m to 100 m in width and hundreds of metres in length to, less commonly, large disseminated, diffuse zones within diatremes (*e.g*., Montana Tunnels, Cripple Creek), volcanic rocks (*e.g*., Cripple Creek) or stratabound within favourable sedimentary lithologies.

TEXTURE/STRUCTURE: Ore minerals in quartz and quartz-adularia veins, vein stockworks, disseminated zones and minor breccias.

ORE MINERALOGY (Principal and *Subordinate*): Fine-grained (auriferous, arsenical?) pyrite, galena, sphalerite, gold tellurides; *chalcopyrite, magnetite, gold, bismuth and tellurium* minerals are suspected at Flathead from elevated geochemical values in samples (to 31 ppm Te, 356 ppm Bi).

GAUNGE MINERALOGY (Principal and *Subordinate*): Quartz, calcite; *adularia, barite, fluorite*.

ALTERATION MINERALOGY (Principal and *Subordinate*): Widespread pyrite and carbonate (calcite) alteration of intrusive rocks, silicic and argillic (illite, sericite, jarosite, *roscoelite*) alteration of wallrocks; also albite and adularia.

WEATHERING: Oxidation with limonite, jarosite, hydrozincite.

ORE CONTROLS: Mineralization is controlled by structural zones within or proximal to alkalic intrusions; also in permeable (*e.g*., sandstone) or chemically favourable units (impure carbonates or bedding contacts) in country rocks. Diatreme breccias are favourable permeable hosts for focused flow of volatiles.

ASSOCIATED DEPOSIT TYPES: Distal base metal mantos are indicated in the Flathead and South Dakota deposit areas. Possible link with porphyry Mo deposits; polymetallic (I05) veins.

COMMENTS: Some authors consider this deposit type to be a subset of the low-sulphidation epithermal suite of precious metal deposits. This deposit model relates to continental rift settings, but related deposit types are present in oceanic arc settings and include Emperor (Fiji), Porgera and Ladolam (Papua New Guinea) deposits. Similar British Columbia settings may include the Quesnel and Stikine Terrane alkalic volcanic belts which host the alkalic porphyry copper-gold deposits (LO3).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, Ag, As, Sb, Pb, Zn, F, Ba, V, Te, Bi

GEOPHYSICAL SIGNATURE: High chargeability (I.P.) will outline pyritic zones; magnetic surveys will outline magnetite-bearing zones.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Highly variable, from very low mineable grades (*e.g*., 0.53 g/t Au at Zortman) to very high bonanza grades (*e.g.*, 126 g/t Au at the Cresson vug, Cripple Creek). Recovered gold from the Cripple Creek district totals in excess of 600 tonnes. Grades at Howell Creek include 58 m of 1.3 g/t Au in silicified limestone, with grab samples containing up to 184 g/t at Flathead. Tonnages and grades from a number of deposits include:

Cresson deposit, Cripple Creek	70 mt	0.99 g/t Au
Cripple Creek, historical prod'n (1891-1989)	41 mt	17.14 g/t Au
Golden Sunlight (Dec., 1994)	42.8 mt	1.9 g/t
Zortman (Dec., 1994)	55.7 mt	0.68 g/t Au
Montana Tunnels (Dec., 1994)	26.6 mt	0.61 g/T Au

H08 - Alkalic Intrusion-Associated Au-Ag

IMPORTANCE: Although these deposits have not been mined in British Columbia, they remain a viable exploration target.

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H09 - Hydrothermal Clays

By Z.D. Hora[1]

Hora, Z. D., 2007. Hydrothermal clays: mineral deposit profile, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Primary kaolin deposits, hypogene kaolin, hydrothermal kaolin, quartz-kaolinite-alunite deposits, Island Arc kaolin model, argillic alteration deposits, epithermal kaolin, hydrothermal alunite.

COMMODITIES (BYPRODUCTS): Kaolin, halloysite, pyrophyllite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Monteith Bay (092L 072, 117, 246, 343), Pemberton Hills (092L 308); *Tintic (Utah, USA), Terraced Hills, (Nevada, USA), Matauri Bay, Mahimahi and Maungaparerua (New Zealand), Chugoku, Itaya and Taishu (Japan), Suzhou (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Kaolin and halloysite, with or without alunite and pyrophyllite, occurs as veins and massive alteration masses in volcanic and granitic rocks. They formed in geothermal fields and hot springs areas associated with volcanic activity nearby.

TECTONIC SETTINGS: Active volcanic arcs (oceanic island arcs, continental margin arcs), extensional and transtensional settings, continental margin rifting. Typically the biggest deposits occur in volcanic island arcs, but may develop also in volcanic centres near continental margins.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Near surface hydrothermal alteration zones associated with subaerial volcanic centres and geothermal areas. The volcanic centres can be stratovolcanoes and calderas. Alteration zones typically occur in rocks of higher permeability and to depths of up to 100 metres from the paleosurface.

AGE OF MINERALIZATION: Mostly Tertiary to Quaternary; due to erosion and metamorphism the older deposits generally have not been preserved. The Suzhou deposit is reported to be related to Jurassic volcanic activity.

HOST/ASSOCIATED ROCK TYPES: Rhyolite, trachyte, andesite flows, sometimes glassy, and volcaniclastic rocks and their hypabyssal equivalents. Also, any older basement with feldspathic or sericitic rocks. Associated rocks are hydrothermal breccias and travertine and siliceous sinters.

DEPOSIT FORM: Structurally controlled, cone or wedge-shaped bodies are common; sometimes irregular shapes result from variable host rock permeability controlled by fracture density and porosity. Many alteration zones spread out as they approach the surface or form large near-surface zones on the flanks of volcanoes. Many of described ore bodies are less than 100 by 200 metres in size. The largest known deposit, Maungaparerua, covers 350 acres and has been explored to 50 m depth. The Itaya deposit has three zones; the largest one was 300 by 350 metres in plan and 100 metres deep. The Taishu has many orebodies, the largest one being 100 by 200 metres in size.

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H09 - Hydrothermal Clays

TEXTURE/STRUCTURE: Relic textures of the original host rock; sometimes aphanitic mixture of clay component with fine-grained silica; stockwork and breccia.

ORE MINERALOGY (Principal and *Subordinate*): Halloysite, kaolin, pyrophyllite; *dickite, nacrite*.

GANGUE MINERALOGY (Principal and *Subordinate*): Quartz, alunite, illite, smectite; *barite, pyrite.*

ALTERATION MINERALOGY: Clay minerals and pyrophyllite are hydrothermal alteration products of host rocks. This process, which starts with alteration of feldspars and other aluminosilicates, can be pervasive or marginal to fractures. In the latter case, some of the rock will be partially altered with hydrous phyllosilicates surrounding relic feldspar, quartz and mica. The alteration minerals can be zoned outward from core zones of silica through alunite to flanking zones of pyrophyllite-kaolinite-halloysite-smectite-illite. Byproduct silica is mobilized and can be precipitated as a silica cap, veins and/or a siliceous matrix to the clay minerals.

WEATHERING: Circulating groundwater may further remove leachable elements (K, Na, Ca, Mg, etc.) and improve the quality of clay for a number of end uses. Residual weathering may overprint primary kaolin deposits resulting in superior quality ceramic clay (Maungaparerua, New Zealand). Silica caps on top of the deposit can form topographic heights.

ORE CONTROLS: Volcanic centres are a key control. Diatreme breccias, normal faults, margins of grabens and collapsed calderas can also be loci for some hypogene clay deposits. Alteration zones are often more extensive near the paleosurface. Hydrothermal clays are often hosted by rocks that are feldspathic, contain felsic glass and/or are permeable.

GENETIC MODELS: Clay deposits develop in feldspathic rocks, with or without volcanic glass, due to the circulation of hydrothermal fluids with low pH values (approximately 3.5 to 5) and temperatures from below 100 to 400°C. Halloysite forms at temperatures under ~100°C, kaolinite and alunite between ~100°C and ~350°C and pyrophyllite between ~300°C and ~400°C. Silica compounds and alunite may precipitate in separate zones, but also as a cementing matrix for kaolinite and pyrophyllite. The deposits occur over a considerable depth, ranging from high temperature geothermal fields at the paleosurface down into cupolas of intrusive bodies at depth.

ASSOCIATED DEPOSIT TYPES: Epithermal Au-Ag - low sulphidation (H05), epithermal Au-Ag-Cu: high sulphidation (H04), hot spring Au-Ag (H03), hot spring Hg (H02), solfatara alteration in vents in modern deposits.

COMMENTS: In some cases, near-surface leaching of these alteration zones can produce altered zones containing more than 95% silica. Alunite deposits can be extensive with potential as an aluminum resource, but they are not presently considered to be economic.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High aluminum contents and reduced alkali contents, increased silica locally. Presence of aluminum sulphate and/or native sulphur.

GEOPHYSICAL SIGNATURE: Seismic techniques can distinguish dense unaltered rock from less dense clay altered zones. Resistivity methods can identify conductive clay zones from resistive unaltered rocks.

OTHER EXPLORATION GUIDES: Presence of siliceous sinters and association with geothermal fields. Search for alteration zones near volcanic centres and associated fault systems.

H09 - Hydrothermal Clays

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Published data on individual deposits are very incomplete. Depending on the original quartz content in the host rock, the clay content may vary from approximately 50 to 80%. Original silica content may be increased by precipitation of mobilized silica released by alteration of feldspars. Only a few hydrothermal deposits are large.

ECONOMIC LIMITATIONS: Production from this deposit type is from open pits. Physical properties and chemical composition of clay affect end use. While some deposits in New Zealand produce high-quality ceramic material, others can be used for white cement only. The high level of processing required to meet industry specifications and transportation cost to the end user are the main limiting factors for kaolin use. While local sources compete for low-value markets, high-quality products may be shipped to users overseas.

END USES: Hydrothermal kaolins are used in ceramics, for a variety of filler applications (paper, rubber, paints), refractory use and white cement manufacturing. A high content of fine silica makes hydrothermal kaolin hard and unusable for some applications; their main use is in ceramic applications. Deposits with a residual weathering overprint may have kaolin suitable for higher end uses, like industrial fillers and paper coating.

IMPORTANCE: Globally the least important of the three kaolin deposit types, but regionally may be very important (Japan, New Zealand).

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I - Vein, Breccia and Stockwork

	Profile Title	Authors
I01	Au-quartz veins	C. Ash and D.J. Alldrick, 1996
I02	Intrusion-related Au pyrrhotite veins	D.J. Alldrick, 1996
I03	Turbidite-hosted Au veins	R.H. McMillan, 1996
I04	Iron formation-hosted Au	R.H. McMillan, 1996
I05	Polymetallic veins Ag-Pb-Zn±Au	D.V. Lefebure and B.N. Church, 1996
I06	Cu±Ag quartz veins	D.V. Lefebure, 1996
I07*	Silica veins	
I08	Silica-Hg carbonate	C. Ash, 1996
I09	Stibnite veins and disseminations	A. Panteleyev, 1996
I10	Vein barite	Z.D. Hora, 1996
I11	Barite-fluorite veins	Z.D. Hora, 1996
I12*	W veins	
I13*	Sn veins and greisens	
I14	Five-element veins Ni-Co-As-Ag±(Bi, U)	D.V. Lefebure, 1996
I15	"Classical" U veins	R.H. McMillan, 1996
I16	Unconformity-associated U	R.H. McMillan, 1996
I17	Cryptocrystalline ultramafic-hosted magnesite veins	S. Paradis and G.J. Simandl, 1996

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

I01 - Au-Quartz Veins

by Chris Ash[1] and Dani Alldrick[1]

Ash, C., and Alldrick, D.J., 1996. Au-quartz veins: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 53–56.

IDENTIFICATION

SYNONYMS: Mother Lode veins, greenstone gold, Archean lode gold, mesothermal gold-quartz veins, shear-hosted lode gold, low-sulphide gold-quartz veins, lode gold.

COMMODITIES (BYPRODUCTS): Au (Ag, Cu, Sb).

EXAMPLES (British Columbia (MINFILE #) - *Canada/ International*):
Phanerozoic: Bralorne-Pioneer (092JNE001), Erickson (104P 029), Taurus (104P 012), Polaris-Taku (104K 003), Mosquito Creek (093H 010), Cariboo Gold Quartz (093H 019), Midnight (082FSW119); *Carson Hill, Jackson-Plymouth, Mother Lode district; Empire Star and Idaho-Maryland, Grass Valley district (California, USA); Alaska-Juneau, Jualin, Kensington (Alaska, USA), Ural Mountains (Russia).*
Archean: *Hollinger, Dome, McIntyre and Pamour, Timmins camp; Lake Shore, Kirkland Lake camp; Campbell, Madsen, Red Lake camp; Kerr-Addison, Larder Lake camp (Ontario, Canada), Lamaque and Sigma, Val d'Or camp (Quebec, Canada); Granny Smith, Kalgoorlie and Golden Mile (Western Australia); Kolar (Karnataka, India), Blanket-Vubachikwe (Zimbabwe, Africa).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold-bearing quartz veins and veinlets with minor sulphides crosscut a wide variety of hostrocks and are localized along major regional faults and related splays. The wallrock is typically altered to silica, pyrite and muscovite within a broader carbonate alteration halo.

TECTONIC SETTINGS:
Phanerozoic: Contained in moderate to gently dipping fault/suture zones related to continental margin collisional tectonism. Suture zones are major crustal breaks which are characterized by dismembered ophiolitic remnants between diverse assemblages of island arcs, subduction complexes and continental-margin clastic wedges.
Archean: Major transcrustal structural breaks within stable cratonic terranes. May represent remnant terrane collisional boundaries.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Veins form within fault and joint systems produced by regional compression or transpression (terrane collision), including major listric reverse faults, second and third-order splays. Gold is deposited at crustal levels within and near the brittle-ductile transition zone at depths of 6-12 km, pressures between 1 to 3 kilobars and temperatures from 200° to 400°C. Deposits may have a vertical extent of up to 2 km, and lack pronounced zoning.

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I01 - Au-Quartz Veins

AGE OF MINERALIZATION: Mineralization is post-peak metamorphism (*i.e.* late syncollisional) with gold-quartz veins particularly abundant in the Late Archean and Mesozoic.
Phanerozoic: In the North America Cordillera gold veins are post-Middle Jurassic and appear to form immediately after accretion of oceanic terranes to the continental margin. In British Columbia deposits are mainly Middle Jurassic (~ 165-170 Ma) and Late Cretaceous (~ 95 Ma). In the Mother Lode belt they are Middle Jurassic (~ 150 Ma) and those along the Juneau belt in Alaska are of Early Tertiary (~56-55 Ma).
Archean: Ages of mineralization for Archean deposits are well constrained for both the Superior Province, Canadian Shield (~ 2.68 to 2.67 Ga) and the Yilgarn Province, Western Australia (~ 2.64 to 2.63 Ga).

HOST/ASSOCIATED ROCK TYPES: Lithologically highly varied, usually of greenschist metamorphic grade, ranging from virtually undeformed to totally schistose.
Phanerozoic: Mafic volcanics, serpentinite, peridotite, dunite, gabbro, diorite, trondhjemite/plagiogranites, graywacke, argillite, chert, shale, limestone and quartzite, felsic and intermediate intrusions.
Archean: Granite-greenstone belts - mafic, ultramafic (komaitiitic) and felsic volcanics, intermediate and felsic intrusive rocks, graywacke and shale.

DEPOSIT FORM: Tabular fissure veins in more competent host lithologies, veinlets and stringers forming stockworks in less competent lithologies. Typically occur as a system of en echelon veins on all scales. Lower grade bulk-tonnage styles of mineralization may develop in areas marginal to veins with gold associated with disseminated sulphides. May also be related to broad areas of fracturing with gold and sulphides associated with quartz veinlet networks.

TEXTURE/STRUCTURE: Veins usually have sharp contacts with wallrocks and exhibit a variety of textures, including massive, ribboned or banded and stockworks with anastamosing gashes and dilations. Textures may be modified or destroyed by subsequent deformation.

ORE MINERALOGY: [Principal and *Subordinate*]: Native gold, pyrite, arsenopyrite, *galena, sphalerite, chalcopyrite, pyrrhotite, tellurides, scheelite, bismuth, cosalite, tetrahedrite, stibnite, molybdenite, gersdorffite (NiAsS), bismuthimite* (Bi_2S_2), *tetradymite* (Bi_2Te_2S).

GANGUE MINERALOGY: [Principal and *Subordinate*]: Quartz, carbonates (ferroan-dolomite, ankerite ferroan-magnesite, calcite, siderite), *albite, mariposite (fuchsite), sericite, muscovite, chlorite, tourmaline, graphite*.

ALTERATION MINERALOGY: Silicification, pyritization and potassium metasomatism generally occur adjacent to veins (usually within a metre) within broader zones of carbonate alteration, with or without ferroan dolomite veinlets, extending up to tens of metres from the veins. Type of carbonate alteration reflects the ferromagnesian content of the primary host lithology; ultramafics rocks - talc, Fe-magnesite; mafic volcanic rocks - ankerite, chlorite; sediments - graphite and pyrite; felsic to intermediate intrusions - sericite, albite, calcite, siderite, pyrite. Quartz-carbonate altered rock (listwanite) and pyrite are often the most prominent alteration minerals in the wallrock. Fuchsite, sericite, tourmaline and scheelite are common where veins are associated with felsic to intermediate intrusions.

WEATHERING: Distinctive orange-brown limonite due to the oxidation of Fe-Mg carbonates cut by white veins and veinlets of quartz and ferroan dolomite. Distinctive green Cr-mica may also be present. Abundant quartz float in overburden.

ORE CONTROLS: Gold-quartz veins are found within zones of intense and pervasive carbonate alteration along second order or later faults marginal to transcrustal breaks. They are commonly closely associated with, late syncollisional, structurally controlled intermediate to felsic magmatism. Gold veins are more commonly economic where hosted by relatively large, competent units, such as intrusions or blocks of obducted oceanic crust. Veins are usually at a high angle to the primary collisional fault zone.

- Phanerozoic: Secondary structures at a high angle to relatively flat-lying to moderately dipping collisional suture zones.
- Archean:. Steep, transcrustal breaks; best deposits overall are in areas of greenstone.

I01 - Au-Quartz Veins

ASSOCIATED DEPOSIT TYPES: Gold placers (C01, C02), sulphide manto Au (J04), silica veins (I07); iron formation Au (I04) in the Archean.

GENETIC MODEL: Gold quartz veins form in lithologically heterogeneous, deep transcrustal fault zones that develop in response to terrane collision. These faults act as conduits for CO_2-H_2O-rich (5-30 mol% CO_2), low salinity (<3 wt% NaCl) aqueous fluids, with high Au, Ag, As, (±Sb, Te, W, Mo) and low Cu, Pb, Zn metal contents. These fluids are believed to be tectonically or seismically driven by a cycle of pressure build-up that is released by failure and pressure reduction followed by sealing and repetition of the process (Sibson *et al.*, 1988). Gold is deposited at crustal levels within and near the brittle-ductile transition zone with deposition caused by sulphidation (the loss of H_2S due to pyrite deposition) primarily as a result of fluid-wallrock reactions, other significant factors may involve phase separation and fluid pressure reduction. The origin of the mineralizing fluids remains controversial, with metamorphic, magmatic and mantle sources being suggested as possible candidates. Within an environment of tectonic crustal thickening in response to terrane collision, metamorphic devolitization or partial melting (anatexis) of either the lower crust or subducted slab may generate such fluids.

COMMENTS: These deposits may be a difficult deposit to evaluate due to "nugget effect", hence the adage, “Drill for structure, drift for grade”. These veins have also been mined in British Columbia as a source of silica for smelter flux.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Au, Ag, As, Sb, K, Li, Bi, W, Te and B ± (Cd, Cu, Pb, Zn and Hg) in rock and soil, Au in stream sediments.

GEOPHYSICAL SIGNATURE: Faults indicated by linear magnetic anomalies. Areas of alteration indicated by negative magnetic anomalies due to destruction of magnetite as a result of carbonate alteration.

OTHER EXPLORATION GUIDES: Placer gold or elevated gold in stream sediment samples is an excellent regional and property-scale guide to gold-quartz veins. Investigate broad 'deformation envelopes' adjacent to regional listric faults where associated with carbonate alteration. Alteration and structural analysis can be used to delineate prospective ground. Within carbonate alteration zones, gold is typically only in areas containing quartz, with or without sulphides. Serpentinite bodies, if present, can be used to delineate favourable regional structures. Largest concentrations of free gold are commonly at, or near, the intersection of quartz veins with serpentinized and carbonate-altered ultramafic rocks.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits average 30 000 t with grades of 16 g/t Au and 2.5 g/t Ag (Berger, 1986) and may be as large as 40 Mt. Many major producers in the Canadian Shield range from 1 to 6 Mt at grades of 7 g/t Au (Thorpe and Franklin, 1984). The largest gold-quartz vein deposit in British Columbia is the Bralorne-Pioneer which produced in excess of 117 800 kilograms of Au from ore with an average grade of 9.3 g/t.

ECONOMIC LIMITATIONS: These veins are usually less than 2m wide and therefore, only amenable to underground mining.

IMPORTANCE: These deposits are a major source of the world’s gold production and account for approximately a quarter of Canada’s output. They are the most prolific gold source after the ores of the Witwatersrand basin.

I01 - Au-Quartz Veins

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I02 - Intrusion-Related Au Pyrrhotite Veins

by Dani J. Alldrick[1]

Alldrick, D.J., 1996, Intrusion-related Au pyrrhotite veins: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, p. 57–58.

IDENTIFICATION

SYNONYMS: Mesothermal veins, extension veins, transitional veins, contact aureole veins.

COMMODITIES (BYPRODUCTS): Au, Ag (Cu).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Scottie Gold (104B 034), Snip (104B 250), Johnny Mountain (104B 107), War Eagle (082FSW097), Le Roi (082FSW093), Centre Star (082FSW094); *no international examples known*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Parallel tabular to cymoid veins of massive sulphide and/or bull-quartz-carbonate with native gold, electrum and chalcopyrite are emplaced in a set of en echelon fractures around the periphery of a subvolcanic pluton. Many previous workers have included these veins as mesothermal veins.

TECTONIC SETTINGS: Volcanic arcs in oceanic and continental margin settings. Older deposits are preserved in accreted arc terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The subvolcanic setting for these deposits is transitional between the setting for subvolcanic porphyry copper systems and for subvolcanic epithermal systems.

AGE OF MINERALIZATION: Recognized examples of this 'new' deposit type are all Early Jurassic.

HOST/ASSOCIATED ROCK TYPES: Hostrocks are andesitic tuffs, turbidites or early intrusive phases around the periphery of phaneritic, locally porphyritic, granodiorite stocks and batholiths.

DEPOSIT FORM: At various deposits the form has been described as: planar, en echelon vein sets, shear veins, cymoid veins, cymoid loops, sigmoidal veins, extension veins, tension gashes, ladder veins, and synthetic Reidel shear veins. Veins vary in width from centimetres to several metres and can be traced up to hundreds of metres.

TEXTURE/STRUCTURE: Two vein types may occur independently or together. Veins may be composed of (i) massive fine-grained pyrrhotite and/or pyrite, or (ii) massive bull quartz with minor calcite and minor to accessory disseminations, knots and crystal aggregates of sulphides. These two types of mineralization may grade into each other along a single vein or may occur in adjacent, but separate veins. Some veins have undergone post-ore ductile and brittle shearing that complicates textural and structural interpretations.

ORE MINERALOGY [Principal and *subordinate]*: Native gold, electrum, pyrite, pyrrhotite, sphalerite, galena, chalcopyrite, bornite, argentite, arsenopyrite; *magnetite, ilmenite, tetrahedrite, tennantite, molybdenite, cosalite, chalcocite, tellurobismuthite, hessite, volynskite, altaite, native bismuth.*

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

I02 - Intrusion-Related Au Pyrrhotite Veins

GANGUE MINERALOGY (Principal and *subordinate):* Quartz, calcite, ankerite, chlorite, *sericite, rhodochrosite, k-feldspar, biotite.*

ALTERATION MINERALOGY: Chlorite, sericite, pyrite, silica, carbonate, rhodochrosite, biotite, epidote, K-feldspar, ankerite. Alteration occurs as narrow (4 cm) vein selvages and as moderate alteration haloes extending up to several metres into the country rock.

ORE CONTROLS: Well defined faults and shears control the mineralization. Veins are peripheral to and spatially associated with porphyritic intrusive rocks which may host porphyry copper mineralization.

GENETIC MODEL: Mineralization is syn-intrusive and synvolcanic and formed along the thermally controlled 'brittle-ductile transition envelope' that surrounds subvolcanic intrusions. Late magma movement caused local shear stress, and resultant en echelon vein sets opened and were filled by sulphides and gangue minerals precipitating from circulating hydrothermal fluids. Subsequent shearing may have superimposed foliation or brecciation onto these early-formed veins.

ASSOCIATED DEPOSIT TYPES: Typical deposits of a volcanic arc, especially those in the subvolcanic setting: porphyry Cu+/-Mo+/-Au (L04), skarns, epithermal veins and breccias (H04, H05), 'transitional' deposits (volcanogenic Cu-As-Sb-Au-Ag, L01) and surficial fumarolic hot spring (H03) and exhalative deposits.

COMMENTS: At least one of these deposits was initially interpreted as a volcanogenic exhalative sulphide lens because a massive sulphide vein was discovered in volcanic rocks with no obvious bedding.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Au, Ag, Cu. (As, Zn).

GEOPHYSICAL SIGNATURE: Electromagnetic (ABEM and VLF-EM) and magnetometer (negative anomalies or 'magnetic troughs').

OTHER EXPLORATION GUIDES: Intense prospecting swath extending from 100 metres inside the intrusive contact to 1000 metres outside the intrusive contact of a prospective (sub-volcanic Early Jurassic) pluton. Detailed soil geochemistry and detailed ground geophysics could be designed to investigate this same area. Small, 'hairline' mineralized fractures are good proximal indicators of a nearby major vein. Increased alteration intensity could also be a good proximal indicator, but this is a more subtle feature. Once the vein orientation on an initial discovery is determined, additional parallel veins should be anticipated and investigated with fences of drill holes.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Gold/silver ratios are close to 1:1. Copper may be a recoverable byproduct. Typical grades are 10 to 20 g/t Au.

IMPORTANCE: The Snip gold mine is currently British Columbia’s largest gold producer and the Rossland veins are the province’s second largest gold camp.

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I03 - Turbidite-Hosted Au Veins[1]

by R.H. McMillan[2]

McMillan, R.H., 1996. Turbidite-hosted Au veins: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 59–62.

IDENTIFICATION

SYNONYMS: Saddle reefs, Bendigo-type.

COMMODITIES (BYPRODUCTS): Au (Ag, W, Sb).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Frasergold (093A 150), Valentine Mountain (092B 108), Island Mountain (093H 019), Mosquito Creek (093H 025), Sheep Creek Deposits - Reno (082FSW036), Queen (082FSW048), Kootenay Belle (082FSW044) and Gold Belt (082FSW040); *Ptarmigan, Burwash, Thompson-Ludmar and other Yellowknife district deposits (Northwest Territories, Canada), Meguma district (Nova Scotia, Canada), Bendigo and Ballarat (Victoria, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold-quartz veins, segregations, lodes and sheeted zones hosted by fractures, faults, folds and openings in anticlines, synclines and along bedding planes in turbidites and associated poorly sorted clastic sedimentary rocks.

TECTONIC SETTING: Hostrocks were deposited in submarine troughs, periarc basins, foreland basins and remnant ocean basins. The sediments were typically formed on continental margins or back-arc basins. Typically these sequences experienced one or two deformational phases with associated metamorphism.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Thick sediment sequences that have been deformed and metamorphosed; relatively few igneous rocks.

AGE OF MINERALIZATION: Archean to Tertiary; the Bendigo and Meguma districts are underlain by Early Paleozoic strata. The veins are generally considered to be related to later deformational event.

HOST/ ASSOCIATED ROCK TYPES: The predominant rock types are greywackes, siliceous wackes, shales and carbonaceous shales. Bedded cherts, iron formations, fine-grained impure carbonate rocks; minor polymictic conglomerate, tuffaceous members and minor marine volcanic flows may also be part of the stratigraphic sequence. There are younger granitic intrusions in many belts. Metamorphic grade is generally greenschist, but may reach amphibolite rank.

DEPOSIT FORM: Typically deposits are composed of multiple quartz veins up to a few metres in width that are commonly stratabound (either concordant or discordant), bedding-parallel, or discordant, and parallel to fold axial planes. Veins are variably deformed and occur as single strands, as sheeted arrays or as stockworks. Bedding-parallel veins within anticlines and synclines in the Bendigo-Ballarat and Meguma districts are commonly called saddle reefs or saddle troughs.

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[1] This deposit type overlaps with and is gradational into gold-quartz veins (I01) and also the iron formation-hosted gold veins (I04). Some classifications group these deposit types as “mesothermal veins”.

[2] Consulting Geologist, Saanich, British Columbia, Canada

I03 - Turbidite-Hosted Au Veins

TEXTURE/STRUCTURE: Veins are well defined with sharp contacts. Bedding veins can be massive or laminated (ribbon texture) with columnar structures or stylolites, while discordant veins are generally massive. Veins can be associated with a variety of structures. Most common are folded veins and saddle reefs related to anticlinal folds. Sheeted, en echelon sigmoidal veins, ladder veins, tension gashes or stockworks may be related to zones of extension or to Reidel shear structures.

ORE MINERALOGY (Principal and *Subordinate*): Native gold, pyrite, arsenopyrite, *pyrrhotite, chalcopyrite, sphalerite, galena, molybdenite, bismuth, stibnite, bournonite and other sulphosalt minerals*. Low sulphide content (<2.5%).

GANGUE MINERALOGY (Principal and *sSubordinate):* Quartz, carbonates (calcite, dolomite or ankerite), *feldspar (albite) and chlorite.*

ALTERATION: Generally not prominent, however, disseminated arsenopyrite, pyrite and tourmaline, and more pervasive silica, sericite and carbonate, may develop in wallrocks adjacent to veins.

WEATHERING: In unglaciated terrains deep weathering and alluvial recycling may produce related rich placer deposits, such as the Bendigo region.

ORE CONTROLS: A strong structural control within dilatent areas in fold crests (saddle and trough reefs), discordant veins and tension gashes. This structural control may extend to district scale alignment of deposits. In some districts the veins appear confined to a specific stratigraphic interval, often near a change in lithologies. In the Meguma district, a more subtle stratigraphic control related to the upper (pelitic) portions of individual bouma cycles as well as regionally to the upper portion of the turbidite section. In the Bendigo district there is a relationship between ore and an abundance of graphite in the adjacent wallrocks.

GENETIC MODEL: Genetic theories range from veins formed by magmatic hydrothermal fluids or metamorphogenic fluids to deformed syngenetic mineralization. Most current workers prefer the metamorphogenic-deformational or lateral secretion theories and interpret the laminations as “crack-seal” phenomena formed during episodic re-opening of the veins during their formation. Workers favoring a syngenetic origin interpret the laminations as primary layering. Structural relationships in the Meguma and Bendigo districts indicate that the veins formed contemporaneously with, or prior to the major deformational event and were metamorphically overprinted during the intrusion of Devonian batholithic granitic rocks. Late post-deformational tension veinlets are generally non-auriferous.

ASSOCIATED DEPOSIT TYPES: Placers (C01), iron formation hosted gold deposits (I04) are also mainly hosted in turbidites - some of the Northwest Territories turbidite-hosted deposits are associated with chemical sediments. In several camps, slate horizons carrying finely disseminated, very low grade gold have been reported.

COMMENTS: Although past classification schemes have not recognized this type of deposit in British Columbia, the Valentine Mountain deposit hosted in Leech River schists and Frasergold hosted in Late Triassic clastic Quesnel River Group can be included. Elsewhere, several important vein gold districts in clastic sedimentary (possibly turbiditic) rocks might also be included. For example, the Sheep Creek camp and some of the Barkerville deposits are hosted in siliceous wackes and phyllites.

I03 - Turbidite-Hosted Au Veins

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Si, Fe, S, As, B, Au and Ag generally show strong enrichment in the deposits, while Cu, Mg, Ca, Zn, Cd, Pb, Sb, W and Mn generally show moderate enrichment, and Hg, In, Li, Bi, Se, Te, Mo, F, Co and Ni may show low levels of enrichment.

GEOPHYSICAL SIGNATURE: The low sulphide content of the majority of quartz veins renders most geophysical techniques ineffective as direct exploration tools. However, airborne and ground electromagnetic and magnetic surveys and induced polarization surveys can be useful where deposits show an association with iron formation, massive sulphides or graphite.

OTHER EXPLORATION GUIDES: Standard prospecting techniques to trace mineralization directly or in float trains in glacial till, talus or other debris derived from the gold mineralization remains the most effective prospecting tool. Areas where there has been past gold production from placers are good candidates for prospecting.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Gold production from the Meguma region has come from 60 deposits at grades ranging from 8 to 50 g/t - a total of 35.13 tonnes has been produced from the district. The Bendigo field is much more significant, having produced a minimum of more than 373.3 t (12 M oz.) of non-alluvial gold from more than 40 Mt of ore since 1851 - grades ranged from a minimum of approximately 5 g/t to more than 30 g/t. The three Barkerville mines produced an aggregate of 2.75 Mt to yield 38.29 t of gold between 1933 and 1987.

ECONOMIC LIMITATIONS: Deposits such as those in the Bendigo and Barkerville districts constitute attractive exploration targets. Although the hand sorting required to recover gold from the Nova Scotia deposits would probably render them uneconomic today, new techniques such as photometric sorting might improve the economics.

IMPORTANCE: Some districts/deposits, such as Bendigo, rank as world class and remain attractive exploration targets. The limited information available about the immense Muruntau deposit suggest that it may be similar to this type.

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ACKNOWLEDGMENTS: Howard Poulsen, Chris Ash, Dani Alldrick and Andre Panteleyev reviewed the profile and provided constructive comments.

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I03 - Turbidite-Hosted Au Veins

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I04 - Iron Formation-Hosted Au[1]

by R.H. McMillan[2]

McMillan, R.H., 1996. Iron formation-hosted Au: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 63–66.

IDENTIFICATION

SYNONYM: Mesothermal veins.

COMMODITIES *(*BYPRODUCTS*)*: Au (Ag, Cu*)*.

EXAMPLES (British Columbia - *Canada/International*): No B.C. examples; *Lupin and Cullaton Lake B-Zone (Northwest Territories, Canada), Detour Lake, Madsen Red Lake, Pickle Crow, Musselwhite, Dona Lake, (Ontario, Canada), Homestake (South Dakota, USA), Mt. Morgans (Western Australia); Morro Vehlo and Raposos, Mineas Gerais (Brazil); Vubachikwe and Bar 20 (Zimbabwe); Mallappakoda, Kolar District (India).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold in crosscutting quartz veins and veinlets or as fine disseminations associated with pyrite, pyrrhotite and arsenopyrite hosted in iron-formations and adjacent rocks within volcanic or sedimentary sequences. The iron-formations may vary between carbonate-oxide iron-formation and arsenical sulphide-silicate iron-formation.

TECTONIC SETTING: In “greenstone belts” believed to be ancient volcanic arcs; and in adjacent submarine troughs.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Sedimentary and submarine volcanic sequences in a range of mutually overlapping settings ranging from turbiditic clastic sedimentary environments to distal mafic (and komatiitic) environments with associated felsic tuffaceous and intrusive porphyries.

AGE OF MINERALIZATION: Archean to Proterozoic.

HOST/ ASSOCIATED ROCK TYPES: Contained mainly within various facies of Algoma-type iron-formation and cherts, although veins may extend into other units. Associated with variolitic, tholeiitic and komatiitic volcanic and clastic (commonly turbiditic) rocks, rarely felsic volcanic and intrusive rocks. Metamorphic rank ranges from lowest greenschist to upper amphibolite facies. Silicate-facies iron-formations are associated in some cases but are generally not gold-bearing.

DEPOSIT FORM: In and near crosscutting structures, such as quartz veins, or stratiform zones within chemical sedimentary rocks. Host strata have generally been folded and deformed to varying degree, consequently the deposits may have developed in axial plane cleavage area or be thickened and remobilized in fold hinges.

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[1] This deposit type overlaps with and is gradational into gold-quartz veins (I01) and also the turbidite-hosted gold veins (I03). Some classifications group the three deposit types together as “mesothermal veins”.

[2] Consulting Geologist, Saanich, British Columbia, Canada

I04 - Iron Formation-Hosted Au

DEPOSIT FORM: In and near crosscutting structures, such as quartz veins, or stratiform zones within chemical sedimentary rocks. Host strata have generally been folded and deformed to varying degree, consequently the deposits may have developed in axial plane cleavage area or be thickened and remobilized in fold hinges.

TEXTURE/STRUCTURE: Highly variable: gold mineralization may be finely disseminated in sulphide minerals in the stratiform examples or occur as the native mineral or in sulphides in crosscutting quartz veins. Sulphidization features such as pyrite overgrowths on magnetite are present in some deposits.

ORE MINERALOGY (Principal and *subordinate*): Native Au, pyrite, arsenopyrite, magnetite, pyrrhotite, *chalcopyrite, sphalerite, galena, stibnite, rarely gold tellurides.*

GANGUE MINERALOGY (Principal and *subordinate*): Vein quartz, chert, carbonates (calcite, dolomite or ankerite), *graphite, grunerite, stilpnomelane, tourmaline, feldspar (albite).*

ALTERATION: In deposits at low metamorphic rank, carbonatization (generally ankeritic or ferroan dolomite) is generally prominent. Sulphidization (pyritization, arsenopyritization and pyrrhotitization) is common in wallrocks adjacent to crosscutting quartz veins.

WEATHERING: Highly variable: sulphide-rich, carbonate-poor deposits will produce significant gossans.

ORE CONTROLS: Mineralization is within, or near, favourable iron-formations. Most deposits occur adjacent to prominent regional structural and stratigraphic “breaks” and mineralization is often related to local structures. Contacts between ultramafic (commonly komatiitic) rocks and tholeiitic basalts or sedimentary rocks are important. All known deposits occur in Precambrian sequences, however, there are some potentially favourable chemical sediment horizons in Paleozoic rocks. Pinch outs and facies changes within geologically favourable units are important loci for ore deposition.

GENETIC MODELS: One model proposed for iron formation-hosted Au is that the mineralization may form due to deformation focusing metamorphogenic or magmatic hydrothermal fluids, from depth, into a chemically and structurally (brittle-ductile transition zone) favourable depositional environment, late in the orogenic cycle. This theory is consistent with both the crosscutting relationships and radiometric dates for the gold mineralization. Another model emphasizes a syngenetic origin for the widespread anomalous gold values, similarity of the geological environments to currently active submarine exhalative systems, and the association with chemical sedimentary strata. Replacement features could be explained as normal diagenetic features and contact areas between sulphide-rich ore and carbonate wallrock as facies boundaries.

ASSOCIATED DEPOSIT TYPES: Au-quartz veins (I01), turbidite-hosted Au-quartz veins (I03), Algoma-type iron-formations (G01).

COMMENTS: This type of deposit has not been documented in British Columbia. The closest analogy is the 900 zone on the Debbie property (092F 331) which contains gold in magnetite-jasper-sulphide-bearing bedded chert, in quartz veins and in stockworks cutting ankeritic aphyric pillow basalt. Some workers consider auriferous stratiform pyrite bodies, such as Bousquet, Doyon, and Agnico Eagle in the Canadian Shield, to be closely related to iron formation-hosted Au.

I04 - Iron Formation-Hosted Au

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Si, Fe, S, As, B, Mg, Ca, Au and Ag generally show strong enrichment in the deposits, while Cu, Zn, Cd, Pb and Mn generally show moderate enrichment.

GEOPHYSICAL SIGNATURE: Airborne and ground electromagnetic and magnetic surveys and induced polarization surveys can be very useful to detect and map the high sulphide and magnetite content of many of the deposits.

OTHER EXPLORATION GUIDES: Standard prospecting techniques to trace mineralization directly or in float trains in glacial till, talus or other debris derived from the gold mineralization remains the most effective prospecting tool. Areas with gold placers are potential targets. Exploration programs should focus on the primary depositional environment for stratiform deposits.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The more significant deposits fall in the ranges from 6 to 17 g/t Au and 1 to 5 Mt (Thorpe and Franklin, 1984). At the adjacent properties of Morro Velho and Raposos in Brazil, approximately 10 million ounces of gold have been produced at a grade of between 15 and 16 g/t since 1834. In Ontario, the Detour Lake mine contains a resource of 48 t Au and the Madsen Red Lake deposit produced 75 t, the Pickle Crow Deposits 45 tonnes and the Central Patricia 19 tonnes. At the Lupin mine 6.66 Mt of ore grading 10.63 g/t Au were produced between 1982 and the end of 1993 with remaining reserves of 5.1 Mt averaging 9.11 g/t.

ECONOMIC LIMITATIONS: The narrow veins in some deposits require selective mining techniques which are no longer highly profitable. On the other hand, deposits, such as Lupin, are sufficiently large to be mined very profitably utilizing modern mechanized equipment.

IMPORTANCE: Although attention in recent years has been focused on the large epithermal volcanic-hosted gold deposits of the circum-Pacific Belt and on Carlin-type deposits, iron-formation hosted gold deposits, such as Lupin, rank as world class and remain attractive exploration targets. For example, the Homestake mine has produced approximately 300 t of gold since starting production in 1876.

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ACKNOWLEDGMENTS: Chris Ash, Dani Alldrick, Andre Panteleyev and Howard Poulsen reviewed the profile and provided constructive comments.

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I04 - Iron Formation-Hosted Au

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I05 - Polymetallic Veins Ag-Pb-Zn±Au

by David V. Lefebure[1] and B. Neil Church[1]

Lefebure, D.V., and Church, B.N., 1996. Polymetallic veins Ag-Pb-Zn±Au: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey, Open File 1996-13, pp. 67–70.

IDENTIFICATION

SYNONYMS: Clastic metasediment-hosted silver-lead-zinc veins, silver/base metal epithermal deposits.

COMMODITIES (BYPRODUCTS): Ag, Pb, Zn (Cu, Au, Mn).

EXAMPLES (British Columbia (MINFILE # - *Canada/International*):

Metasediment host: Silvana (082FNW050) and Lucky Jim (082KSW023), Slocan-New Denver-Ainsworth district, St. Eugene (082GSW025), Silver Cup (082KNW027), Trout Lake camp; *Hector-Calumet and Elsa*, Mayo *district (Yukon, Canada), Coeur d'Alene district (Idaho, USA), Harz Mountains and Freiberg district (Germany), Pribram district (Czechoslavakia).*

Igneous host: Wellington (082ESE072) and Highland Lass - Bell (082ESW030, 133), Beaverdell camp; Silver Queen (093L 002), Duthie (093L 088), Cronin (093L127), Porter-Idaho (103P 089), Indian (104B 031); *Sunnyside and Idorado, Silverton district and Creede (Colorado, USA), Pachuca (Mexico).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sulphide-rich veins containing sphalerite, galena, silver and sulphosalt minerals in a carbonate and quartz gangue. These veins can be subdivided into those hosted by metasediments and another group hosted by volcanic or intrusive rocks. The latter type of mineralization is typically contemporaneous with emplacement of a nearby intrusion.

TECTONIC SETTINGS: These veins occur in virtually all tectonic settings except oceanic, including continental margins, island arcs, continental volcanics and cratonic sequences.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING:

Metasediment host: Veins are emplaced along faults and fractures in sedimentary basins dominated by clastic rocks that have been deformed, metamorphosed and intruded by igneous rocks. Veins postdate deformation and metamorphism.

Igneous host: Veins typically occur in country rock marginal to an intrusive stock. Typically veins crosscut volcanic sequences and follow volcano-tectonic structures, such as caldera ring-faults or radial faults. In some cases the veins cut older intrusions.

AGE OF MINERALIZATION: Proterozic or younger; mainly Cretaceous to Tertiary in British Columbia.

HOST/ASSOCIATED ROCK TYPES: These veins can occur in virtually any host. Most commonly the veins are hosted by thick sequences of clastic metasediments or by intermediate to felsic volcanic rocks. In many districts there are felsic to intermediate intrusive bodies and mafic igneous rocks are less common. Many veins are associated with dikes following the same structures.

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I05 - Polymetallic Veins Ag-Pb-Zn±Au

DEPOSIT FORM: Typically steeply dipping, narrow, tabular or splayed veins. Commonly occur as sets of parallel and offset veins. Individual veins vary from centimetres up to more than 3 m wide and can be followed from a few hundred to more than 1000 m in length and depth. Veins may widen to tens of metres in stockwork zones.

TEXTURE/STRUCTURE: Compound veins with a complex paragenetic sequence are common. A wide variety of textures, including cockade texture, colloform banding and crustifications and locally druzy. Veins may grade into broad zones of stockwork or breccia. Coarse-grained sulphides as patches and pods, and fine-grained disseminations are confined to veins.

ORE MINERALOGY [Principal and *Subordinate*]: Galena, sphalerite, tetrahedrite-tennantite, other sulphosalts including pyrargyrite, stephanite, bournonite and acanthite, native silver, chalcopyrite, pyrite, arsenopyrite, stibnite. Silver minerals often occur as inclusions in galena. Native gold and electrum in some deposits. Rhythmic compostional banding sometimes present in sphalerite. Some veins contain more chalcopyrite and gold at depth and Au grades are normally low for the amount of sulphides present.

GANGUE MINERALOGY [Principal and *Subordinate*]:

Metasediment host: Carbonates (most commonly siderite with minor dolomite, ankerite and calcite), quartz, *barite, fluorite, magnetite, bitumen*.

Igneous host: Quartz, carbonate (rhodochrosite, siderite, calcite, dolomite), *sometimes specular hematite, hematite, barite, fluorite*. Carbonate species may correlate with distance from source of hydrothermal fluids with proximal calcium and magnesium-rich carbonates and distal iron and manganese-rich species.

ALTERATION MINERALOGY: Macroscopic wall rock alteration is typically limited in extent (measured in metres or less). The metasediments typically display sericitization, silicification and pyritization. Thin veining of siderite or ankerite may be locally developed adjacent to veins. In the Coeur d'Alene camp a broader zone of bleached sediments is common. In volcanic and intrusive hostrocks the alteration is argillic, sericitic or chloritic and may be quite extensive.

WEATHERING: Black manganese oxide stains, sometimes with whitish melanterite, are common weathering products of some veins. The supergene weathering zone associated with these veins has produced major quantities of manganese. Galena and sphalerite weather to secondary Pb and Zn carbonates and Pb sulphate. In some deposits supergene enrichment has produced native and horn silver.

ORE CONTROLS: Regional faults, fault sets and fractures are an important ore control; however, veins are typically associated with second order structures. In igneous rocks the faults may relate to volcanic centers. Significant deposits restricted to competent lithologies. Dikes are often emplaced along the same faults and in some camps are believed to be roughly contemporaneous with mineralization. Some polymetallic veins are found surrounding intrusions with porphyry deposits or prospects.

GENETIC MODELS: Historically these veins have been considered to result from differentiation of magma with the development of a volatile fluid phase that escaped along faults to form the veins. More recently researchers have preferred to invoke mixing of cooler, upper crustal hydrothermal or meteoric waters with rising fluids that could be metamorphic, groundwater heated by an intrusion or expelled directly from a differentiating magma. Any development of genetic models is complicated by the presence of other types of veins in many districts. For example, the Freiberg district has veins carrying F-Ba, Ni-As-Co-Bi-Ag and U.

COMMENTS: Ag-tetrahedrite veins, such as the Sunshine and Galena mines in Idaho, contain very little sphalerite or galena. These may belong to this class of deposits or possibly the five-element veins. The styles of alteration, mineralogy, grades and different geometries can usually be used to distinguish the polymetallic veins from stringer zones found below syngenetic massive sulphide deposits.

I05 - Polymetallic Veins Ag-Pb-Zn±Au

ASSOCIATED DEPOSIT TYPES:

- Metasediment host: Polymetallic mantos (M01).
- Igneous host: May occur peripheral to virtually all types of porphyry mineralization (L01, L03, L04, L05, L06, L07, L08) and some skarns (K02, K03).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Zn, Pb, Ag, Mn, Cu, Ba and As. Veins may be within arsenic, copper, silver, mercury aureoles caused by the primary dispersion of elements into wallrocks or broader alteration zones associated with porphyry deposit or prospects.

GEOPHYSICAL SIGNATURE: May have elongate zones of low magnetic response and/or electromagnetic, self potential or induced polarization anomalies related to ore zones.

OTHER EXPLORATION GUIDES: Strong structural control on veins and common occurrence of deposits in clusters can be used to locate new veins.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual vein systems range from several hundred to several million tonnes grading from 5 to 1500 g/t Ag, 0.5 to 20% Pb and 0.5 to 8% Zn. Average grades are strongly influenced by the minimum size of deposit included in the population. For B.C. deposits larger than 20 000 t the average size is 161 000 t with grades of 304 g/t Ag, 3.47 % Pb and 2.66 % Zn. Copper and gold are reported in less than half the occurrences, with average grades of 0.09 % Cu and 4 g/t Au.

ECONOMIC LIMITATIONS: These veins usually support small to medium-size underground mines. The mineralization may contain arsenic which typically reduces smelting credits.

IMPORTANCE: The most common deposit type in British Columbia with over 2 000 occurrences; these veins were a significant source of Ag, Pb and Zn until the 1960s. They have declined in importance as industry focused more on syngenetic massive sulphide deposits. Larger polymetallic vein deposits are still attractive because of their high grades and relatively easy benefication. They are potential sources of cadmium and germanium.

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ACKNOWLEDGEMENTS: Georges Beaudoin and Don Sangster are thanked for their suggestions to improve the profile.

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I06 - Cu-Ag Quartz Veins

by David V. Lefebure

Lefebure, D.V., 1996. Cu±Ag quartz veins: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 71–73.

IDENTIFICATION

SYNONYMS: Churchill-type vein copper, vein copper

COMMODITY (BYPRODUCTS): Cu (Ag, rarely Au).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Davis-Keays (094K 012, 050), Churchill Copper (Magnum, 094K 003), Bull River (082GNW002), Copper Road (092K 060), Copper Star (092HNE036), Copper Standard (092HNE079), Rainbow (093L 044); *Bruce Mines and Crownbridge (Ontario, Canada), Blue Wing and Seaboard (North Carolina, USA), Matahambre (Cuba), Inyati (Zimbabwe), Copper Hills (Western Australia), Tocopilla area (Chile), Burgas district (Bulgaria), Butte (Montana, USA), Rosario (Chile).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Quartz-carbonate veins containing patches and disseminations of chalcopyrite with bornite, tetrahedrite, covellite and pyrite. These veins typically crosscut clastic sedimentary or volcanic sequences, however, there are also Cu quartz veins related to porphyry Cu systems and associated with felsic to intermediate intrusions.

TECTONIC SETTINGS: A diversity of tectonic settings reflecting the wide variety of hostrocks including extensional sedimentary basins (often Proterozoic) and volcanic sequences associated with rifting or subduction-related continental and island arc settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Veins emplaced along faults; they commonly postdate major deformation and metamorphism. The veins related to felsic intrusions form adjacent to, and are contemporaneous with, mesozonal stocks.

AGE OF MINERALIZATION: Any age; can be much younger than hostrocks.

HOST/ASSOCIATED ROCK TYPES: Cu-Ag quartz veins occur in virtually any rocks although the most common hosts are clastic metasediments and mafic volcanic sequences. Mafic dikes and sills are often spatially associated with metasediment-hosted veins. These veins are also found within and adjacent to felsic to intermediate intrusions.

DEPOSIT FORM: The deposits form simple to complicated veins and vein sets which typically follow high-angle faults which may be associated with major fold sets. Single veins vary in thickness from centimetres up to tens of metres. Major vein systems extend hundreds of metres along strike and down dip. In some exceptional cases the veins extend more than a kilometre along the maximum dimension.

TEXTURE/STRUCTURE: Sulphides are irregularly distributed as patches and disseminations. Vein breccias and stockworks are associated with some deposits.

I06 - Cu-Ag Quartz Veins

ORE MINERALOGY (Principal and *subordinate*):
Metasediment and volcanic-hosted: Chalcopyrite, pyrite, chalcocite*; bornite, tetrahedrite, argentite, pyrrhotite, covellite, galena*.
Intrusion-related: Chalcopyrite, bornite, chalcocite, pyrite, pyrrhotite; *enargite, tetrahedrite-tennantite, bismuthinite, molybdenite, sphalerite, native gold and electrum.*

GANGUE MINERALOGY (Principal and *subordinate)*: Quartz and carbonate (calcite, dolomite, ankerite or siderite); *hematite, specularite, barite*.

ALTERATION MINERALOGY: Wallrocks are typically altered for distances of centimetres to tens of metres outwards from the veins.
Metasediment and volcanic-hosted: The metasediments display carbonatization and silicification. At the Churchill and Davis-Keays deposits, decalcification of limy rocks and zones of disseminated pyrite in roughly stratabound zones are reported. The volcanic hostrocks exhibit abundant epidote with associated calcite and chlorite.
Intrusion-related: Sericitization, in places with clay alteration and chloritization.

WEATHERING: Malachite or azurite staining; silicified linear “ridges”.

ORE CONTROLS: Veins and associated dikes follow faults. Ore shoots commonly localized along dilational bends within veins. Sulphides may occur preferentially in parts of veins which crosscut carbonate or other favourable lithologies. Intersections of veins are an important locus for ore.

GENETIC MODEL: The metasediment and volcanic-hosted veins are associated with major faults related to crustal extension which control the ascent of hydrothermal fluids to suitable sites for deposition of metals. The fluids are believed to be derived from mafic intrusions which are also the source for compositionally similar dikes and sills associated with the veins. Intrusion-related veins, like Butte in Montana and Rosario in Chile, are clearly associated with high-level felsic to intermediate intrusions hosting porphyry Cu deposits or prospects.

ASSOCIATED DEPOSIT TYPES:
Metasediment and volcanic-hosted: Possibly related to sediment-hosted Cu (E04) and basaltic Cu (D03).
Intrusion-related: High sulphidation (H04), copper skarns (K01), porphyries (L01?, L03, L04) and polymetallic veins (I05).

COMMENTS: Cu-Ag quartz veins are common in copper metallogenetic provinces; they often are more important as indicators of the presence of other types of copper deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High Cu and Ag in regional silt samples. The Churchill-type deposits appear to have very limited wallrock dispersion of pathfinder elements; however, alteration halos of silica and carbonate addition or depletion might prove useful. Porpyhyry-related veins exhibit many of the geochemical signatures of porphyry copper systems.

GEOPHYSICAL SIGNATURE: Large veins with conductive massive sulphides may show up as electromagnetic conductors, particularly on ground surveys. Associated structures may be defined by ground magnetic, very low frequency or electromagnetic surveys. Airborne surveys may identify prospective major structures.

OTHER EXPLORATION GUIDES: Commonly camp-scale or regional structural controls define a dominant orientation for veins.

I06 - Cu-Ag Quartz Veins

ECONOMIC FACTORS

GRADE AND TONNAGE: Typically range from 10 000 to 100 0000 t with grades of 1 to 4% Cu, nil to 300 g/t Ag. The Churchill deposit has reserves of 90 000 t of 3 % Cu and produced 501,019 t grading 3% Cu and the Davis-Keays deposit has reserves of 1,119,089 t grading 3.43 % Cu. The Big Bull deposit has reserves of 732,000 t grading 1.94% Cu. The intrusion-related veins range up to millions of tonnes with grades of up to 6% Cu. The Butte veins in Montana have produced several hundred million tonnes of ore with much of this production from open-pit operations.

ECONOMIC LIMITATIONS: Currently only the large and/or high-grade veins (usually associated with porphyry deposits) are economically attractive.

IMPORTANCE: From pre-historic times until the early 1900s, high-grade copper veins were an important source of this metal. With hand sorting and labour intensive mining they represented very attractive deposits.

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ACKNOWLEDGEMENTS: This deposit profile represents the results of a literature review. It benefited from comments by David Sinclair and Vic Preto.

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I08 - Silica-Carbonate Hg

by Chris Ash[1]

Ash, C., 1996. Silica-carbonate Hg: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 75–76.

IDENTIFICATION

SYNONYMS: Serpentinite-type, listwanite-type.

COMMODITIES (BYPRODUCTS): Hg (Sb, Ag, Au).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Pinchi (093K 049), Bralorne Takla (093N 008), Eagle Mercury (092JNE062), Silverquick (092O 017), Manitou (092O 023); *New Almaden, New Idria (California, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cinnabar occurs associated with quartz and carbonate alteration in zones of intense brittle fracturing at relatively shallow levels along major fault zones. Commonly occur in areas of active geothermal systems.

TECTONIC SETTING: Within orogenic belts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: At shallow levels within high-angle, regional-scale, deep crustal faults marked by the presence of ophiolitic ultramafic rocks. Typically at brittle faulted contacts between competent lithologies, *e.g.* carbonate-altered ultramafics, limestone, etc. Locally associated with recent volcanism and hot spring activity. Mercury deposits in B.C. are concentrated along several north to northwest-trending, high-angle transcurrent fault zones which border oceanic terranes. These include the Pinchi, Yalakom and Germansen faults.

AGE OF MINERALIZATION: Eocene to Recent?

HOST/ASSOCIATED ROCK TYPES: Serpentinite, limestone, siltstone, graywacke, conglomerate, mafic volcanic rocks.

DEPOSIT FORM: Deposits are typically highly irregular within major fault zones.

TEXTURE/STRUCTURE: Thin discontinuous stringers or fracture and cavity coatings in areas of shattering and brecciation along major faults.

ORE MINERALOGY [Principal and subordinate]: Cinnabar, *native mercury (quicksilver), metacinnabar, livingstonite* ($HgSb_4S_9$).

GANGUE MINERALOGY: Pyrite, marcasite, quartz, carbonate, limestone, serpentinite.

ALTERATION MINERALOGY: "Silica-carbonate rock" or "listwanite/listvenite", magnesite, ankerite, dolomite, quartz, chalcedony, kaolinite, sericite (fuchsite/mariposite).

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I08 - Silica-Carbonate Hg

WEATHERING: Mineralized areas display distinctive limonite stain due to the presence of iron carbonates.

ORE CONTROLS: High-angle fault zones marginal to accreted oceanic terranes. In general, grade of ore increases with fracture density in the hostrock.

GENETIC MODELS: Deposits form where relatively low temperature (between 100º and 200ºC) CO_2-H_2O aqueous fluids (< 2 wt. % chlorine), charged with Hg migrate upward along permeable fault zones and precipitate cinnabar in fractured hostrocks at shallow levels due to cooling and mixing with meteoric water. At this stage a vapour phase evolves which emanates from hot springs at surface.

ASSOCIATED DEPOSIT TYPES: Sb veins.

COMMENTS: Due to the liquid state of this metal, mercury is generally measured in “flasks” and quoted in dollar value per flask. Flasks are standard steel containers that hold 76 lb (about 2.5 L) of the liquid metal.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Hg, Sb (Cu, Zn).

GEOPHYSICAL SIGNATURE: Not generally applicable.

OTHER EXPLORATION GUIDES: Soil, stream sediment and geobotanical sampling for Hg has proven successful. The spatial association of hot springs with major fault zones associated with ophiolitic ultramafic rocks.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits of this type are typically less than 1 Mt, but may be up to several million tonnes with mercury grades averaging 0.5% and ranging from 0.2 to 0.8%.

ECONOMIC LIMITATIONS: The low grade of these deposits relative to other mercury deposit types, extreme fluctuations in the price of the metal, and inherent pollution problems are all factors in the economics of this deposit type.

IMPORTANCE: Although historically significant as a source of mercury, these deposits are not currently mined due to their low grades and small size relative to the much larger and richer Almaden-type mercury deposits. The only significant past-producing mines in B.C. include the Pinchi and Bralorne Takla. Both deposits are along the Pinchi fault.

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I08 - Silica-Carbonate Hg

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I09 - Stibnite Veins and Disseminations

by Andre Panteleyev[1]

Pantelyev, A., 1996. Stibnite veins and disseminations: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 77–79.

IDENTIFICATION

SYNONYMS: Quartz-stibnite, simple antimony, syntectonic stibnite, mesothermal Sb-Au.

COMMODITIES (BYPRODUCTS): Sb (Au).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): a) Veins - Minto (092JNE075) and Congress (092JNE029), Bridge River area; Snowbird (093K 036); *Becker-Cochran (Yukon, Canada), Lake George (New Brunswick, Canada), Beaver Brook (Newfoundland, Canada*), *Murchison Range deposits (South Africa), Caracota and numerous other deposits in the Cordillera Occidental (Bolivia).*
b) Disseminated - *Caracota and Espiritu Santo (Bolivia), many deposits (Turkey).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stibnite veins, pods, disseminations and stibnite-bearing quartz and quartz-carbonate veins occur in, or adjacent to, shears, fault zones and brecciated rocks in sedimentary or metasedimentary sequences.

TECTONIC SETTING: Any orogenic area, particularly where large-scale fault structures are present

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Fault and shear zones, notably in fault splays and fault-related breccias in which shallow to intermediate-depth hydrothermal systems have been operative.

AGE OF MINERALIZATION: Deposits range from Paleozoic to Tertiary age.

HOST/ASSOCIATED ROCK TYPES: Any faulted lithologies with a wide variety of rock types; sedimentary and metasedimentary rocks are commonly present. British Columbia deposits tend to be near major fault zones with attendant serpentinized mafic and ultramafic rocks.

DEPOSIT FORM: Stibnite occurs in veins; also as fine to coarse grains in sheared or brecciated rocks. Some stibnite is disseminated in carbonate-altered wallrocks surrounding structures and may form within pressure shadows at crests of folds. Massive stibnite-pyrite replacements which may form pods or lenses up to tens of metres long, are relatively uncommon, but are sources of rich ore.

TEXTURE/STRUCTURE: Veins have fine to coarse-grained, commonly euhedral bladed crystals of stibnite, quartz and carbonate in masses of stibnite. Quartz and quartz-carbonate gangue minerals range from fine to coarse grained, commonly with white ‘bull quartz” present.

ORE MINERALOGY [Principal and *Subordinate*]: Stibnite, pyrite, arsenopyrite; *sphalerite, galena, tetrahedrite, marcasite, chalcopyrite, jamesonite, berthierite, gold, cinnabar, scheelite, argentite and sulphosalt minerals*. Other than stibnite, the overall sulphide content of the veins is low.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

I09 - Stibnite Veins and Disseminations

GANGUE MINERALOGY [Principal and *Subordinate*]: Quartz, calcite, dolomite; *chalcedony, siderite, rare barite and fluorite.*

ALTERATION MINERALOGY: Quartz-carbonate envelopes on veins; some silicification, sericite, and intermediate argillic alteration. Chlorite, serpentinization and 'listwanite' (quartz-carbonate-talc-chromian mica-sulphide minerals) green-coloured alteration may be present when mafic and untramafic rocks are involved.

WEATHERING: Stibnite weathers to various oxides of yellowish (kermsite) or whitish (cerrantite or stibiconite) colour.

ORE CONTROLS: Fissure, shear zones and breccia associated with faults. Some open-space filling in porous rocks and structurally induced openings (joints, saddle reefs, ladder veins). Minor replacement in limestones.

GENETIC MODEL: The origin is not well documented. Deposits are spatially closely associated with, and in many ways resemble, low-sulphide gold-quartz (mesothermal) veins. Their (mutual) origin is thought to be from dilute, CO_2 rich fluids generated by metamorphic dehydration. Structural channelways focus the hydrothermal fluids during regional deformation. Some deposits are associated with felsic intrusive bodies, for example a Tertiary rhyolite plug at Becker-Cochran deposit, Yukon, and with porphyry W-Mo mineralization in granitic rocks at the Lake George Sb deposit, New Brunswick.

ASSOCIATED DEPOSIT TYPES: Quartz-carbonate gold (low-sulphide gold-quartz vein or I01), polymetallic vein Ag-Pb-Zn (I05), epithermal Au-Ag: low sulphidation (H05), hot spring Au-Ag (H03), Sn-W vein (??), W-Mo porphyry (L07); silica-carbonate Hg (I08), placer gold (C01, C02); possibly Carlin-type sediment-hosted Ag-Ag (E03).

COMMENTS: Occurrences of typical stibnite veins in the Bridge River gold camp in British Columbia were thought to be part of a regional deposit zoning pattern. The deposits are now known to be younger than the gold deposits by about 15-20 Ma. Farther north, the Snowbird deposit near Stuart Lake, has been shown to be Middle Jurassic in age by radiometric dating and is interpreted to be related to large-scale crustal structures. This deformation possibly involves the Pinchi fault system in which the largest known mercury deposits in the province are found.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sb, As, Au, Ag, Pb, Zn; locally W or Hg.

GEOPHYSICAL SIGNATURE: VLF surveys may detect faults.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Veins typically have high grade but small ore shoots; the disseminated deposits are also relatively small. Grade-tonnage data from 81 "typical" vein deposits (predominately, hand-sorted ore from USA mines) is 180 t with 35 % Sb; 10 % of the deposits contained > 1 g/t Au and > 16 g/t Ag. The disseminated deposits average 88 000 t with an average grade of 3.6 % Sb.

ECONOMIC LIMITATIONS: Antimony is a low-priced metal so only high-grade deposits are mined. Deposits (veins and disseminations) containing gold offer the best potential.

IMPORTANCE: Bolivia, Turkey and China dominate the antimony market; Cordilleran production will likely be only as a byproduct from precious metal bearing deposits.

I09 - Stibnite Veins and Disseminations

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I10 - Vein Barite

by Z.D. Hora[1]

Hora, Z.D., 1996. Vein barite: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 81-84.

IDENTIFICATION

SYNONYM: Epigenetic vein barite.

COMMODITIES (BYPRODUCTS): Barite (Ag, Pb, Zn, Cu*)*.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Parson (082N 002), Brisco (082KNE013), Fireside (094M 003); *Matchewan (Ontario, Canada), Lake Ainslie (Nova Scotia, Canada), Collier Cove (Newfoundland, Canada), Nevada, Montana, Virginia, Pennsylvania, Georgia in USA; Bonarta, Jbel Ighoud (Morocco); Wolfach, Bad Lauterberg (Germany); Roznava (Slovakia), China*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Barite in fissure-filling voids resulting from mechanical deformation, including dilatant zones along faults and folds, gash fractures, joints and bedding planes; also in shear and breccia zones along faults.

TECTONIC SETTINGS: Highly varied, frequently but not exclusively at or near the margins of basins with sedex or Kuroko type deposits, or abrupt deep basin-platform sedimentation facies change.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Highly varied; almost any type of sedimentary, metamorphic or intrusive rocks. Veins associated with regional faults and lineaments, also the breccia zones along the margins of rift basins. In carbonate rocks, barite may fill karst cavities and collapse structures and forms manto-like replacement orebodies.

AGE OF MINERALIZATION: Precambrian to Tertiary.

HOST/ASSOCIATED ROCK TYPES: Any sedimentary, metamorphic or even igneous rocks.

DEPOSIT FORM: Tabular/lenticular bodies and breccias, collapse breccias and related cavity fills, veins with manto-type orebodies in carbonate hostrocks. The veins are several hundreds up to over 1000 m in length and sometimes up to 20 m thick. Some veins are mined to the depth of 500 m from surface.

TEXTURE/STRUCTURE: Massive, banded, brecciated. Texture typical of high-level veins, occasional druzy textures.

ORE MINERALOGY (Principal and *Subordinate)*: Barite, *fluorspar, siderite, Pb-Zn-Cu sulphides*.

GANGUE MINERALOGY: (Principal and *Subordinate*): *Quartz, calcite, siderite, witherite, barytocalcite, cinnabar, pyrite*.

ALTERATION MINERALOGY: Insignificant.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

I10 - Vein Barite

WEATHERING: Barite float and detrital fragments as a result of physical weathering.

ORE CONTROLS: Dominant structural control with veins along faults, fractures, and shear zones, sometimes related to dilatant zones in major fault systems.

GENETIC MODEL: Epithermal barite veins, with or without sulphides, are common at and near the margins of rift basins, both in continental and continental margin settings. The veins and orebodies occur as open-space fillings in high-angle faults or fractures in sedimentary rocks or adjacent crystalline rocks, sills, and irregular and stratabound collapse structures or mantos. The source fluids are inferred to have been brines of moderate salinity (10 to 16 equivalent weight percent NaCl) and temperatures of 100º to 250º C. Pre-existing fractures and faults are apparently important in localizing the veins and orebodies. Multiple mineralizing episodes and several pulses of fluid migration are evident in many of the vein systems.

ASSOCIATED DEPOSIT TYPES: Polymetallic veins (I05) and replacement deposits (J01, E10-E12), sedex (E14) and Kuroko massive sulphide (G06) deposits, carbonatites (N03).

COMMENTS: This type of barite vein is distinct from barite associated with fluorspar veins. These (fluorspar-barite) veins may have, at least in part, a different barium source and are closely associated with Mississippi Valley type deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ba, Sr, sometimes Hg, Ag, Pb, Zn and Cu anomalies in soils and silts.

GEOPHYSICAL SIGNATURE: Linear gravity highs over large veins.

OTHER EXPLORATION GUIDES: Clastic barite in stream sediments, both in sand and silt fractions.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Most deposits in production are selectively mining high-grade orebodies with over 80% barite. The deposit size varies from a few thousand up to some 3 Mt. Brisco mine produced approximately 250,000 tonnes during its life; Parson is expected to produce close to 1 Mt.

ECONOMIC LIMITATIONS: Dependant on the end use. White, high-purity barite is suitable for filler and chemical applications and can be mined from even very small deposits. Drilling mud is a lower priced grade and, if processing is required to reach the required 4.2 specific gravity, only large deposits can be operated successfully. Even a small amount of contamination by siderite or witherite may make the barite unusable in drilling mud applications. Barite which is contaminated with small quantities (ppm) of heavy metals like Pb, Zn, Cu and Hg may result in environmental problems with disposal of spent drilling mud.

END USES: Drilling muds, fillers, chemicals, radiation shields, speciality glass and ceramics.

IMPORTANCE: Probably the main source of barite worldwide, but in North America very subordinate to bedded barite deposits.

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I10 - Vein Barite

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I11 - Vein Fluorite-Barite

by Z.D. Hora[1]

Hora, Z.D., 1996. Vein fluorite-barite: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 85–88.

IDENTIFICATION

SYNONYM: Epigenetic fluorite/barite vein.

COMMODITIES (BYPRODUCTS): Fluorite, sometimes barite (occasionally Pb, Zn, and Cu. Some fluorites contain the recoverable Be minerals bertrandite and phenacite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Rock Candy (082ESE070), Eaglet (093A 046), Rexspar (82M 007); *Madoc (Ontario, Canada); St. Lawrence (Newfoundland, Canada); Nevada, Utah, New Mexico (USA); Nabburg-Woelsendorf, Ilmenau, Schoenbrunn (Germany); Torgola, Prestavel, Gerrai (Italy); Auvergne, Morvan (France); Mongolia, China*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Fluorite and barite fill dilatant shear and breccia zones along faults and folds, gash fractures, joints and bedding planes as well as stockworks. In carbonate rocks, the fissure veins are frequently associated with replacement bodies and mantos. Fluorite veins commonly show affinities with barite veins and may grade into polymetallic veins with barite gangue.

TECTONIC SETTINGS: Highly varied - but in terrains underlain by sialic crust. In young orogenic belts: postorogenic and lateorogenic granite intrusions or rift-related alkaline rocks (from syenites to nepheline syenites to carbonatites) may be associated with fluorite veins. In old orogenic belts: proximity of major tectonic zones, grabens, tensional rifts and lineaments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Highly varied, sometimes linked to volatile-rich intrusives of alkaline to granite composition. In the Cordillera, topaz rhyolites, particularly, are associated with many fluorite veins.

AGE OF MINERALIZATION: Precambrian to Tertiary; in B.C. Devono-Mississippian (Rexspar), Cretaceous (Eaglet) and Tertiary (Rock Candy).

HOST/ASSOCIATED ROCK TYPES: Any sedimentary, metamorphic or igneous rock; in volcanic environment usually associated with topaz rhyolite.

DEPOSIT FORM: Tabular or lenticular bodies and breccias or stockworks and breccia pipes. The veins are usually 1-5 m thick and may be over a 1000 m long. Some particularly large veins in Sardinia are 3 km in length; the Torgola vein is reported to be 20 m thick. Some vein deposits were mined up to 500 m below surface, however the usual mining depth is 200 to 300 m down the dip from the outcrop.

TEXTURE/STRUCTURE: Massive, banded, brecciated. Drusy textures are common, fluorspar may be coarse grained or fine grained with radiating texture. Banding of different colour varieties of fluorspar is very common (coontail type). Bands of barite in fluorite, or young silica replacement of fluorspar along the cleavage and crystal borders are common features.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

I11 - Vein Fluorite-Barite

ORE MINERALOGY [Principal and *Subordinate*]: Fluorite, barite, *celestite, barytocalcite, galena, sphalerite, chalcopyrite, pyrite, adularia or K-feldspar, red jasper*. *Dark purple fluorite may contain uraninite. Bertrandite and other Be minerals are sometimes accessory components*. Fluorite is often the main or even only vein mineral.

GANGUE MINERALOGY: (Principal and *Subordinate)* Gangue may be a variety of minerals such as quartz, chalcedony, jasper, barite and Ca-Fe-Mg carbonates. Barite commonly varies in colour from yellow to pink or red; jasper may have a red colour due to finely dispersed hematite.

ALTERATION MINERALOGY: Kaolinization and/or silicification of wallrocks, sometimes pervasive potassic alteration (Eaglet, Rexspar); occasionally montmorillonite in wallrocks.

WEATHERING: Physical weathering mostly; in high-sulphide environment fluorspar may be dissolved by sulphuric acid. Floats of vein quartz with voids after weathered out fluorspar crystals are a common feature.

ORE CONTROLS: Faults, fractures, shear zones. Vertical zoning of veins is a common feature, but not very well understood.

GENETIC MODEL: Fluorite veins are generally found in the proximity of continental rifts and lineaments. In young orogenic belts fluorite can be linked to late or postorogenic granitic intrusions, particularly in areas of sialic crust. Rift-related alkaline intrusions are also linked to some fluorite veins. In old orogenic belts, fluorite veins are also in fracture zones within major faults and graben structures which facilitated circulation of mineralized fluids far from original fluorine source. Fluorite is precipitated from fluids by cooling low-pH solutions or by an increase in the pH of acid ore fluids. The fluids usually have a high Na/K ratio.

ASSOCIATED DEPOSIT TYPES: Pb-Zn veins (I05), carbonatite plugs, dikes and sills with Nb-REE (N02); Sn-W greisen (I13), F/Be deposits (Spor Mountain), Pb-Zn mantos (J01) and Mississippi Valley type deposits (E10, E11, E12).

COMMENT: End uses of fluorine chemicals in aluminium and chemical industries are very sensitive to P and As contents of only a few ppm.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: F in stream waters.

GEOPHYSICAL SIGNATURE: Sometimes gamma radiometric anomalies as an expression of potassic alteration or uranium content in certain types of fluorite.

OTHER EXPLORATION GUIDES: Fault control in some districts; regional silicified zones and major quartz veins.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Past producers reported grades in general between 30% and 60% fluorite, with occasional higher grade orebodies. The deposit size varies; up to 6 Mt. In B.C., Eaglet reported 1.8 million tonnes of 15% CaF_2, Rexspar 1.4 million tonnes of 23% CaF_2.

ECONOMIC LIMITATIONS: In recent years, shipments of high quality fluorspar from China, at very low prices, resulted in the collapse of most fluorspar production centres worldwide.

I11 - Vein Fluorite-Barite

END USES: Metallurgy of aluminum and uranium, fluorine chemicals, flux in iron and steel metallurgy, glass and ceramics.

IMPORTANCE: Main source of fluorspar worldwide. In B.C., the Rock Candy mine produced 51,495 t of 68% CaF_2 between 1918 and 1929.

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I14 - Five-Element Veins Ag-Ni-Co-As+/-(Bi, U)

by David V. Lefebure[1]

Lefebure, D.V., 1996. Five element veins Ag-Ni-Co-As+/-(Bi,U): In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey, Open File 1996-13, pp. 89–92.

IDENTIFICATION

SYNONYMS: Five-element (Ni-Co-As-Ag-Bi) veins, nickel-cobalt-native silver veins, Cobalt-type silver-sulpharsenide veins, Ni-Co-Bi-Ag-U (As) association, Ag-As (Ni, Co, Bi) veins, Schneeberg-Joachimsthal-type.

COMMODITY (BYPRODUCTS): Ag, Ni, Co, Bi, U (barite).

EXAMPLES (British Columbia - Canada/International): No B.C. examples; *Beaver and Timiskaming, Cobalt camp, Silver Islet, Thunder Bay district (Ontario, Canada), Echo Bay and Eldorado (Port Radium, Northwest Territories, Canada), Black Hawk district (New Mexico, USA), Batopilas district (Mexico), Johanngeogenstadt, Freiberg and Jachymov, Erzgebirge district (Germany), Konsberg-Modum (Norway).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Native silver occurs in carbonate veins associated with a variety of mineral assemblages that are rare in other settings, such as Ni-Co-Fe arsenides, Ni-Co-Fe-Sb sulpharsenides and bismuth minerals. In many cases only some of these minerals are present, although the best examples of this deposit type typically contain significant Ag-Ni-Co. In some deposits uraninite (pitchblende) is an important ore mineral.

TECTONIC SETTINGS: Virtually all occur in areas underlain by continental crust and are generally believed to have formed late or post-tectonically. In some cases the veins appear related to basinal subsidence and continental rifting.

DEPOSTIONAL ENVIRONMENT/GEOLOGICAL SETTING: Veins are believed to be emplaced at shallow depths in a continental setting along high-angle fault systems.

AGE OF MINERALIZATION: Proterozoic or younger, can be much younger than hostrocks.

HOST/ASSOCIATED ROCK TYPES: Found in a wide variety of hostrocks, although metasediments, metamorphosed intrusive rocks and granitic sequences are the most common. Diabase sills are an important host in the Cobalt camp and a number of the deposits in the Thunder Bay region are within a gabbro dike.

DEPOSIT FORM: Simple veins and vein sets. Veins vary from centimetre to metre thicknesses, typically changing over distances of less than tens of metres. Most vein systems appear to have limited depth extent, although some extend more than 500 m.

TEXTURE/STRUCTURE: Commonly open space filling with mineral assemblages and textures commonly due to multiple episodes of deposition. Sulphides are irregularly distributed as massive pods, bands, dendrites, plates and disseminations. The mineralization is more common near the interesections of veins or veins with crosscutting faults. Fragments of wallrock are common in some veins. Faults may be filled with graphite-rich gangue, mylonite or breccia.

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I14 - Five-Element Veins Ag-Ni-Co-As+/-(Bi, U)

ORE MINERALOGY (Principal and *subordinate*): Native silver associated with Ni-Co arsenide minerals (rammelsbergite, safflorite, niccolite, cloanthite, maucherite), sulpharsenides of Co, Ni, Fe and Sb, native bismuth, bismuthinite, argentite, ruby silver, pyrite and uraninite (pitchblende). *Chalcopyrite, bornite and chalcocite are common, but minor, constituents of ore. Minor to trace galena, tetrahedrite, jamesonite, cosalite, sphalerite, arsenopyrite and rare pyrrhotite.* In many deposits only a partial mineral assemblage occurs containing a subset of the many elements which may occur in these veins. These veins are characterized by the absence of gold.

GANGUE MINERALOGY (Principal and *subordinate*): Calcite and dolomite are usually associated directly with native silver mineralization; quartz, *jasper, barite and fluorite are less common.* The carbonate minerals are common in the cores of some veins.

ALTERATION MINERALOGY: Not conspicuous or well documented. In the Cobalt camp calcite and chlorite alteration extends 2-5 cm from the vein, approximately equivalent in width to the vein.

WEATHERING: No obvious gossans because of the low sulphide content; locally “cobalt bloom”.

ORE CONTROLS: Veins occupy faults which often trend in only one or two directions in a particular district. Ore shoots may be localized at dilational bends within veins. Intersections of veins are an important locus for ore. Possibly five-element veins are more common in Proterozoic rocks.

GENETIC MODEL: In regions of crustal extension, faults controled the ascent of hydrothermal fluids to suitable sites for deposition of metals at depths of approximately 1 to 4 km below surface. The fluids were strongly saline brines at temperatures of 150° to 250° C, which may have been derived from late-stage differentiation of magmas, convective circulation of water from the country rocks driven by cooling intrusive phases or formation brines migrating upwards or towards the edge of sedimentary basins. Sulphide-rich strata (including Fahlbands) and carbonaceous shales in the stratigraphy are potential sources of the metals. Deposition occurs where the fluid encounters a reductant or structural trap.

ASSOCIATED DEPOSIT TYPES: ‘Classical’ U veins (I15), polymetallic veins (I05). In the Great Bear Lake area there are associated “giant” quartz veins with virtually no other minerals.

COMMENTS: Several Co-Ag-Ni-Bi veins are found in the Rossland Camp in British Columbia. These may be five-element veins, however, they also contain the atypical elements Au and Mo.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: The rare association of anomalous values of Ag with Ni, Co, Bi, U and As in rock samples is diagnostic.

GEOPHYSICAL SIGNATURE: Associated structures may be defined by ground magnetic or VLF-EM surveys. Airborne surveys may identify prospective major structures. Gamma ray scintillometers and spectrometers can be used to detect the uraninite-bearing veins in outcrop or in float trains in glacial till, frost boils, talus or other debris.

OTHER EXPLORATION GUIDES: Commonly camp or regional structural controls will define a dominant orientation for veins.

I14 - Five-Element Veins Ag-Ni-Co-As+/-(Bi, U)

ECONOMIC FACTORS

GRADE AND TONNAGE: Typically range from tens of thousands of tonnes to a few hundreds of thousands of tonnes with very high grades of silver (more than 1000 g/t Ag for Canadian mines, with grades up to 30,000 g/t Ag).

IMPORTANCE: There has been no significant production from a native silver vein in British Columbia, however, these veins have historically been an important Canadian and world source of Ag and U with minor production of Co. More recently the narrow widths and discontinuous nature of these veins has led to the closure of virtually all mines of this type.

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I15 - “Classical” U Veins

by R.H. McMillan[1]

McMillan, R.H., 1996. “Classical” U Veins: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 93–96.

IDENTIFICATION

SYNONYMS: Pitchblende veins, vein uranium, intragranitic veins, perigranitic veins.

COMMODITIES (BYPRODUCTS): U (Bi, Co, Ni, As, Ag, Cu, Mo).

EXAMPLES (British Columbia - *Canada/International*): In the Atlin area structurally controlled scheelite-bearing veins host uranium at the Purple Rose (104N 005), Fisher (104N 084), Dixie (104N 086), Cy 4 (104N 087), Mir 3 (104N 113) and IRA (104N 110) occurrences; *Ace Fay-Verna and Gunnar, Beaverlodge area (Saskatchewan, Canada), Christopher Island-Kazan-Angikuni district, Baker Lake area (Northwest Territories, Canada), Millet Brook (Nova Scotia, Canada), Schwartzwalder (Colorado, USA), Xiazhuang district (China), La Crouzille area, Massif Central and Vendee district, Armorican Massif (France), Jachymov and Pribram districts (Czeck Republic), Shinkolobwe (Shaba province, Zaire).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Pitchblende (Th-poor uraninite), coffinite or brannerite with only minor amounts of associated metallic minerals in a carbonate and quartz gangue in veins. These deposits show affinities with, and can grade into, five-element veins which have significant native silver, Co-Ni arsenides, Bi or other metallic minerals.

TECTONIC SETTING: Postorogenic continental environments, commonly associated with calcalkaline felsic plutonic and volcanic rocks. “Red beds” and sediments of extensional successor basins are common in the host sequence. The economic deposits appear confined to areas underlain by Proterozoic basement rocks.

DEPOSITIONAL ENVIRONMENT: Ore is deposited in open spaces within fracture zones, breccias and stockworks commonly associated with major or subsidiary, steeply dipping fault systems.

AGE OF MINERALIZATION: Proterozoic to Tertiary. None are older than approximately 2.2 Ga, the time when the atmosphere evolved to the current oxygen-rich condition.

HOST/ ASSOCIATED ROCK TYPES: A wide variety of hostrocks, including granitic rocks, commonly peraluminous two-mica granites and syenites, felsic volcanic rocks, and older sedimentary and metamorphic rocks. The uranium-rich veins tend to have an affinity to felsic igneous rocks. Some veins are closely associated with diabase and lamprophyre dikes and sills.

DEPOSIT FORM: Orebodies may be tabular or prismatic in shape generally ranging from centimetres up to a few metres thick and rarely up to about 15 m. Many deposits have a limited depth potential of a few hundred metres, however, some deposits extend from 700 m up to 2 km down dip. Disseminated mineralization is present within the alteration envelopes in some deposits.

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I15 - “Classical” U Veins

TEXTURE/STRUCTURE: Features such as drusy textures, crustification banding, colloform, botryoidal and dendritic textures are common in deposits which have not undergone deformation and shearing. The veins typically fill subsidiary dilatant zones associated with major faults and shear zones. Mylonites are closely associated with the St. Louis fault zone at the Ace-Fay-Verna mines.

ORE MINERALOGY (Principal and *Subordinate*): Pitchblende (Th-poor uraninite), coffinite, *uranophane, thucolite, brannerite, iron sulphides, native silver, Co-Ni arsenides and sulpharsenides, selenides, tellurides, vanadinites, jordesite, chalcopyrite, galena, sphalerite, native gold and platinum group elements*. Some deposits have a “simple” mineralogy of with only pitchblende and coffinite. Those veins with the more complex mineralogy are often interpreted to have had the other minerals formed at an earlier or later stage.

GANGUE MINERALOGY (Principal and *Subordinate*): Carbonates (calcite and dolomite), quartz (often chalcedonic), hematite, *K-feldspar, albite, muscovite, fluorite, barite.*

ALTERATION: Chloritization, hematization, feldspathization. A few of the intrusive-hosted deposits are surrounded by desilicated, porous feldspar-mica rock called “episyenite” in the La Crouzille area of France and “sponge-rock” at the Gunnar mine in Saskatchewan. In most cases the hematization is due to oxidation of ferrous iron bearing minerals in the wallrocks during mineralization. The intense brick-red hematite adjacent to some high-grade uranium ores is probably due to loss of electrons during radioactive disintegration of uranium and its daughter products.

WEATHERING: Uranium is highly soluble in the +6 valence state above the water table. It will re-precipitate as uraninite and coffinite below the water table in the +4 valence state in the presence of reducing agents such as humic material or carbonaceous “trash”. Some uranium phosphates, vanadinites, sulphates, silicates and arsenates are semi-stable under oxidizing conditions, consequently autunite, torbernite, carnotite, zippeite, uranophane, uranospinite and numerous other secondary minerals may be found in the zone of oxidation , particularly in arid environments.

ORE CONTROLS: Pronounced structural control related to dilatant zones in major fault systems and shear zones. A redox control related to the loss of electrons associated with hematitic alteration and precipitation of uranium is evident but not completely understood. Many deposits are associated with continental unconformities and have affinities with unconformity-associated U deposits (I16).

GENETIC MODEL: Vein U deposits are generally found in areas of high uranium Clarke, and generally there are other types of uranium deposits in the vicinity. The veins might be best considered polygenetic. The U appears to be derived from late magmatic differentiates of granites and alkaline rocks with high K or Na contents. Uranium is then separated from (or enriched within) the parent rocks by aqueous solutions which may originate either as low-temperature hydrothermal, connate or meteoric fluids. Current opinion is divided on the source of the fluids and some authors prefer models that incorporate mixing fluids. Studies of carbon and oxygen isotopes indicate that the mineralizing solutions in many cases are hydrothermal fluids which have mixed with meteoric water. In some cases temperatures exceeding 400° C were attained during mineralization. The uranium minerals are precipitated within faults at some distance from the source of the fluids. Wallrocks containing carbonaceous material, sulphide and ferromagnesian minerals are favourable loci for precipitation of ore. Radiometric age dating indicates that mineralization is generally significantly younger than the associated felsic igneous rocks, but commonly close to the age of associated diabase or lamprophyre dikes.

ASSOCIATED DEPOSIT TYPES: Stratabound, disseminated and pegmatitic occurrences of U are commonly found in older metamorphic rocks. Sandstone-hosted U deposits (D05) are commonly found in associated red-bed supracrustal strata, and surficial deposits (B08) in arid or semi-arid environments.

I15 - “Classical” U Veins

COMMENTS: The Cretaceous to Tertiary Surprise Lake batholith in the Atlin area hosts several fracture-controlled veins with zeunerite, kasolite, autunite and Cu, Ag, W, Pb and Zn minerals. These include the Purple Rose, Fisher, Dixie, Cy 4, Mir 3 and IRA. Southwest of Hazelton, Th-poor uraninite associated with Au, Ag, Co-Ni sulpharsenides, Mo and W is found in high-temperature quartz veins within the Cretaceous Rocher Deboule granodiorite stock at the Red Rose, Victoria and Rocher Deboule properties. Although the veins are past producers of Au, Ag, Cu and W, no U has been produced.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Uranium and sometimes any, or all, of Ni, Co, Cu, Mo, Bi, As and Ag are good pathfinder elements which can be utilized in standard stream silt, lake bottom sediment and soil surveys. Stream and lake bottom water samples can be analyzed for U and Ra. In addition, the inert gases He and Ra can often be detected above a U-rich source in soil and soil gas surveys, as well as in groundwater and springs.

GEOPHYSICAL SIGNATURE: Standard prospecting techniques using sensitive gamma ray scintillometers and spectrometers to detect U mineralization in place or in float trains in glacial till, frost boils, talus or other debris remains the most effective prospecting methods. Because most deposits do not contain more than a few percent metallic minerals, electromagnetic and induced polarization surveys are not likely to provide direct guides to ore. VLF-EM surveys are useful to map the fault zones which are hosts to the veins. Magnetic surveys may be useful to detect areas of magnetite destruction in hematite-altered wallrocks.

OTHER EXPLORATION GUIDES: Secondary uranium minerals are typically yellow and are useful surface indicators.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits are generally small (< 100 000 t) with grades of 0.15% to 0.25% U, however districts containing several deposits can aggregate considerable tonnages. The large Ace-Fay-Verna system produced 9 Mt of ore at an average grade of 0.21% U from numerous orebodies over a length of 4.5 km. and a depth of 1500 m. Gunnar produced 5 Mt of ore grading 0.15% U from a single orebody. The Schwartzwalder mine in Colorado was the largest “hardrock” uranium mine in the United States, producing approximately 4 300 tonnes U, and contains unmined reserves of approximately the same amount.

ECONOMIC LIMITATIONS: The generally narrow mining widths and grades of 0.15% to 0.25% U rendered most vein deposits uneconomic after the late 1960s discovery of the high-grade unconformity-type deposits.

IMPORTANCE: This type of deposit was the source of most of the world’s uranium until the 1950s. By 1988, significant production from veins was restricted to France, with production of 3 372 tonnes U or 9.2% of the world production for that year.

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I15 - "Classical" U Veins

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I16 - Unconformity-Associated U

by R.H. McMillan[1]

McMillan, R.H., 1998, Unconformity-associated U: mineral deposit profile I16 In: Geological Fieldwork 1997, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey, Paper 1998-1, p. 24G1-24G4.

IDENTIFICATION

SYNONYMS: Unconformity-veins, unconformity-type uranium, unconformity U.

COMMODITIES (*BYPRODUCTS*): U (*Au, Ni)*.

EXAMPLES (British Columbia - *Canada/International*): None in British Columbia; *Rabbit Lake, Key Lake, Cluff Lake, Midwest Lake, McClean Lake, McArthur River, Cigar Lake and Maurice Bay in the Athabasca uranium district (Saskatchewan, Canada), Lone Gull (Kiggavik) and Boomerang Lake, Thelon Basin district (Northwest Territories, Canada), Jabiluka, Ranger, Koongarra and Nabarlek, Alligator River district (Northern Territory, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Uranium minerals, generally pitchblende and coffinite, occur as fracture and breccia fillings and disseminations in elongate, prismatic-shaped or tabular zones hosted by sedimentary/metasedimentary rocks located below, above or across a major continental unconformity.

TECTONIC SETTING: Intracratonic sedimentary basins.

GEOLOGICAL SETTING/DEPOSITIONAL ENVIRONMENT: Structurally-prepared and porous zones within chemically favourable reduced or otherwise reactive strata.

AGE OF MINERALIZATION: Mid-Proterozoic, however, there is potential for younger deposits.

HOST/ ASSOCIATED ROCK TYPES: Shelf facies metasedimentary (amphibolite or granulite facies) rocks of Early Proterozoic age (graphitic or sulphide-rich metapelites, calcsilicate rocks and metapsammites), regolith and overlying continental sandstones of Middle Proterozoic age. The Early Proterozoic hostrocks in many cases are retrograded amphibolite-facies metamorphic rocks on the flanks of Archean gneiss domes. The overlying continental sandstones are well sorted fluviatile quartz-rich psammites; generally with a clay or siliceous matrix and red or pale in colour. Dikes and sills, commonly diabases and lamprophyres, occur in some districts.

DEPOSIT FORM: Orebodies may be tabular, pencil shaped or irregular in shape extending up to few kilometres in length. Most deposits have a limited depth potential below the unconformity of less than a 100 m, however, the Jabiluka and Eagle Point deposits are concordant within the Lower Proterozoic host rocks and extend for several hundred metres below the unconformity.

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I16 - Unconformity-Associated U

TEXTURE/STRUCTURE: Most deposits fill pore space or voids in breccias and vein stockworks. Some Saskatchewan deposits are exceptionally rich with areas of "massive" pitchblende/coffinite. Features such as drusy textures, crustification banding, colloform, botryoidal and dendritic textures are present in some deposits.

ORE MINERALOGY (Principal and *subordinate*): Pitchblende (Th-poor uraninite), coffinite, uranophane, thucolite, brannerite, iron sulphides, *native gold, Co-Ni arsenides and sulpharsenides, selenides, tellurides, vanadinites, jordesite (amorphous molybedenite), vanadates, chalcopyrite, galena, sphalerite, native Ag and PGE*. Some deposits are "simple" with only pitchblende and coffinite, while others are "complex" and contain Co-Ni arsenides and other metallic minerals.

GANGUE MINERALOGY: Carbonates (calcite, dolomite, magnesite and siderite), chalcedonic quartz, sericite (illite) chlorite and dravite (tourmaline).

ALTERATION: Chloritization, hematization, kaolinization, illitization and silicification. In most cases hematization is due to oxidation of ferrous iron bearing minerals in the wallrocks caused by oxidizing mineralizing fluids, however, the intense brick-red hematite adjacent to some high grade uranium ores is probably due to loss of electrons during radioactive disintegration of U and its daughter products. An interesting feature of the clay alteration zone is the presence of pseudomorphs of high grade metamorphic minerals, such as cordierite and garnet, in the retrograded basement wallrock.

WEATHERING: Uranium is highly soluble in the +6 valence state above the water table. It will re-precipitate as uraninite and coffinite below the water table in the +4 valence state in the presence of a reducing agents such as humic material or carbonaceous "trash". Some U phosphates, vanadates, sulphates, silicates and arsenates are semi-stable under oxidizing conditions, consequently autunite, torbernite, carnotite, zippeite, uranophane, uranospinite and numerous other secondary minerals may be found in the near-surface zone of oxidation, particularly in arid environments.

ORE CONTROLS: A pronounced control related to a mid-Proterozoic unconformity and to favourable stratigraphic horizons within Lower Proterozoic hostrocks - these strata are commonly graphitic. Local and regional fault zones that intersect the unconformity may be important features. Generally found close to basement granitic rocks with a high U clarke.

GENETIC MODEL: The exceptionally rich ore grades which characterize this type of deposit point to a complex and probably polygenetic origin. Some form of very early preconcentration of U in the Archean basement rocks seems to have been important. The hostrocks are commonly Lower Proterozoic in age, and are comprised of metamorphosed rocks derived from marginal marine and near-shore facies sedimentary rocks which may have concentrated U by syngenetic and diagenetic processes. Although the behaviour of U under metamorphic and ultrametamorphic conditions is poorly known, it is possible that U could have been mobilized in the vicinity of Archean gneiss domes and anatectic granites and precipitated in pegmatites and stratabound deposits as non-refractory, soluable uraninite. Supergene enrichment in paleo regoliths, that now underlie the unconformity, may have been an important process in the additional concentration of U. Typically the overlying quartz-rich fluviatile sandstones have undergone little deformation, but are affected by normal and reverse faults that are probably re-activated basement faults. In Saskatchewan, these faults carry ore in several deposits and in others appear to have facilitated the transport of U within the cover sandstones. Hydrothermal/diagenetic concentration of U through mixing of oxidized basinal and reduced basement fluids appear to have resulted in exceptional concentrations of U and Ni. There is a possibility that radiogenic heat developed in these extremely rich deposits may have been instrumental in heating formational fluids and in remobilizing the metals upwards above the deposit. Diabase dikes occur in faults near some deposits and some researchers have suggested that the dikes might have provided the thermal energy that remobilized and further upgraded U concentrations. Recent age dates of the Mackenzie dikes in the Athabaska district do not support this interpretation.

I16 - Unconformity-Associated U

ASSOCIATED DEPOSIT TYPES: Sandstone-hosted U deposits (D05) are found in associated supracrustal quartz-rich arenites. Stratabound disseminated or skarn deposits, such as the Dudderidge Lake and Burbidge Lake deposits (Saskatchewan) and pegmatitic occurrences are commonly present in the metamorphosed basement rocks. In arid or semi-arid environments surficial deposits may be present in the overburden. The deposits have affinities to “Classical” U veins (I15).

COMMENTS: Virtually all the known unconformity-associated uranium deposits are found in the Athabasca Basin, Alligator River district and Thelon Basin. In British Columbia favourable target areas for this style of mineralization might be found within strongly metamorphosed shelf-facies Proterozoic strata near gneiss domes, particularly in plateau areas near the Cretaceous-Tertiary paleosurface. The Midnite mine, located 100 km south of Osoyoos, British Columbia, may be an unconformity-associated U deposit. The ore comprises fracture-controlled and disseminated U and alteration minerals (pitchblende, coffinite as well as autunite and other secondary minerals) within metamorphosed shelf-facies pelitic and calcareous rocks of the Precambrian Togo Formation. Production and reserves prior to closing at the Midnite mine are estimated at approximately 3.9 Mt grading 0.12% U.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: U, Ni, Co, As, Pb and Cu are good pathfinder elements which can be utilized in standard stream silt, lake bottom sediment and soil surveys. Stream and lake bottom water samples can be analyzed for U and Ra. In addition, the inert gases He and Ra can often be detected above a U-rich source in soil and soil gas surveys, as well as in groundwater and springs. In Saskatchewan, lithogeochemical signatures have been documented in Athabasca Group quartz arenites for several hundred metres directly above the deposits and in glacially dispersed boulders located “down ice” - the signature includes boron (dravite) and low, but anomalous U as well as K and/or Mg clay mineral alteration (illite and chlorite).

GEOPHYSICAL SIGNATURE: During early phases of exploration of the Athabasca Basin, airborne and ground radiometric surveys detected near surface uranium deposits and their glacial dispersions. Currently, deeply penetrating ground and airborne elecromagnetic surveys are used to map the graphitic argillites associated with most deposits. The complete spectrum of modern techniques (gravity, magnetic, magneto-telluric, electromagnetic, VLF-EM, induced polarization, resistivity) can be utilized to map various aspects of structure as well as hostrock and alteration mineral assemblages in the search for deep targets.

OTHER EXPLORATION GUIDES: Standard techniques using sensitive gamma ray scintillometers to detect mineralization directly in bedrock or in float trains in glacial till, frost boils, talus or other debris derived from U mineralization remain the most effective prospecting methods.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits are generally small, but can be exceedingly high-grade, up to several percent U. The median size for 36 Saskatchewan and Australian deposits is 260 000 t grading 0.42% U (Grauch and Mosier, 1986). Some deposits are exceptionally high grade such as the Key Lake Gaertner-Deilmann deposits (2.5 Mt @ 2.3% U), Cigar Lake deposits (900 000 t @ 12.2% U) and McArthur River (1.4 Mt @ 12.7% U).

ECONOMIC LIMITATIONS: Since the early 1980s, average ore grades have generally risen to exceed 0.25% U. Problems related to the pervasively clay-altered wallrocks and presence of radon gas and other potentially dangerous elements associated with some high-grade uranium deposits in Saskatchewan have resulted in exceptionally high mining costs in some cases.

IMPORTANCE: The Rabbit Lake mine, opened in 1975, was the first major producer of unconformity-type ore. Since then the proportion of the world’s production to come from unconformity-type deposits has increased to 33% and is expected to rise in the future.

I16 - Unconformity-Associated U

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ACKNOWLEDGMENTS: Nirankar Prasad and Sunil Gandhi of the Geological Survey of Canada, Larry Jones of the British Columbia Geological Survey and Jim Murphy of Uranerz Exploration reviewed the profile and provided many constructive comments.

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I17 - Cryptocrystalline Ultramafic-Hosted Magnesite Veins

by S. Paradis[1] and G.J. Simandl[2]

Paradis, S., and Simandl, G.J., 1996. Cryptocrystalline ultramafic-hosted magnesite veins: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 97–100.

IDENTIFICATION

SYNONYMS: Cryptocrystalline or microcrystalline magnesite, "Kraubath-type" magnesite, "Bone magnesite", "amorphous magnesite".

COMMODITY: Magnesite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Sunny (092O 014), Pinchi Lake (093K 065); *Chalkidiky area (Greece); Kraubath (Austria); Eskisehir and Kutaya (Turkey)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cryptocrystalline magnesite deposits are related to faults cutting ultramafic rocks. Individual deposits may consist of two styles of mineralization. Steeply dipping magnesite veins, up to several metres thick, pass gradually upward into magnesite stockworks or breccias cemented by magnesite.

TECTONIC SETTINGS: Typically in allochthonous serpentinized ophiolitic sequences or along structural breaks within ultramafic layered complexes; however, other settings containing ultramafic rocks are also favourable.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The veins are emplaced along steep faults in near surface environments.

AGE OF MINERALIZATION: Post-date ultramafic hostrock that is Archean to Paleogene in age.

HOST/ASSOCIATED ROCK TYPES: Serpentinite, peridotite; other olivine-rich rocks of the typical ophiolitic sequence and layered ultramafic complexes.

DEPOSIT FORM: Stockworks, branching veins, single veins up to several metres in thickness, and less frequently, irregular masses. The maximum reported vertical extent is 200 m. The footwall of the deposits is commonly sharp and slickensided and coincides with a fault zone. The hangingwall of the fault contains magnesite veins and/or magnesite-cemented breccias.

TEXTURE/STRUCTURE: Magnesite is commonly cryptocrystalline and massive with microscopic "pinolite" texture; rarely granular, fibrous, or "cauliflower-like".

ORE MINERALOGY: Magnesite.

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I17 - Cryptocrystalline Ultramafic-Hosted Magnesite Veins

GANGUE MINERALOGY [Principal and *subordinate*]: Serpentine, chlorite, talc, iron oxides, dolomite, hydromagnesite, calcite, sepiolite, quartz, opal, chalcedony and quartz in vugs.

ALTERATION MINERALOGY: Ultramafic rocks hosting magnesite are typically, but not always, intensely serpentinised. Alteration minerals are dolomite, quartz, montmorillonite, sepiolite, talc, goethite and deweylite.

WEATHERING: Varies with climatic environment, gangue mineralogy and iron content in the crystal structure of magnesite.

ORE CONTROLS: Tectonic boundaries or major fault breaks, secondary fault zones parallel to major breaks cutting ultramafic rocks. The large magnesite-cemented breccias are commonly located below paleoerosional or erosional surfaces. Most contacts between the magnesite and country rock are sharp and irregular.

GENETIC MODEL: Two hypothesis competing to explain the origin of these deposits are:
1) hypogene low-temperature, CO_2-metasomatism of ultramafic rocks (Pohl, 1991):
2) low-temperature descending, meteoric waters containing biogenic CO_2 and enriched in Mg^{2+} (Zachmann and Johannes, 1989).

ASSOCIATED DEPOSIT TYPES: Lateritic deposits, chromite deposits and platinum deposits occur in the same geological environment but are not genetically related. The ultramafic-hosted talc deposits (M07) may be genetically related.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: May contain above average Hg.

GEOPHYSICAL SIGNATURE: N/A

OTHER EXPLORATION GUIDES: Favourable lithologic and structural setting. Commonly underlying unconformities. Near-surface (or paleosurface) magnesite deposits may be capped by stratiform magnesite, dolomite-quartz (chalcedony) or chert zones. Some of these deposits are overlain by laterites. Boulder tracing in glaciated areas.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: For stockwork (upper) portions of the deposits the grades vary from 20 to 40% magnesite and reserves ranging from hundreds of thousands to several millions tonnes are typical. The deeper vein portions of these deposits have higher grades and may be almost monomineralic. A representative specimen of Greek cryptocrystalline magnesite is reported to contain 46.6 % MgO, 49.9 % CO_2, 0.70 % SiO_2, 1.35 % CaO, 0.85% Fe_2O_3 and Al_2O_3 combined (Harben and Bates, 1990).

ECONOMIC LIMITATIONS: These deposits compete for markets with sediment-hosted sparry magnesite deposits and seawater or brine-derived magnesia compounds. In the past, European refractory producers preferred cryptocrystalline magnesite over sparry magnesite, because of its higher density and lower iron, manganese and boron content. Recently this advantage was largely lost by availability of excellent quality sparry magnesite exports and by new technical developments in the refractory industry. Natural magnesite-derived compounds in general have to compete with seawater and brine-derived magnesia compounds.

END USES: Source of wide variety of magnesia products used mainly in refractories, cements, insulation, chemicals, fertilizers, fluxes and environmental applications.

I17 - Cryptocrystalline Ultramafic-Hosted Magnesite Veins

IMPORTANCE: These deposits are substantially smaller and, in the case of stockwork-type portions, lower grade than sparry magnesite deposits.

COMMENTS: Stockworks and adjacent ultramafic hostrock are capped in some cases by sediments that may contain nodular magnesite concretions or magnesite/hydromagnesite layers and/or dolomite, quartz or chert. It is not well established if sediments are of sabkha /playa affinity or directly linked to fluids that formed stockworks and veins.

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J - Manto

	Profile Title	Authors
J01	Polymetallic manto Ag-Pb-Zn	J.L. Nelson, 1996,
J02	Manto and stockwork Sn	W.D. Sinclair, 1996
J03*	dropped - Mn veins and replacements	
J04*	Sulphide manto Au	

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

J01 - Polymetallic Mantos Ag-Pb-Zn[1]

by J.L. Nelson[2]

Nelson, J.L., 1996, Polymetallic mantos Ag-Pb-Zn: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, p. 101–103.

IDENTIFICATION

SYNONYM: Polymetallic replacement deposits.

COMMODITIES (*BYPRODUCTS*): Ag, Pb, Zn (Au, Cu, Sn, Bi).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Midway (104O038) and Bluebell (082ENW026); *Sa Dena Hes (Yukon, Canada), Prairie Creek (Northwest Territories, Canada), Leadville District (Colorado, USA), East Tintic District (Utah, USA), Eureka District (Nevada, USA), Santa Eulalia, Naica, Fresnillo, Velardena, Providencia (Mexico)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Irregularly shaped, conformable to crosscutting bodies, such as massive lenses, pipes and veins, of sphalerite, galena, pyrite and other sulphides and sulphosalts in carbonate hosts; distal to skarns and to small, high-level felsic intrusions.

TECTONIC SETTING: Intrusions emplaced into miogeoclinal to platformal, continental settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: In northern Mexico, most are hosted by Cretaceous limestones. In Colorado, the principal host is the Devonian-Mississippian Leadville limestone; in Utah, the Permian Torweap Formation hosts the Deer Trail deposit. The most favourable hosts in the Canadian Cordillera are massive Lower Cambian and Middle Devonian limestones, rather than impure carbonates and dolostone-quartzite units.

AGE OF MINERALIZATION: Canadian Cordilleran examples are Cretaceous to Eocene age; those in the southern Cordillera are typically Tertiary.

HOST/ASSOCIATED ROCK TYPES: Hosted by limestone and dolostone. The carbonates are typically within a thick sediment package with siliciclastic rocks that is cut by granite, quartz monzonite and other intermediate to felsic hypabyssal, porphyritic lithologies. There may be volcanic rocks in the sequence, or more commonly above, which are related to the intrusive rocks.

DEPOSIT FORM: Irregular: mantos (cloak shaped), lenses, pipes, chimneys, veins; in some deposits the chimneys and/or mantos are stacked.

TEXTURE/STRUCTURE: Massive to highly vuggy, porous ore. In some cases fragments of wallrock are incorporated into the ore. Some deposits have breccias: fragments of wallrock and also of sulphide ore within a sulphide matrix.

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[1] Manto is a Spanish mining term denoting a blanket-shaped orebody which is widely used for replacement deposits found in Latin America. It has been used to describe the orientation of individual lenses and also to describe a class of orebodies.

[2] British Columbia Geological Survey, Victoria, British Columbia, Canada

J01 - Polymetallic Mantos Ag-Pb-Zn

ORE MINERALOGY (Principal and *Subordinate*): Sphalerite, galena, pyrite, chalcopyrite, marcasite; *arsenopyrite, pyrargyrite/proustite, enargite, tetrahedrite, geocronite, electrum, digenite, jamesonite, jordanite, bournonite, stephanite, polybasite, rhodochrosite, sylvanite, calaverite*. Chimneys may be more Zn-rich, Pb-poor than mantos.

GANGUE MINERALOGY (Principal and *subordinate*): Quartz, barite, gypsum; minor *calc-silicate minerals*.

ALTERATION MINERALOGY: Limestone wallrocks are commonly dolomitized and/or silicified, whereas shale and igneous rocks are argillized and chloritized. Jasperoid occurs in some U.S. examples.

WEATHERING: In some cases, a deep oxidation zone is developed. Mexican deposits have well developed oxide zones with cassiterite, hematite, Cu and Fe carbonates, cerrusite and smithsonite.

ORE CONTROLS: The irregular shapes of these deposits and their occurrence in carbonate hosts emphasize the importance of ground preparation in controlling fluid channels and depositional sites. Controlling factors include faults, fault intersections, fractures, anticlinal culminations, bedding channelways (lithologic contrasts), karst features and pre-existing permeable zones. In several districts karst development associated with unconformities is believed to have led to development of open spaces subsequently filled by ore. Some deposits are spatially associated with dikes.

GENETIC MODEL: Manto deposits are high-temperature replacements as shown by fluid inclusion temperatures in excess of 300° C, high contents of Ag, presence of Sn, W and complex sulphosalts, and association with skarns and small felsic intrusions. They are the product of pluton-driven hydrothermal solutions that followed a variety of permeable pathways, such as bedding, karst features and fracture zones.

ASSOCIATED DEPOSIT TYPES: There is probably an overall outward gradation from granite-hosted Mo-Cu porphyries (L04), endoskarns (K) and possibly W- and Sn mineralization (L06?), through exoskarns (K01, K02) and into Ag-Pb-Zn veins (I05), mantos (J01) and possibly Carlin-type sediment-hosted Au-Ag deposits (E03). Only some, or possibly one, of these types may be manifest in a given district. Ag-Pb-Zn vein, manto and skarn deposits belong to a continuum which includes many individual occurrences with mixed characteristics.

COMMENTS: In the Canadian Cordillera, most mantos are located in the miogeocline (western Ancestral North America, Cassiar and Kootenay terranes) because of the essential coincidence of abundant carbonate and presence of felsic intrusions. There is one known example in Upper Triassic limestone on Vancouver Island, which probably formed distal to skarn mineralization related to a mid-Jurassic intrusion. Most mantos in the Canadian Cordillera are Late Cretaceous to Eocene, coinciding with the age of youngest, F-rich intrusions of the A-type (anorogenic) granite suite. In Mexico, mantos are associated with Early to mid-Tertiary volcanic rocks and cogenetic intrusions. The Colorado deposits may be associated with Tertiary sills, and the Deer Trail deposit in Utah has given a 12 Ma sericite age.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: B.C.: Ag, Pb, Zn, Sn in stream silts, F in waters. U.S.: Districts show outward zoning from Cu-rich core through broad Ag-Pb zone to Zn-Mn fringe. Locally Au, As, Sb, Bi. Jasperoid contains elevated Ba + Ag.

GEOPHYSICAL SIGNATURE: Subsurface granite associated with Midway deposit has negative magnetic signature.

OTHER EXPLORATION GUIDES: Concentration of Ag-Pb-Zn vein deposits in or near carbonates.

J01 - Polymetallic Mantos Ag-Pb-Zn

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits average about a million tonnes grading tens to hundreds of grams/tonne Ag and approximately 5 to 20% combined Pb-Zn. Mexico: Santa Eulalia district produced about 24 Mt in this century, grading about 300 g/t Ag, 8% Pb, 9% Zn. U.S.: Leadville deposit mined 30 Mt 70-130 g/t Ag, 12-15% Pb-Zn. B.C.: Midway geological resource is 1 Mt grading 400 g/t Ag 7% Pb, 9.6% Zn. In many mining districts the early production came from oxidized ore zones that can have higher grades and be easier to mine.

ECONOMIC LIMITATIONS: Generally, although not always, these deposits tend to be small, highly irregular and discontinuous. The Mexican deposits have yielded large quantities of ore because, due to low labour costs, mining provided an effective and low-cost exploration tool.

IMPORTANCE: As sources of base metals, manto deposits are overshadowed on a world scale by the giant syngenetic classes such as sedimentary exhalitive and volcanogenic massive sulphides. However, because of their high precious metal contents, they provide exciting targets for small producers.

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J02 - Manto and Stockwork Sn

by W. David Sinclair[1]

Sinclair, W.D., 1996. Manto and stockwork Sn: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 105–107.

IDENTIFICATION

SYNONYMS: Replacement Sn, distal Sn skarn, Renison-type.

COMMODITIES (BYPRODUCTS): Sn (Cu, Zn, Pb, Ag, Sb, Cd, Bi, In).

EXAMPLES (British Columbia - *Canada/International*): *Renison Bell, Cleveland and Mt. Bischoff (Tasmania, Australia), Dachang and Gejiu districts (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Disseminated cassiterite occurs in massive sulphide replacement bodies in carbonate rocks and in associated veins, stockworks and breccias. Felsic intrusions are nearby, or adjacent to the deposits and may also be mineralized.

TECTONIC SETTING: Postorogenic underlain by cratonic crust containing carbonate rocks.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Carbonate rocks intruded by epizonal felsic intrusive rocks.

AGE OF MINERALIZATION: Mainly Paleozoic to Mesozoic, but other ages possible.

HOST/ASSOCIATED ROCK TYPES: Mainly limestone or dolomite; chert, pelitic and Fe-rich sediments, and volcanic rocks may also be present. Genetically-related granitic plutons and associated felsic dikes are typically F and/or B rich. They are commonly porphyritic.

DEPOSIT FORM: Variable: massive, lensoid to tabular, concordant sulphide-rich bodies in carbonate rocks; veins and irregular stockwork zones in associated rocks.

TEXTURE/STRUCTURE: Massive sulphide-rich bodies tend to follow bedding in host carbonate rocks; associated veins and stockworks include mineralized fractures, veinlets, quartz veins and breccias.

ORE MINERALOGY [Principal and *subordinate*]: Cassiterite, chalcopyrite, sphalerite and galena; *stannite, stibnite, bismuth, bismuthinite* and a wide variety of sulphosalt minerals including *jamesonite, bournonite, franckeite, boulangerite, geocronite, matildite and galenobismutite* may also be present.

GANGUE MINERALOGY [Principal and *subordinate*]: Pyrrhotite (often predominant sulphide) and/or pyrite, arsenopyrite, quartz, calcite, siderite, rhodochrosite, flourite and tourmaline.

ALTERATION MINERALOGY: Dolomite near massive sulphide bodies is typically altered to siderite, and, to a lesser extent, talc, phlogopite and quartz. Rocks hosting vein or stockwork zones may be tourmalinized. Greisen-type alteration, characterized by flourite and/or topaz, F-bearing micas and tourmaline, is best developed in and around genetically related felsic intrusive rocks.

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[1] Geological Survey of Canada, Ottawa, Ontario, Canada

J02 - Manto and Stockwork Sn

WEATHERING: Oxidation of pyrite and pyrrhotite produces limonitic gossans. Deep weathering and erosion may result in residual concentrations of cassiterite *in situ* or in placer deposits downslope or downstream.

ORE CONTROLS: Carbonate rocks in the vicinity of F and B rich felsic intrusive rocks; faults and fracture zones in the carbonates and associated rocks provide channelways and also alternate sites of deposition for ore-forming fluids.

GENETIC MODEL: Magmatic-hydrothermal. Magmatic, highly saline aqueous fluids strip Sn and other ore metals from temporally and genetically related magma. Early Sn deposition is dominantly from these magmatic fluids, mainly in response to increase in pH due to carbonate replacement. Mixing of magmatic with meteoric water during waning stages of the magmatic-hydrothermal system may result in deposition of Sn and other metals in late-stage veins and stockworks.

ASSOCIATED DEPOSIT TYPES: Sn-W skarn deposits (K06, K05), Sn-W vein deposits, Sb-Hg veins, placer deposits (C01, C02).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sn, Cu, Pb, Zn, As, Ag, Sb, Hg, F, W, Bi and In may be anomalously high in hostrocks adjacent to and overlying mineralized zones; Sb and Hg anomalies may extend as much as several hundred metres. Sn, W, F, Cu, Pb and Zn may be anomalously high in stream sediments and Sn, W, and B (tourmaline) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Massive pyrrhotite may be detected by magnetic surveys; massive sulphide zones may also be detected by electromagnetic and resistivity surveys.

OTHER EXPLORATION GUIDES: Deposits commonly occur in zoned, polymetallic districts; Sn and base metal bearing skarns and veins occur close to related intrusive rocks, carbonate-hosted Sn mantos and stockworks are at intermediate distances from the intrusive rocks, and Sb and Hg veins are the outermost deposits. Genetically related felsic intrusive rocks typically have high contents of silica (>74% SiO_2) and F (>0.1% F); tourmaline may also be present.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits are large and high grade, containing millions to tens of millions of tonnes averaging about 1% Sn. The following figures are for production plus reserves:

Renison Bell (Australia): 27 Mt at 1.1% Sn (Newnham, 1988)
Cleveland (Australia): 5.3 Mt at 0.5% Sn, 0.2% Cu (Cox and Dronseika, 1988)
Mt. Bischoff (Australia): 6.1 Mt at 0.49% Sn (Newnham, 1988)
Dachang (China): 100 Mt at 1% Sn, 3-5% combined Cu, Pb, Zn and Sb (Fu *et al*., 1993)
Gejiu (China): 100 Mt at 1% Sn, 2-5% Cu, 0.5% Pb (Sutphin *et al*., 1990)

IMPORTANCE: The large tonnage and relatively high grade of these deposits makes them attractive for exploration and development.The Renison Bell deposit in Australia and the Dachang and Gejiu deposits in China are currently major producers of tin on a world scale.

J02 - Manto and Stockwork Sn

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ACKNOWLEGEMENT: Rod Kirkham kindly reviewed this profile.

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K - Skarn

	Profile Title	Authors
K01	Cu skarns	G.E. Ray, 1995
K02	Pb-Zn skarns	G.E. Ray, 1995
K03	Fe skarns	G.E. Ray, 1995
K04	Au skarns	G.E. Ray, 1998
K05	W skarns	G.E. Ray, 1995
K06	Sn skarns	G.E. Ray, 1995
K07	Mo skarns	G.E. Ray, 1995
K08	Garnet skarns	G.E. Ray, 1999
K09	Wollastonite skarns	G.J. Simandl, S. Paradis, G. Orris and G.E. Ray, 1999

K01 - Cu Skarns

by Gerald E. Ray[1]

Ray, G.E., 1995. Cu skarns: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 59–60.

IDENTIFICATION

SYNONYMS: Pyrometasomatic and contact metasomatic copper deposits.

COMMODITIES (BYPRODUCTS): Cu (Au, Ag, Mo, W, magnetite)

EXAMPLES (British Columbia - *Canada/International*): Craigmont (092ISE 035), Phoenix (082ESE 020), Old Sport (092L 035), Queen Victoria (082FSW 082); *Mines Gaspé deposits (Québec, Canada), Ruth, Mason Valley and Copper Canyon (Nevada, USA), Carr Fork (Utah, USA), Ok Tedi (Papua New Guinea), Rosita (Nicaragua*).

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cu-dominant mineralization (generally chalcopyrite) genetically associated with a skarn gangue (includes calcic and magnesian Cu skarns).

TECTONIC SETTING: They are most common where Andean-type plutons intrude older continental-margin carbonate sequences. To a lesser extent (but important in British Columbia), they are associated with oceanic island arc plutonism.

AGE OF MINERALIZATION: Mainly Mesozoic, but may be any age. In British Columbia they are mostly Early to mid-Jurassic.

HOST/ASSOCIATED ROCK TYPES: Porphyritic stocks, dikes and breccia pipes of quartz diorite, granodiorite, monzogranite and tonalite composition, intruding carbonate rocks, calcareous volcanics or tuffs. Cu skarns in oceanic island arcs tend to be associated with more mafic intrusions (quartz diorite to granodiorite), while those formed in continental margin environments are associated with more felsic material.

DEPOSIT FORM: Highly varied; includes stratiform and tabular orebodies, vertical pipes, narrow lenses, and irregular ore zones that are controlled by intrusive contacts.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Some hornfelsic textures.

ORE MINERALOGY (Principal and *subordinate*): Moderate to high sulphide content. Chalcopyrite ± pyrite ± magnetite in inner garnet-pyroxene zone. Bornite ± chalcopyrite ± sphalerite ± tennantite in outer wollastonite zone. Either hematite, pyrrhotite or magnetite may predominate (depending on oxidation state). Scheelite and traces of *molybdenite, bismuthinite, galena, cosalite, arsenopyrite, enargite, tennantite, loellingite, cobaltite and tetrahedrite* may be present.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

K01 - Cu Skarns

ALTERATION MINERALOGY: Exoskarn alteration: high garnet:pyroxene ratios. High Fe, low Al, Mn andradite garnet (Ad35-100), and diopsidic clinopyroxene (Hd2-50). The mineral zoning from stock out to marble is commonly: diopside + andradite (proximal); wollastonite ± tremolite ± garnet ± diopside ± vesuvianite (distal). Retrograde alteration to actinolite, chlorite and montmorillonite is common. In British Columbia, skarn alteration associated with some of the alkalic porphyry Cu-Au deposits contains late scapolite veining. Magnesian Cu skarns also contain olivine, serpentine, monticellite and brucite.
Endoskarn alteration: Potassic alteration with K-feldspar, epidote, sericite ± pyroxene ± garnet. Retrograde phyllic alteration generates actinolite, chlorite and clay minerals.

ORE CONTROLS: Irregular or tabular orebodies tend to form in carbonate rocks and/or calcareous volcanics or tuffs near igneous contacts. Pendants within igneous stocks can be important. Cu mineralization is present as stockwork veining and disseminations in both endo and exoskarn; it commonly accompanies retrograde alteration.

COMMENTS: Calcic Cu skarns are more economically important than magnesian Cu skarns. Cu skarns are broadly separable into those associated with strongly altered Cu-porphyry systems, and those associated with barren, generally unaltered stocks; a continuum probably exists between these two types (Einaudi *et al.*, 1981). Copper skarn deposits related to mineralized Cu porphyry intrusions tend to be larger, lower grade, and emplaced at higher structural levels than those associated with barren stocks. Most Cu skarns contain oxidized mineral assemblages, and mineral zoning is common in the skarn envelope. Those with reduced assemblages can be enriched in W, Mo, Bi, Zn, As and Au. Over half of the 340 Cu skarn occurrences in British Columbia lie in the Wrangellia Terrane of the Insular Belt, while another third are associated with intraoceanic island arc plutonism in the Quesnellia and Stikinia terranes. Some alkalic and calcalkalic Cu and Cu-Mo porphyry systems in the province (e.g. Copper Mountain, Mount Polley) are associated with variable amounts of Cu-bearing skarn alteration.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Rock analyses may show Cu-Au-Ag-rich inner zones grading outward through Au-Ag zones with high Au:Ag ratios to an outer Pb-Zn-Ag zone. Co-As-Sb-Bi-Mo-W geochemical anomalies are present in the more reduced Cu skarn deposits.

GEOPHYSICAL SIGNATURE: Magnetic, electromagnetic and induced polarization anomalies.

ASSOCIATED DEPOSIT TYPES: Porphyry Cu deposits (L04), Au (K04), Fe (K03) and Pb-Zn (K02) skarns, and replacement Pb-Zn-Ag deposits (M01).

ECONOMIC FACTORS

GRADE AND TONNAGE: Average 1 to 2 % copper. Worldwide, they generally range from 1 to 100 Mt, although some exceptional deposits exceed 300 Mt. Craigmont, British Columbia's largest Cu skarn, contained approximately 34 Mt grading 1.3 % Cu.

IMPORTANCE: Historically, these deposits were a major source of copper, although porphyry deposits have become much more important during the last 30 years. However, major Cu skarns are still worked throughout the world, including in China and the U.S.

K01 - Cu Skarns

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K02 - Pb-Zn Skarns

by Gerald E. Ray[1]

Ray, G.E., 1995. Pb-Zn skarns: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 61–62.

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic Pb-Zn deposits.

COMMODITIES (BYPRODUCTS): Pb, Zn, Ag, (Cu, Cd, W, Au).

EXAMPLES (British Columbia - *Canada/International*): Piedmont (082FNW 129), Contact (104P 004); *Quartz Lake (Yukon, Canada), Groundhog (New Mexico, USA), Darwin (California, USA) San Antonio, Santa Eulalia and Naica (Mexico), Yeonhwa-Ulchin deposits (South Korea), Nakatatsu deposits (Japan), Shuikoushan and Tienpaoshan (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Galena and/or sphalerite-dominant mineralization genetically associated with a skarn gangue.

TECTONIC SETTING: Along continental margins where they are associated with late orogenic plutonism. Pb-Zn skarns occur at a wide range of depths, being associated with subvolcanic aphanitic dikes and high-level breccia pipes, as well as deep-level batholiths. In British Columbia, some Pb-Zn skarns are found in oceanic island arcs where they form distally to larger calcic Fe or Cu skarn systems.

AGE OF MINERALIZATION: Mainly Mesozoic, but may be any age. In British Columbia, the 80 Pb-Zn skarn occurrences identified have a wide age range; over 40 % are Early to mid-Jurassic, 22 % are Cretaceous, and a further 17 % are Eocene-Oligocene in age.

HOST/ASSOCIATED ROCK TYPES: Variable; from high-level skarns in thick limestones, calcareous tuffs and sediment to deeper level skarns in marbles and calcsilicate-bearing migmatites. Associated intrusive rocks are granodiorite to leucogranite, diorite to syenite (mostly quartz monzonite). Pb-Zn skarns tend to be associated with small stocks, sills and dikes and less commonly with larger plutons. The composition of the intrusions responsible for many distal Pb-Zn skarns is uncertain.

DEPOSIT FORM: Variable; commonly occurs along igneous or stratigraphic contacts. Can develop as subvertical chimneys or veins along faults and fissures and as subhorizontal blankets. Pb-Zn skarn deposits formed either at higher structural levels or distal to the intrusions tend to be larger and more Mn-rich compared to those formed at greater depths or more proximal.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn.

ORE MINERALOGY (Principal and *subordinate*): Sphalerite ± galena ± pyrrhotite ± pyrite ± magnetite ± arsenopyrite ± chalcopyrite ± bornite. Other trace minerals reported include *scheelite, bismuthinite, stannite, cassiterite, tetrahedrite, molybdenite, fluorite, and native gold*. Proximal skarns tend to be richer in Cu and W, whereas distal skarns contain higher amounts of Pb, Ag and Mn.

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K02 - Pb-Zn Skarns

ALTERATION MINERALOGY: Endoskarn mineralogy is dominated by epidote ± amphibole ± chlorite ± sericite with lesser rhodonite ± garnet ± vesuvianite ± pyroxene ± K-feldspar ± biotite and rare topaz. Marginal phases may contain greisen and/or tourmaline.

ORE CONTROLS: Carbonate rocks, particularly along structural and/or lithogical contacts (e.g. shale-limestone contacts or pre-ore dikes). Deposits may occur considerable distances (100-1000 m) from the source intrusions.

ASSOCIATED DEPOSIT TYPES: Pb-Zn-Ag veins (I05), Cu skarns (K01) and Cu porphyries (L03, L04). In B.C., small Pb-Zn skarns occur distally to some Fe (K03) and W (K04) skarns.

COMMENTS: In British Columbia Pb-Zn skarn occurrences are preferentially developed in: (1) continental margin sedimentary rocks of the Cassiar and Ancestral North America terranes, (2) oceanic island arc rocks of the Quesnellia and Stikinia terranes, and (3) arc rocks of the Wrangellia Terrane. Their widespread terrane distribution partly reflects their formation as small distal mineralized occurrences related to other skarns (notably Cu, Fe and W skarns), as well as some porphyry systems. British Columbia is endowed with some large and significant Pb-Zn reserves classified as manto deposits (Nelson, 1991; Dawson et al., 1991). These deposits lack skarn gangue, but are sometimes grouped with the Pb-Zn skarns.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Pb, Zn, Ag, Cu, Mn, As, Bi, W, F, Sn, Mo, Co, Sb, Cd and Au geochemical anomalies.

GEOPHYSICAL SIGNATURE: Generally good induced polarization response. Galena-rich orebodies may be marked by gravity anomalies whereas pyrrhotite-rich mineralization may be detected by magnetic surveys. CS-AMT may also be a useful exploration system.

OTHER EXPLORATION GUIDES: Thick limestones distal to small granitoid stocks; structural traps and lithological contacts; exoskarns with low garnet/pyroxene ratios.

ECONOMIC FACTORS

GRADE AND TONNAGE: Pb-Zn skarns tend to be small (<3 Mt) but can reach 45 Mt, grading up to 15 % Zn, 10 % Pb and > 150 g/t Ag with substantial Cd. Cu grades are generally < 0.2 %. Some deposits (e.g. Naica (Mexico) and Falun (Sweden)) contain Au. The 80 British Columbia Pb-Zn skarn occurrences are generally small and have had no major metal production.

IMPORTANCE: Important past and current producers exist in Mexico, China, U.S.A (New Mexico and California), and Argentina. No large, productive Pb-Zn skarns have been discovered in B.C.

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K02 - Pb-Zn Skarns

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K03 - Fe Skarns

by Gerald E. Ray[1]

Ray, G.E., 1995. Fe skarns: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 63–65.

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic iron deposits.

COMMODITIES (BYPRODUCTS): Magnetite (Cu, Ag, Au, Co, phlogopite, borate minerals).

EXAMPLES (British Columbia - *Canada/International*): Tasu (103C003), Jessie (103B 026), Merry Widow (092L 044), Iron Crown (092L 034), Iron Hill (092F 075), Yellow Kid (092F 258), Prescott (092F 106), Paxton (092F 107), Lake (092F 259); *Shinyama (Japan), Cornwall (Pennsylvania), Iron Springs (Utah, USA) Eagle Mountain (California, USA), Perschansk, Dashkesan, Sheregesh and Teya (Russia), Daiquiri (Cuba), San Leone (Italy).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Magnetite-dominant mineralization genetically associated with a skarn gangue (includes calcic and magnesian Fe skarns).

TECTONIC SETTING: Calcic Fe skarns: Intra and non-intraoceanic island arcs; rifted continental margins. Magnesian Fe skarns: Cordilleran-type, synorogenic continental margins.

AGE OF MINERALIZATION: Can be of any age, mainly Mesozoic to Cenozoic. Typically Early to mid-Jurassic in British Columbia.

HOST/ASSOCIATED ROCK TYPES: Calcic Fe skarns: Fe-rich, Si-poor intrusions derived from primitive oceanic crust. Large to small stocks and dikes of gabbro to syenite (mostly gabbro-diorite) intruding limestone, calcareous clastic sedimentary rocks, tuffs or mafic volcanics at a high to intermediate structural level. Magnesian Fe skarns: Small stocks, dikes and sills of granodiorite to granite intruding dolomite and dolomitic sedimentary rocks.

DEPOSIT FORM: Variable and includes stratiform orebodies, vertical pipes, fault-controlled sheets, massive lenses or veins, and irregular ore zones along intrusive margins.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Some hornfelsic textures. Magnetite varies from massive to disseminated to veins.

ORE MINERALOGY (Principal and *Subordinate*): Calcic Fe skarns: Magnetite ± chalcopyrite ± pyrite ± cobaltite ± pyrrhotite ± arsenopyrite ± sphalerite ± galena ± molybdenite ± bornite ± hematite ± martite ± gold. Rarely, can contain *tellurobismuthite* ± *fluorite* ± *scheelite*. Magnesian Fe skarns: Magnetite ± chalcopyrite ± bornite ± pyrite ± pyrhhotite ± sphalerite ± molybdenite.

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K03 - Fe Skarns

EXOSKARN ALTERATION (both calcic and magnesian): High Fe, low Mn, diopside-hedenbergite clinopyroxene (Hd20-80) and grossular-andradite garnet (Ad20-95), ± epidote ± apatite. Late stage amphibole ± chlorite ± ilvaite ± epidote ± scapolite ± albite ± K-feldspar. Magnesian Fe skarns can contain olivine, spinel, phlogopite, xanthophyllite, brucite, serpentine, and rare borate minerals such as ludwigite, szaibelyite, fluorborite and kotoite.

ENDOSKARN ALTERATION: <u>Calcic Fe skarns</u>: Extensive endoskarn with Na-silicates ± garnet ± pyroxene ± epidote ± scapolite. <u>Magnesian skarns</u>: Minor pyroxene ± garnet endoskarn, and propyllitic alteration.

ORE CONTROLS: Stratigraphic and structural controls. Close proximity to contacts between intrusions and carbonate sequences, volcanics or calcareous tuffs and sediments. Fracture zones near igneous contacts can also be important.

ASSOCIATED DEPOSIT TYPES: Cu porphyries (L03, L04); Cu (K01) and Pb-Zn (K02) skarns; small Pb-Zn veins (I05).

COMMENTS: In both calcic and magnesian Fe skarns, early magnetite is locally intergrown with, or cut by, garnet and magnesian silicates (Korzhinski, 1964, 1965;. Sangster, 1969; Burt, 1977). Some calcic Fe skarns contain relatively small pockets of pyrrhotite-pyrite mineralization that postdate the magnetite; this mineralization can be Au-rich. Byproduct magnetite is also derived from some Sn, Cu and calcic Pb-Zn skarns. Over 90% of the 146 Fe skarn occurrences in British Columbia lie within the Wrangellia Terrane of the Insular Belt. The majority of these form where Early to mid-Jurassic dioritic plutons intrude Late Triassic limestones.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: <u>Calcic Fe skarn</u>: enriched in Fe, Cu, Co, Au, Ni, As, Cr. Overall Cu and Au grades are low (<0.2% Cu and 0.5 g/t Au). <u>Magnesian Fe skarn</u>: enriched in Fe, Cu, Zn, Bo.

GEOPHYSICAL SIGNATURE: Strong positive magnetic, electromagnetic and induced polarization anomalies. Possible gravity anomalies.

OTHER EXPLORATION GUIDES: Magnetite-rich float. In the Wrangellia Terrane of British Columbia, the upper and lower contacts of the Late Triassic Quatsino limestone (or equivalent units) are favorable horizons for Fe skarn development.

ECONOMIC FACTORS

GRADE AND TONNAGE: Grades are typically 40 to 50 % Fe. Worldwide, calcic Fe skarns range from 3 to 150 Mt whereas magnesian Fe skarns can be larger (exceeding 250 Mt). In British Columbia, they reach 20 Mt and average approximately 4 Mt mined ore.

IMPORTANCE: Worldwide, these deposits were once an important source of iron, but in the last 40 years the market has been increasingly dominated by iron formation deposits. Nearly 90 % of British Columbia's historic iron production was from skarns.

K03 - Fe Skarns

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K04 - Au Skarns

by Gerald E. Ray[1]

Ray, G.E., 1998. Au skarns: In: Geological Fieldwork 1997, Ministry of Employment and Investment, British Columbia Geological Survey, Paper 1998-1, pp. 24H1-24H4.

IDENTIFICATION

SYNONYMS: Pyrometasomatic, tactite, or contact metasomatic Au deposits.

COMMODITIES (BYPRODUCTS): Au (Cu, Ag).

EXAMPLES (British Columbia - *Canada/International*): Nickel Plate (092HSE038), French (092HSE059), Canty (092HSE064), Good Hope (092HSE060), QR - Quesnel River (093A 121); *Fortitude, McCoy and Tomboy-Minnie (Nevada, USA), Buckhorn Mountain (Washington, USA), Diamond Hill, New World district and Butte Highlands (Montana, USA), Nixon Fork (Alaska, USA), Thanksgiving (Philippines), Browns Creek and Junction Reefs-Sheahan-Grants (New South Wales, Australia), Mount Biggenden (Queensland, Australia), Savage Lode, Coogee (Western Australia, Australia), Nambija (Ecuador), Wabu (Irian Jaya, Indonesia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold-dominant mineralization genetically associated with a skarn gangue consisting of Ca - Fe - Mg silicates, such as clinopyroxene, garnet and epidote. Gold is often intimately associated with Bi or Au-tellurides, and commonly occurs as minute blebs (<40 microns) that lie within or on sulphide grains. The vast majority of Au skarns are hosted by calcareous rocks (calcic subtype). The much rarer magnesian subtype is hosted by dolomites or Mg-rich volcanics. On the basis of gangue mineralogy, the calcic Au skarns can be separated into either pyroxene-rich, garnet-rich or epidote-rich types; these contrasting mineral assemblages reflect differences in the hostrock lithologies as well as the oxidation and sulphidation conditions in which the skarns developed.

TECTONIC SETTINGS: Most Au skarns form in orogenic belts at convergent plate margins. They tend to be associated with syn to late island arc intrusions emplaced into calcareous sequences in arc or back-arc environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Most deposits are related to plutonism associated with the development of oceanic island arcs or back arcs, such as the Late Triassic to Early Jurassic Nicola Group in British Columbia.

AGE OF MINERALIZATION: Phanerozoic (mostly Cenozoic and Mesozoic); in British Columbia Au skarns are mainly of Early to Middle-Jurassic age. The unusual magnesian Au skarns of Western Australia are Archean.

HOST/ASSOCIATED ROCK TYPES: Gold skarns are hosted by sedimentary carbonates, calcareous clastics, volcaniclastics or (rarely) volcanic flows. They are commonly related to high to intermediate level stocks, sills and dikes of gabbro, diorite, quartz diorite or granodiorite composition. Economic mineralization is rarely developed in the endoskarn. The I-type intrusions are commonly porphyritic, undifferentiated, Fe-rich and calc-alkaline. However, the Nambija, Wabu and QR Au skarns are associated with alkalic intrusions.

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K04 - Au Skarns

DEPOSIT FORM: Variable from irregular lenses and veins to tabular or stratiform orebodies with lengths ranging up to many hundreds of metres. Rarely, can occur as vertical pipe-like bodies along permeable structures.

TEXTURE/STRUCTURE: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to layered textures in exoskarn. Some hornfelsic textures. Fractures, sill-dike margins and fold hinges can be important loci for mineralization.

ORE MINERALOGY (Principal and *subordinate*): The gold is commonly present as micron-sized inclusions in sulphides, or at sulphide grain boundaries. To the naked eye, ore is generally indistinguishable from waste rock. Due to the poor correlation between Au and Cu in some Au skarns, the economic potential of a prospect can be overlooked if Cu-sulphide-rich outcrops are preferentially sampled and other sulphide-bearing or sulphide-lean assemblages are ignored. The ore in pyroxene-rich and garnet-rich skarns tends to have low Cu:Au (<2000:1), Zn:Au (<100:1) and Ag/Au (<1:1) ratios, and the gold is commonly associated with Bi minerals (particularly Bi tellurides).

Magnesian subtype: Native gold ± pyrrhotite ± chalcopyrite ± pyrite ± *magnetite* ± *galena* ± *tetrahedrite*.

Calcic subtype:

Pyroxene-rich Au skarns: Native gold ± pyrrhotite ± arsenopyrite ± *chalcopyrite* ± *tellurides* (e.g. *hedleyite, tetradymite, altaite* and *hessite*) ± *bismuthinite* ± *cobaltite* ± *native bismuth* ± *pyrite* ± *sphalerite* ± *maldonite*. They generally have a high sulphide content and high pyrrhotite:pyrite ratios. Mineral and metal zoning is common in the skarn envelope. At Nickel Plate for example, this comprises a narrow proximal zone of coarse-grained, garnet skarn containing high Cu:Au ratios, and a wider, distal zone of finer grained pyroxene skarn containing low Cu:Au ratios and the Au-sulphide orebodies.

Garnet-rich Au skarns: Native gold ± chalcopyrite ± pyrite ± arsenopyrite ± sphalerite ± magnetite ± hematite ± *pyrrhotite* ± *galena* ± *tellurides* ± *bismuthinite*. They generally have a low to moderate sulphide content and low pyrrhotite:pyrite ratios.

Epidote-rich Au skarn: Native gold ± chalcopyrite ± pyrite ± arsenopyrite ± hematite ± magnetite ± *pyrrhotite* ± *galena* ± *sphalerite* ± *tellurides*. They generally have a moderate to high sulphide content with low pyrrhotite:pyrite ratios.

EXOSKARN MINERALOGY (GANGUE):

Magnesian subtype: Olivine, clinopyroxene (Hd2-50), garnet (Ad7-30), chondrodite and monticellite. Retrograde minerals include serpentine, epidote, vesuvianite, tremolite-actinolite, phlogopite, talc, K-feldspar and chlorite.

Calcic subtype:

Pyroxene-rich Au skarns: Extensive exoskarn, generally with high pyroxene:garnet ratios. Prograde minerals include diopsidic to hedenbergitic clinopyroxene (Hd 20-100), K-feldspar, Fe-rich biotite, low Mn grandite garnet (Ad 10-100), wollastonite and vesuvianite. Other less common minerals include rutile, axinite and sphene. Late or retrograde minerals include epidote, chlorite, clinozoisite, vesuvianite, scapolite, tremolite-actinolite, sericite and prehnite.

Garnet-rich Au skarns: Extensive exoskarn, generally with low pyroxene:garnet ratios. Prograde minerals include low Mn grandite garnet (Ad 10-100), K-feldspar, wollastonite, diopsidic clinopyroxene (Hd 0-60), epidote, vesuvianite, sphene and apatite. Late or retrograde minerals include epidote, chlorite, clinozoisite, vesuvianite, tremolite-actinolite, sericite, dolomite, siderite and prehnite.

Epidote-rich Au skarns: Abundant epidote and lesser chlorite, tremolite-actinolite, quartz, K-feldspar, garnet, vesuvianite, biotite, clinopyroxene and late carbonate. At the *QR* deposit, epidote-pyrite and carbonate-pyrite veinlets and coarse aggregates are common, and the best ore occurs in the outer part of the alteration envelope, within 50 m of the epidote skarn front.

ENDOSKARN MINERALOGY (GANGUE): Moderate endoskarn development with K-feldspar, biotite, Mg-pyroxene (Hd 5-30) and garnet. Endoskarn at the epidote-rich *QR* deposit is characterized by calcite, epidote, clinozoisite and tremolite whereas at the *Butte Highlands* Mg skarn it contains argillic and propyllitic alteration with garnet, clinopyroxene and epidote.

K04 - Au Skarns

WEATHERING: In temperate and wet tropical climates, skarns often form topographic features with positive relief.

ORE CONTROLS: The ore exhibits strong stratigraphic and structural controls. Orebodies form along sill-dike intersections, sill-fault contacts, bedding-fault intersections, fold axes and permeable faults or tension zones. In the pyroxene-rich and epidote-rich types, ore commonly develops in the more distal portions of the alteration envelopes. In some districts, specific suites of reduced, Fe-rich intrusions are spatially related to Au skarn mineralization. Ore bodies in the garnet-rich Au skarns tend to lie more proximal to the intrusions.

GENETIC MODEL: Many Au skarns are related to plutons formed during oceanic plate subduction. There is a worldwide spatial, temporal and genetic association between porphyry Cu provinces and calcic Au skarns. Pyroxene-rich Au skarns tend to be hosted by siltstone-dominant packages and form in hydrothermal systems that are sulphur-rich and relatively reduced. Garnet-rich Au skarns tend to be hosted by carbonate-dominant packages and develop in more oxidising and/or more sulphur-poor hydrothermal systems.

ASSOCIATED DEPOSIT TYPES: Au placers (C01,C02), calcic Cu skarns (K01), porphyry Cu deposits (L04) and Au-bearing quartz and/or sulphide veins (I01, I02). Magnesian subtype can be associated with porphyry Mo deposits (L05) and possibly W skarns (K05). In British Columbia there is a negative spatial association between Au and Fe skarns at regional scales, even though both classes are related to arc plutonism. Fe skarns are concentrated in the Wrangellia Terrane whereas most Au skarn occurrences and all the economic deposits lie in Quesnellia.

COMMENTS: Most Au skarns throughout the world are calcic and are associated with island arc plutonism. However, the *Savage Lode* magnesian Au skarn occurs in the Archean greenstones of Western Australia and the *Butte Highlands* magnesian Au skarn in Montana is hosted by Cambrian platformal dolomites. Note: although the Nickel Plate deposit lies distal to the Toronto stock in the pyroxene-dominant part of the skarn envelope, the higher grade ore zones commonly lie adjacent to sills and dikes where the exoskarn contains appreciable amounts of garnet with the clinopyroxene.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, As, Bi, Te, Co, Cu, Zn or Ni soil, stream sediment and rock anomalies, as well as some geochemical zoning patterns throughout the skarn envelope (notably in Cu/Au, Ag/Au and Zn/Au ratios). Calcic Au skarns (whether garnet-rich or pyroxene-rich) tend to have lower Zn/Au, Cu/Au and Ag/Au ratios than any other skarn class. The intrusions related to Au skarns may be relatively enriched in the compatible elements Cr, Sc and V, and depleted in lithophile incompatible elements (Rb, Zr, Ce, Nb and La), compared to intrusions associated with most other skarn types.

GEOPHYSICAL SIGNATURE: Airborne magnetic or gravity surveys to locate plutons. Induced polarization and ground magnetic follow-up surveys can outline some deposits.

OTHER EXPLORATION GUIDES: Placer Au. Any carbonates, calcareous tuffs or calcareous volcanic flows intruded by arc-related plutons have a potential for hosting Au skarns. Favorable features in a skarn envelope include the presence of: (a) proximal Cu-bearing garnet skarn and extensive zones of distal pyroxene skarn which may carry micron Au, (b) hedenbergitic pyroxene (although diopsidic pyroxene may predominate overall), (c) sporadic As-Bi-Te geochemical anomalies, and, (d) undifferentiated, Fe-rich intrusions with low Fe_2O_3/FeO ratios. Any permeable calcareous volcanics intruded by high-level porphyry systems (particularly alkalic plutons) have a potential for hosting epidote-rich skarns with micron Au. During exploration, skarns of all types should be routinely sampled and assayed for Au, even if they are lean in sulphides.

K04 - Au Skarns

ECONOMIC IMPORTANCE

TYPICAL GRADE AND TONNAGE: These deposits range from 0.4 to 13 Mt and from 2 to 15 g/t Au. Theodore *et al*. (1991) report median grades and tonnage of 8.6 g/t Au, 5.0 g/t Ag and 213 000 t. *Nickel Plate* produced over 71 tonnes of Au from 13.4 Mt of ore (grading 5.3 g/t Au). The 10.3 Mt *Fortitude* (Nevada) deposit graded 6.9 g/t Au whereas the 13.2 Mt *McCoy* skarn (Nevada) graded 1.5 g/t Au. The *QR* epidote-rich Au skarn has reserves exceeding 1.3 Mt grading 4.7 g/t Au.

IMPORTANCE: Recently, there have been some significant Au skarn deposits discovered around the world (e.g. *Buckhorn Mountain, Wabu, Fortitude*). Nevertheless, total historic production of Au from skarn (more than 1 000 t of metal) is minute compared to production from other deposit types. The *Nickel Plate* deposit (Hedley, British Columbia) was probably one of the earliest major Au skarns in the world to be mined. Skarns have accounted for about 16 % of British Columbia's Au production, although nearly half of this was derived as a byproduct from Cu and Fe skarns.

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K04 - Au Skarns

Ray, G.E., Ettlinger, A.D. and Meinert, L.D. (1990): Gold Skarns: Their Distribution, Characteristics and Problems in Classification; *in* Geological Fieldwork 1989, *B.C. Ministry of Energy, Mines and Petroleum Resources*, Paper 1990-1, pages 237-246.

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K05 - W Skarns

by Gerald E. Ray[1]

Ray, G.E., 1995. W skarns: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 71–73.

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic tungsten deposits.

COMMODITIES (BYPRODUCTS): W (Mo, Cu, Sn, Zn).

EXAMPLES (British Columbia - *Canada/International*): Emerald Tungsten (082FSW010), Dodger (082FSW011), Feeney (082FSW247), Invincible (082FSW218), Dimac (082M 123); *Fostung (Ontario, Canada), MacTung (Yukon, Canada), Cantung (Northwest Territories, Canada), Pine Creek and Strawberry (California, USA), Osgood Range (Nevada, USA), King Island (Tasmania, Australia), Sang Dong (South Korea).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Scheelite-dominant mineralization genetically associated with a skarn gangue.

TECTONIC SETTING: Continental margin, synorogenic plutonism intruding deeply buried sequences of eugeoclinal carbonate-shale sedimentary rocks. Can develop in tectonically thickened packages in back-arc thrust settings.

AGE OF MINERALIZATION: Mainly Mesozoic, but may be any age. Over 70% of the W skarns in British Columbia are related to Cretaceous intrusions.

HOST/ASSOCIATED ROCK TYPES: Pure and impure limestones, calcareous to carbonaceous pelites. Associated with tonalite, granodiorite, quartz monzonite and granite of both I and S-types. W skarn-related granitoids, compared to Cu skarn-related plutonic rocks, tend to be more differentiated, more contaminated with sedimentary material, and have crystallized at a deeper structural level.

DEPOSIT FORM: Stratiform, tabular and lens-like orebodies. Deposits can be continous for hundreds of metres and follow intrusive contacts.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Biotite hornfelsic textures common.

ORE MINERALOGY (Principal and *subordinate*): Scheelite ± molybdenite ± chalcopyrite ± pyrrhotite ± sphalerite ± arsenopyrite ± pyrite ± powellite. May contain *trace wolframite, fluorite, cassiterite, galena, marcasite and bornite*. Reduced types are characterized by pyrrhotite, magnetite, bismuthinite, native bismuth and high pyrrhotite:pyrite ratios. Variable amounts of quartz-vein stockwork (with local molybdenite) can cut both the exo and endoskarn. The Emerald Tungsten skarns in British Columbia include pyrrhotite-arsenopyrite veins and pods that carry up to 4 g/t Au.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

K05 - W Skarns

ALTERATION MINERALOGY: Exoskarn alteration: Inner zone of diopside-hedenbergite (Hd60-90, Jo5-20) ± grossular-andradite (Ad 10-50, Spess5-50) ± biotite ± vesuvianite, with outer barren wollastonite-bearing zone. An innermost zone of massive quartz may be present. Late-stage spessartine ± almandine ± biotite ± amphibole ± plagioclase ± phlogopite ± epidote ± fluorite ± sphene. Reduced types are characterized by hedenbergitic pyroxene, Fe-rich biotite, fluorite, vesuvianite, scapolite and low garnet:pyroxene ratios, whereas oxidized types are characterized by salitic pyroxene, epidote and andraditic garnet and high garnet:pyroxene ratios. Exoskarn envelope can be associated with extensive areas of biotite hornfels. Endoskarn alteration: Pyroxene ± garnet ± biotite ± epidote ± amphibole ± muscovite ± plagioclase ± pyrite ± pyrrhotite ± trace tourmaline and scapolite; local greisen developed.

ORE CONTROLS: Carbonate rocks in extensive thermal aureoles of intrusions; gently inclined bedding and intrusive contacts; structural and/or stratigraphic traps in sedimentary rocks, and irregular parts of the pluton/country rock contacts.

ASSOCIATED DEPOSIT TYPES: Sn (K06), Mo (K07) and Pb-Zn (K02) skarns. Wollastonite-rich industrial mineral skarns (K09).

COMMENTS: W skarns are separable into two types (Newberry, 1982): reduced skarns (e.g. Cantung, Mactung), formed in carbonaceous rocks and/or at greater depths, and oxidized skarns (e.g. King Island), formed in hematitic or non-carbonaceous rocks, and/or at shallower depths. Late retrograde alteration is an important factor in many W skarns because, during retrogression, the early low-grade mineralization is often scavenged and redeposited into economic high-grade ore zones (e.g. Bateman, 1945; Dick, 1976, 1980). Dolomitic rocks tend to inhibit the development of W skarns; consequently magnesian W skarns are uncommon. In British Columbia they are preferentially associated with Cretaceous intrusions and hosted by calcareous, Cambrian age cratonic, pericratonic and displaced continental margin rocks in the Cassiar, Kootenay-Barkerville, Dorsay and Ancestral North American terranes.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: W, Cu, Mo, As, Bi and B. Less commonly Zn, Pb, Sn, Be and F geochemical anomalies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Grades range between 0.4 and 2 % WO_3 (typically 0.7 %). Deposits vary from 0.1 to >30 Mt.

IMPORTANCE: Skarn deposits have accounted for nearly 60 % of the western world's production, and over 80 % of British Columbia's production.

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K05 - W Skarns

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K06 - Sn Skarns

by Gerald E. Ray[1]

Ray, G.E., 1995. Sn skarns: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 75–76.

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic tin deposits.

COMMODITIES (BYPRODUCTS): Sn (W, Zn, magnetite).

EXAMPLES (British Columbia - *Canada/International*): Only three in British Columbia - Silver Diamond, Atlin Magnetite, and Daybreak (104N 069, 126 and 134 respectively); *JC (Yukon, Canada), Moina, Mount Lindsay, Hole 16 and Mt. Garnet (Tasmania, Australia), Lost River (Alaska, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cassiterite-dominant mineralization genetically associated with a skarn gangue (includes calcic and magnesian Sn skarns).

TECTONIC SETTINGS: Late to post orogenic granites emplaced into thick and deeply buried continental margin sedimentary sequences, or sequences in rifted or stable cratonic environments.

AGE OF MINERALIZATION: Most economic deposits are Mesozoic or Paleozoic, but occurrences may be any age (the occurrences in British Columbia are Late Cretaceous).

HOST/ASSOCIATED ROCK TYPES: Carbonates and calcareous sedimentary sequences. Associated with differentiated (low Ca, high Si and K) ilmenite-series granite, adamellite and quartz monzonitic stocks and batholiths (of both I and S-type) intruding carbonate and calcareous clastic rocks. Sn skarns tend to develop in reduced and deep-level environments and may be associated with greisen alteration.

DEPOSIT FORM: Variable; can occur as either stratiform, stockwork, pipe-like or irregular vein-like orebodies.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn; wrigglite skarns contain thin rhythmic and alternating layers rich in either magnetite, fluorite, vesuvianite or tourmaline. Some hornfelsic textures.

ORE MINERALOGY: Cassiterite ± scheelite ± arsenopyrite ± pyrrhotite ± chalcopyrite ± stannite ± magnetite ± bismuthinite ± sphalerite ± pyrite ± ilmenite.

ALTERATION MINERALOGY: Exoskarn alteration: Grandite garnet (Ad15-75, Pyralsp 5-30) (sometimes Sn, F, and Be enriched), hedenbergitic pyroxene (Hd40-95) ± vesuvianite (sometimes Sn and F-enriched) ± malayaite ± Fe and/or F-rich biotite ± stanniferous sphene ± gahnite ± rutile ± Sn-rich ilvaite ± wollastonite ± adularia. Late minerals include muscovite, Fe-rich biotite, chlorite, tourmaline, fluorite, sellaite, stilpnomelane, epidote and amphibole (latter two minerals can be Sn rich). Associated greisens include quartz and muscovite ± tourmaline ± topaz ± fluorite ± cassiterite ± sulphides. Magnesian Sn skarns can also contain olivine, serpentine, spinel, ludwigite, talc and brucite.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

K06 - Sn Skarns

ORE CONTROLS: Differentiated plutons intruding carbonate rocks; fractures, lithological or structural contacts. Deposits may develop some distance (up to 500 m) from the source intrusions.

ASSOCIATED DEPOSIT TYPES: W skarns (K05), Sn ± Be greisens (I13), Sn-bearing quartz-sulphide veins and mantos (J02). In British Columbia, some of the Sn and W skarn-related intrusions (e.g. Cassiar batholith, Mount Haskin stock) are associated with small Pb-Zn skarn occurrences (K02).

COMMENTS: Sn skarns generally form at deep structural levels and in reduced oxidation states. However, wrigglite Sn skarns tend to develop in relatively near-surface conditions, such as over the cupolas of high-level granites. The three Sn skarn occurrences in British Columbia are all associated with an S-type, fluorine-rich accretionary granite, the Surprise Lake batholith. However, they are unusual in being hosted in allochthonous oceanic rocks of the Cache Creek Terrane.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sn, W, F, Be, Bi, Mo, As, Zn, Cu, Rb, Li, Cs and Re geochemical anomalies. Borate-bearing magnesian Sn skarns may exhibit B enrichment.

GEOPHYSICAL SIGNATURE: Magnetic, induced polarization and possible radiometric anomalies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Deposits can grade up to 1 % Sn, but much of the metal occurring in malayaite, garnet, amphibole and epidote is not economically recoverable. Worldwide, deposits reach 30 Mt, but most range between 0.1 and 3 Mt.

IMPORTANCE: Worldwide, Sn skarns represent a major reserve of tin. However, current production from skarn is relatively minor compared to that from placer Sn deposits and Sn-rich greissens and mantos. British Columbia has had no Sn production from skarns.

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K07 - Mo Skarns

by Gerald E. Ray[1]

Ray, G.E., 1995. Mo skarns: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 77–78.

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic Mo deposits.

COMMODITIES (BYPRODUCTS): Mo (W, Cu, Pb, Zn, Sn, Bi, U, Au).

EXAMPLES (British Columbia - *Canada/International*): Coxey (082FSW110), Novelty (082FSW107); *Mount Tennyson (New South Wales, Australia), Little Boulder Creek (Idaho, USA), Cannivan Gulch (Montana, USA), Azegour (Morocco), Yangchiachangtze (China)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Molybdenite-dominant mineralization genetically associated with a skarn gangue (includes calcic and magnesian Mo skarns). Mo skarns are broadly separable into polymetallic and "molybdenite-only" types (see comments below).

TECTONIC SETTING: Late orogenic plutonism (derived from transitional crust) intruding continental margin carbonate sequences. Also, some are associated with Mo-bearing porphyry systems developed within intra-oceanic island arcs.

AGE OF MINERALIZATION: Mainly Mesozoic and Paleozoic, but may be any age. In British Columbia, they are mainly of Early to mid-Jurassic in age.

HOST/ASSOCIATED ROCK TYPES: Stocks and dikes of evolved, commonly leucocratic quartz monzonite to granite (some containing primary biotite and muscovite) intruding calcareous clastic rocks. Deposits tend to develop close to intrusive contacts. Some of the Mo skarns in British Columbia are associated with high-level intrusions that have explosive breccia textures.

DEPOSIT FORM: Irregular orebodies along, and controlled by, the intrusive contacts.

TEXTURES: Igneous textures in endoskarn; local explosive breccia textures. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Some hornfelsic textures.

ORE MINERALOGY (Principal and *subordinate*): Molybdenite ± scheelite ± pyrrhotite ± powellite ± chalcopyrite ± arsenopyrite ± pyrite ± pyrrhotite ± bismuthinite ± sphalerite ± fluorite. In rare instances also *galena ± magnetite ± uraninite ± pitchblende ± cassiterite ± cobalite ± stannite ± gold.*

EXOSKARN ALTERATION: Calcic Mo skarns: Hedenbergite pyroxene (Hd50-80, Jo1-3) ± low Mn grossular-andradite garnet (Ad40-95) ± wollastonite ± biotite ± vesuvianite. Magnesian Mo skarns: olivine (Fo96). Retrograde minerals: Calcic skarns: amphibole ± epidote ± chlorite and muscovite. Magnesian skarns: serpentine ± tremolite ± chlorite.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

K07 - Mo Skarns

ENDOSKARN ALTERATION: Clinopyroxene, K-feldspar, hornblende, epidote, quartz veining, sericite, molybdenite.

ORE CONTROLS: Carbonate or calcareous rocks in thermal aureoles adjacent to intrusive margins.

ASSOCIATED DEPOSIT TYPES: Mo porphyries of quartz monzonite type (L05), Mo-sulphide veins, and Zn-sulphide veins (I05). Some Mo skarns in China are associated with distal, sphalerite-rich mineralization.

COMMENTS: Mo skarns are broadly separable into two types: polymetallic (containing molybdenite with other W, Zn, Pb, Bi, Sn, Co or U-rich minerals), and "molybedenite-only" (containing mainly molybdenite with no or few other sulphides). Over 85% of the 21 Mo skarns recorded in British Columbia occur in the Omineca Belt. More than 60% are hosted in cratonic, pericratonic and displaced continental margin rocks of the Kootenay, Cassiar and Ancestral North America terranes, and a further 19% are found in the Quesnellia Terrane.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Enriched in Mo, Zn, Cu, Sn, Bi, As, F, Pb, U, Sb, Co (Au).

GEOPHYSICAL SIGNATURE: Positive magnetic and induced polarization anomalies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Worldwide, grades range from 0.1 to 2 % MoS_2, and tonnages between 0.1 and 2 Mt. In British Columbia, the Coxey deposit produced 1 Mt of ore grading approximately 0.17 % MoS_2. The Novelty and Giant are polymetallic Mo skarns near Rossland, British Columbia with unusually high grades of up to 47 g/t Au, 1.4 % Ni, 30.5 % As and 4.84 % Co.

IMPORTANCE: Mo skarns tend to be smaller tonnage and less economically important than porphyry Mo deposits.

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K08 - Garnet Skarns

by Gerald E. Ray[1]

Ray, G.E., 1999. Garnet skarns: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 51–52.

IDENTIFICATION

SYNONYM: Pyrometasomatic or contact metasomatic garnet deposits.

COMMODITIES (BYPRODUCTS): Garnet (wollastonite, magnetite).

EXAMPLES (British Columbia - *Canada/International*): Mount Riordan (Crystal Peak, 082ESW102); *San Pedro (New Mexico, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Garnet-dominant skarn hosted by calcareous rocks generally near an intrusive contact.

TECTONIC SETTINGS: Virtually any setting.

AGE OF DEPOSIT: May be any age.

HOST/ASSOCIATED ROCK TYPES: Garnet is hosted by carbonate or altered calcareous mafic volcanic sequences that are intruded by relatively oxidized plutons.

DEPOSIT FORM: Irregular zones of massive garnet developed in exoskarn close to plutonic contacts. The shape of the deposit may be controlled partly by the morphology of the original conformable units.

TEXTURES: Coarse grained, massive granoblastic textures in exoskarn.

ORE MINERALOGY (Principal and *Subordinate*): Abundant and massive, coarse grained garnet (grossular-andradite) ± *wollastonite* ± *magnetite*.

ALTERATION MINERALOGY (Principal and *Subordinate*): Garnet, clinopyroxene, quartz, feldspar, calcite, sphene, apatite, axinite, vesuvianite and sericite.

OPAQUE MINERALOGY: Economically viable garnet deposits typically have very little or no sulphides.

ORE CONTROLS: Plutonic contacts and oxidized carbonate host rocks. The Mount Riordan garnet skarn lies proximal to the intrusion.

ASSOCIATED DEPOSIT TYPES: Cu, Fe, Au and wollastonite skarns (K01, K03, K04 and K09).

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

K08 - Garnet Skarns

COMMENTS: The best industrial garnets (due to higher specific gravity and hardness) are almandine-pyrope composition. These generally occur in high grade metamorphic rocks and require secondary concentration in beach or stream placers to be mined economically. Examples include the Emerald Creek deposit located in Idaho, USA, and a 6 Mt beach-sand deposit situated near Geraldton, Western Australia that grades 35 per cent garnet. The Mount Riordan deposit is one of the largest and highest grade garnet skarns yet identified; its garnet is suitable for the production of sandblasting and other abrasive products that require high angularity and a wide range of grain sizes. In British Columbia, there have been intermittent attempts to process the garnet-rich tailings from the Iron Hill-Argonaut Fe skarn (092F075).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: May get very weak W, Mo, Zn and Cu geochemical anomalies.

GEOPHYSICAL SIGNATURE: Gravity and possible magnetic anomalies.

ECONOMIC FACTORS

GRADE AND TONNAGE: To be economic, garnet skarn deposits should be large tonnage (>20 Mt) and high grade (> 70% garnet). The Mount Riordan (Crystal Peak) deposit contains reserves of 40 Mt grading 78% garnet and San Pedro is a 22 to 30 Mt deposit with 85% andraditic garnet.

ECONOMIC LIMITATIONS: The garnet should be free of inclusions, possess a relatively high specific gravity and high angularity, and be present as discrete grains that can be processed easily by conventional benefication techniques. Economic concentrations of clean and industrially suitable grossularite-andradite garnet in skarn are rare. This is because skarn garnets tend to be relative soft and many contain fine-grained carbonate inclusions. Easy access, low cost transportation and a ready and reliable market for the product are essential features controlling the economic viability of a deposit.

END USES: Sandblasting, water-jet equipment and abrasives, such as sandpaper. Grossular-andradite garnets have more restricted uses than almandine.

IMPORTANCE: World production in 1995 of industrial garnet was approximately 110 000 tonnes, of which just under half (valued at $US 11 million) was produced in the U.S. Worldwide, most garnet is obtained from placer deposits or as a byproduct during hard rock mining of other commodities. The demand in North America for industrial garnet is growing; skarns are expected to be an important future source for the mineral.

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K09 - Wollastonite Skarns

by G.J. Simandl[1], S. Paradis[2], G.J Orris[3] and G.E. Ray[1]

Simandl, G.J., Paradis, S., Orris, G. and Ray, G.E., 1999. Wollastonite skarns: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 53–56.

IDENTIFICATION

COMMODITIES (BYPRODUCTS): Wollastonite (in some cases garnet, clinopyroxene, high calcium carbonate, limestone, marble, Cu and possibly other metals).

EXAMPLES (British Columbia (MINFILE#) - *Canada/International*): Mineral Hill (092GNW052), Zippa Mountain (104B 384), Rossland wollastonite (082FSW341); *Fox Knoll and Lewis (New York, USA), Lappeenranta (Finland), Khila (Belkapahar, India), Koytash (Uzbekistan, Commonwealth of Independent States).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Wollastonite deposits form irregular masses or lenses in metamorphosed calcareous rocks. Most form adjacent to or some distance from known igneous intrusions. Some deposits are located in medium to high grade metamorphic terrains and appear unrelated to intrusions.

TECTONIC SETTINGS: Magmatism associated with continental margin orogenesis and rifting; or intracratonic catazonal and/or magmatic settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Exoskarns around granitic, syenitic, anorthositic or other intrusions in carbonate rocks. Epizonal to catazonal metamorphic environments. Some deposits are located in catazonal metasedimentary sequences lacking known intrusive bodies and are associated with mylonite zones that acted as channels for fluids. In these cases, it is difficult to determine if they are distal to the intrusions or related to the regional metamorphism.

AGE OF MINERALIZATION: Typically Precambrian to Tertiary.

HOST/ASSOCIATED ROCK TYPES: Hosts are typically calcitic marble, limestone or calcite-rich siliceous metasedimentary rocks. The most common associated igneous rocks are felsic intrusives, charnockites, pegmatites and lithologies of the anorthositic suite including gabbros.

DEPOSIT FORM: Irregular, lens-shaped or planar. Some deposits are several metres to tens of metres thick and can be traced for hundreds of metres.

TEXTURE/STRUCTURE: Wollastonite crystals are accicular and may be porphyroblastic. They can form rosettes, fan-like textures, and millimeter to decimeter scale layering. Sometimes the wollastonite is massive. The wollasonite-rich rocks may contain remnants of the carbonate protolith.

ORE MINERALOGY (Principal and *subordinate)*: Wollastonite, sometimes garnet and clinopyroxene or calcite, rarely Cu and other sulphides.

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[2] Geological Survey of Canada, Pacific Geoscience Centre, Sidney, British Columbia, Canada
[3] United States Geological Survey, Tuscon, Arizona, United States of America

K09 - Wollastonite Skarns

GANGUE MINERALOGY (Principal and *Subordinate*): Garnet, clinopyroxene, calcite and quartz may be major constituents. *Tremolite-actinolite, zoisite, clinozoisite, anorthite, prehnite, sulphides, oxides, graphite, vesuvianite and titanite* may be minor constituents.

ALTERATION MINERALOGY: Calc-silicate minerals in high grade metamorphic terrains are commonly affected by retrograde metamorphism. In some of these cases, retrograde clinozoisite, zoisite, prehnite and/or chlorite are present. Wollastonite crystal may be partially corroded and retrograded to quartz and/or calcite.

WEATHERING: Wollastonite commonly weathers with a positive relief in temperate regions.

ORE CONTROLS: Wollastonite often occurs at contacts of carbonate or siliceous calcareous rocks with igneous intrusions or within horses and roof pendants of carbonate rocks in intrusive bodies. Fracture and mylonite zones and hinges of folds and other zones of high paleo-permeability are extremely important, since an open system is the main pre-requisite for formation of high grade wollastonite deposits (Simandl, 1992; pages 265-277).

GENETIC MODEL: Most wollastonite deposits are formed through contact metamorphism or metasomatism of siliceous limestone or other calcareous rocks. Typically fluids emanating from the intrusive rocks provide silica, alumina, iron and manganese which react with calcareous rocks to form skarn minerals. Introduction of silica under favorable physical and chemical conditions results in the formation of wollastonite according to the following reaction:

$$1 \text{ calcite} + 1\ SiO_2 = 1 \text{ wollastonite} + 1\ CO_2$$

Stability of the wollastonite is dependent on pressure, temperature and $X(CO_2)$ and $X(H_2O)$ of the ambient fluid. The temperature required for wollastonite formation increases with increase in $X(CO_2)$ of the fluid and lithostatic pressure. In some cases, the silica required for wollastonite formation may have been present as impurities within the limy sedimentary protolith. Some deposits in medium to high grade regional metamorphic settings are interpreted to form by interaction of metamorphic or metasomatic fluids with calcareous rocks along permeable zones such as saddle reefs, fracture or fault zones.

ASSOCIATED DEPOSIT TYPES: Cu, Zn, Pb, W, Mo and Au-bearing skarns (K01, K02, K05, K07, K04) and porphyry Cu (L04). Wollastonite rocks in catazonal environments may be in some cases be cut by crystalline graphite veins.

COMMENTS: Some W, Pb-Zn, or Cu skarn prospects are currently considered as potential sources of wollastonite.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: No direct chemical indicators are known for wollastonite, however associated metallic occurrences can be detected by geochemical methods.

GEOPHYSICAL SIGNATURE: Electromagnetic and magnetic methods may be used to delineate intrusive contacts with calcareous rocks.

OTHER EXPLORATION GUIDES: Commonly found in calcareous sediments cut by igneous rocks. Boulder tracing is a successfully used exploration method; boulders have a rotten wood-like appearance. Wollastonite usually has a positive relief relative to carbonate host rock. In some areas, greenish calcite porphyroblasts within calcitic marbles are common in proximity of wollastonite deposits located in catazonal metamorphic environments.

K09 - Wollastonite Skarns

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Highly variable. Wollastonite skarns vary from 0.1 million to 50 million tonnes. Grades vary between 20 and 80% wollastonite. Clinopyroxene and garnet are recovered from some deposits and calcite (limestone or marble) is recovered from others. In rare deposits Cu and wollastonite are recovered as co-products. Median tonnage is 1.3 million tonnes and median grade is 49% wollastonite (Orris, 1992).

ECONOMIC LIMITATIONS: Deposits that can supply high aspect ratio wollastonite products are highly sought after. The relative whiteness, brightness, color, aspect ratio of the particles, oil absorption, particle size, refractive index, pH of 10% slurry, specific gravity and type of impurities do determine possible applications. Specialized milling techniques and surface modification significantly increases the price of the wollastonite concentrate. Diopside and garnet may be separated by electromagnetic methods. If calcite is present and a high quality wollastonite concentrate is sought, then flotation is required. Flotation increases substantially the initial capital costs of the project. Wollastonite with a high iron content and impurities, such as garnet, diopside, oxides and sulphides, can be a problem in glass and ceramic uses.

END USES: The major end uses of wollastonite are in ceramics, such as semi-vitreous bodies, heat insulators, acoustic tiles, electrical insulators, and fire-resistant products, such as interior or exterior construction boards, roofing materials, specialty refractors and glazes. It is also used as a functional filler in paint, coatings and plastics and metallurgical applications. Use of wollastonite as reinforcing agent in plastics and as asbestos substitute is increasing. High aspect ratio wollastonite (>15:1) with favorable physical properties is used mainly in plastic and paint as functional filler. Markets for low aspect ratio wollastonite are dependent mainly on the chemical composition and impurities and its end uses are in ceramics, fluxes, glass and limited filler applications.

IMPORTANCE: These deposits are the only commercial sources of natural wollastonite. Competition from synthetic wollastonite is limited to specialty products in the low aspect ratio segment of the market.

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K09 - Wollastonite Skarns

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L - Porphyry

	Profile Title	Authors
L01	Subvolcanic Cu-Ag-Au (As-Sb)	A. Panteleyev, 1995
L02*	Porphyry-related Au	
L03	Alkalic porphyry Cu-Au	A. Panteleyev, 1995
L04	Porphyry Cu ± Mo ± Au	A. Panteleyev, 1995
L05	Porphyry Mo (Low F- type)	W.D. Sinclair, 1995
L06	Porphyry Sn	W.D. Sinclair, 1995
L07	Porphyry W	W.D. Sinclair, 1995
L08	Porphyry Mo (Climax-type)	W.D. Sinclair, 1995
L09	Plutonic-related Au quartz veins & veinlets	D.V. Lefebure and C. Hart, 2005

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

L01 - Subvolcanic Cu-Au-Ag (As-Sb)

by Andre Panteleyev[1]

Panteleyev, A., 1995. Subvolcanic Cu-Au-Ag (As-Sb): In: Selected Mineral Deposit Profiles, Volume 1 - Metallics and Coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey, Open File 1995-20, pp. 79–82.

IDENTIFICATION

SYNONYMS: Transitional, intrusion-related (polymetallic) stockwork and vein.

COMMODITIES (BYPRODUCTS): Cu, Au, Ag (As, Sb).

EXAMPLES (British Columbia - *Canada/International*): Equity Silver (93L 001); Thorn prospect (104K 031,116); *Rochester District (Nevada, USA), Kori Kollo (Bolivia), the 'epithermal gold' zones at Lepanto (Philippines), parts of Recsk (Hungary) and Bor (Serbia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Pyritic veins, stockworks and breccias in subvolcanic intrusive bodies with stratabound to discordant massive pyritic replacements, veins, stockworks, disseminations and related hydrothermal breccias in country rocks. These deposits are located near or above porphyry Cu hydrothermal systems and commonly contain pyritic auriferous polymetallic mineralization with Ag sulphosalt and other As and Sb-bearing minerals.

TECTONIC SETTINGS: Volcano-plutonic belts in island arcs and continental margins; continental volcanic arcs. Subvolcanic intrusions are abundant. Extensional tectonic regimes allow high-level emplacement of the intrusions, but compressive regimes are also permissive.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Uppermost levels of intrusive systems and their adjoining fractured and permeable country rocks, commonly in volcanic terrains with eroded stratovolcanoes. Subvolcanic domes and flow-dome complexes can also be mineralized; their uppermost parts are exposed without much erosion.

AGE OF MINERALIZATION: Mainly Tertiary, a number of older deposits have been identified.

HOST/ASSOCIATED ROCK TYPES: Subvolcanic (hypabyssal) stocks, rhyodacite and dacite flow-dome complexes with fine to coarse-grained quartz-phyric intrusions are common. Dike swarms and other small subvolcanic intrusions are likely to be present. Country rocks range widely in character and age. Where coeval volcanic rocks are present, they range from andesite to rhyolite in composition and occur as flows, breccias and pyroclastic rocks with related erosion products (epiclastic rocks).

DEPOSIT FORM: Stockworks and closely-spaced to sheeted sets of sulphide-bearing veins in zones within intrusions and as structurally controlled and stratabound or bedding plane replacements along permeable units and horizons in hostrocks. Veins and stockworks form in transgressive hydrothermal fluid conduits that can pass into pipe-like and planar breccias. Breccia bodies are commonly tens of metres and, rarely, a few hundred metres in size. Massive sulphide zones can pass outward into auriferous pyrite-quartz-sericite veins and replacements.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

L01 - Subvolcanic Cu-Ag-Au (As-Sb)

TEXTURE/STRUCTURE: Sulphide and sulphide-quartz veins and stockworks. Open space filling and replacement of matrix in breccia units. Bedding and lithic clast replacements by massive sulphide, disseminations and veins. Multiple generations of veins and hydrothermal breccias are common. Pyrite is dominant and quartz is minor to absent in veins.

ORE MINERALOGY [Principal and *Subordinate*]: Pyrite, commonly as auriferous pyrite, chalcopyrite, terahedrite/tennantite; *enargite/luzonite, covellite, chalcocite, bornite, sphalerite, galena, arsenopyrite, argentite, sulphosalts, gold, stibnite, molybdenite, wolframite or scheelite, pyrrhotite, marcasite, realgar, hematite, tin and bismuth minerals*. Depth zoning is commonly evident with pyrite-rich deposits containing enargite near surface, passing downwards into tetrahedrite/tennantite + chalcopyrite and then chalcopyrite in porphyry intrusions at depth.

GANGUE MINERALOGY [Principal and *Subordinate*]: Pyrite, sericite, quartz; *kaolinite, alunite, jarosite* (mainly in supergene zone).

ALTERATION MINERALOGY [Principal and *subordinate*]: Pyrite, sericite, quartz; kaolinite, dickite, pyrophyllite, andalusite, diaspore, corundum, tourmaline, alunite, anhydrite, barite, chalcedony, dumortierite, lazulite (variety scorzalite), rutile and chlorite. Tourmaline as schorlite (a black Fe-rich variety) can be present locally; it is commonly present in breccias with quartz and variable amounts of clay minerals. Late quartz-alunite veins may occur.

WEATHERING: Weathering of pyritic zones can produce limonitic blankets containing abundant jarosite, goethite and, locally, alunite.

GENETIC MODEL: These deposits represent a transition from porphyry copper to epithermal conditions with a blending and blurring of porphyry and epithermal characteristics. Mineralization is related to robust, evolving hydrothermal systems derived from porphyritic, subvolcanic intrusions. Vertical zoning and superimposition of different types of ores is typical due, in large part, to overlapping stages of mineralizations. Ore fluids with varying amounts of magmatic-source fluids have temperatures generally greater than those of epithermal systems, commonly in the order of 300° C and higher. Fluid salinities are also relatively high, commonly more than 10 weight per cent NaCl-equivalent and rarely in the order of 50%, and greater.

ORE CONTROLS: Strongly fractured to crackled zones in cupolas and internal parts of intrusions and flow-dome complexes; along faulted margins of high-level intrusive bodies. Permeable lithologies, both primary and secondary in origin, in the country rocks. Primary controls are structural features such as faults, shears, fractured and crackled zones and breccias. Secondary controls are porous volcanic units, bedding plane contacts and unconformities. Breccia pipes provide channelways for hydrothermal fluids originating from porphyry Cu systems and commonly carry elevated values of Au and Ag. The vein and replacement style deposits can be separated from the deeper porphyry Cu mineralization by 200 to 700 m.

ASSOCIATED DEPOSIT TYPES: Porphyry Cu-Au±Mo (L04); epithermal Au-Ag commonly both high-sulphidation (H04) and low-sulphidation (H05) pyrite-sericite-bearing types; auriferous quartz-pyrite veins, enargite massive sulphide also known as enargite gold.

COMMENTS: This deposit type is poorly defined and overall, uncommon. It is in large part stockworks and a closely spaced to sheeted sulphide vein system with local massive to disseminated replacement sulphide zones. It forms as a high-temperature, pyrite-rich, commonly tetrahderite, and rarely enargite-bearing, polymetallic affiliate of epithermal Au-Ag mineralization. Both low and high-sulphidation epithermal styles of mineralization can be present. As and Sb enrichments in ores are characteristic. If abundant gas and gas condensates evolve from the hydrothermal fluids there can be extensive acid leaching and widespread, high-level advanced argillic alteration. This type of alteration is rarely mineralized.

L01 - Subvolcanic Cu-Ag-Au (As-Sb)

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Au, Cu, Ag, As, Sb, Zn, Cd, Pb, Fe and F; at deeper levels Mo, Bi, W and locally Sn. In some deposits there is local strong enrichment in B, Co, Ba, K and depletion of Na. Both depth zoning and lateral zoning are evident.

GEOPHYSICAL SIGNATURE: Induced polarization to delineate pyrite zones. Magnetic surveys are useful in some cases to outline lithologic units and delineate contacts. Electromagnetic surveys can be used effectively where massive sulphide bodies are present.

OTHER EXPLORATION GUIDES: Association with widespread sericite-pyrite and quartz-sericite-pyrite that might be high-level leakage from buried porphyry Cu ± Au ± Mo deposits. Extensive overprinting of sericite/illite by kaolinite; rare alunite. In some deposits, high-temperature aluminous alteration minerals pyrophyllite and andalusite are present but are generally overprinted by abundant sericite and lesser kaolinite. Tourmaline and phosphate minerals can occur. There is commonly marked vertical mineralogical and geochemical depth-zoning.

ECONOMIC FACTORS

GRADE AND TONNAGE: The deposits have pyritic orebodies of various types; vertical stacking and pronounced metal zoning are prevalent. Small, high-grade replacement orebodies containing tetrahedrite/tennantite, and rarely enargite, can form within larger zones of pyritization. The massive sulphide replacement ores have associated smaller peripheral, structurally controlled zones of sericitic alteration that constitute pyritic orebodies grading ~ 4 g/t gold. Similar tetrahedrite-bearing ores with bulk mineable reserves at Equity Silver were in the order of 30 Mt with 0.25% Cu and ~86 g/t Ag and 1 g/t Au. At the Recsk deposit, Hungary, shallow breccia-hosted Cu-Au ores overlie a porphyry deposit containing ~1000 Mt with 0.8 % Cu. The closely spaced pyritic fracture and vein systems at Kollo, La Joya district, Bolivia contained 10 Mt oxide ore with 1.62 g/t Au and 23.6 g/t Ag and had sulphide ore reserves of 64 Mt at 2.26 g/t Au and 13.8 g/t Ag.

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L03 - Porphyry Cu-Au: Alkalic

by Andre Panteleyev[1]

Panteleyev, A., 1995. Porpyhyry Cu-Au: Alkalic: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 83–86.

IDENTIFICATION

SYNONYMS: Porphyry copper, porphyry Cu-Au, diorite porphyry copper.

COMMODITIES (BYPRODUCTS): Cu, Au (Ag).

EXAMPLES (British Columbian - *Canada/International*): Iron Mask batholith deposits - Afton (092INE023), Ajax (092INE012, 013), Mt. Polley (Cariboo Bell, 093A 008), Mt. Milligan (093N 196, 194), Copper Mt./Ingerbelle (092HSE001, 004), Galore Creek (104G 090), Lorraine? (093N 002); *Ok Tedi (Papua New Guinea); Tai Parit and Marian? (Philippines).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockworks, veinlets and disseminations of pyrite, chalcopyrite, bornite and magnetite occur in large zones of economically bulk-mineable mineralization in or adjoining porphyritic intrusions of diorite to syenite composition. The mineralization is spatially, temporally and genetically associated with hydrothermal alteration of the intrusive bodies and hostrocks.

TECTONIC SETTING(S): In orogenic belts at convergent plate boundaries, commonly oceanic volcanic island arcs overlying oceanic crust. Chemically distinct magmatism with alkalic intrusions varying in composition from gabbro, diorite and monzonite to nepheline syenite intrusions and coeval shoshonitic volcanic rocks, takes place at certain times in segments of some island arcs. The magmas are introduced along the axis of the arc or in cross-arc structures that coincide with deep-seated faults. The alkalic magmas appear to form where there is slow subduction in steeply dipping, tectonically thickened lithospheric slabs, possibly when polarity reversals (or `flips') take place in the subduction zones. In British Columbia all known deposits are found in Quesnellia and Stikinia terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High level (epizonal) stock emplacement levels in magmatic arcs, commonly oceanic volcanic island arcs with alkalic (shoshonitic) basic flows to intermediate and felsic pyroclastic rocks. Commonly the high-level stocks and related dikes intrude their coeval and cogenetic volcanic piles.

AGE OF MINERALIZATION: Deposits in the Canadian Cordillera are restricted to the Late Triassic/Early Jurassic (215-180 Ma) with seemingly two clusters around 205-200 and ~ 185 Ma. In southwest Pacific island arcs, deposits are Tertiary to Quaternary in age.

HOST/ASSOCIATED ROCK TYPES: Intrusions range from fine through coarse-grained, equigranular to coarsely porphyritic and, locally, pegmatitic high-level stocks and dike complexes. Commonly there is multiple emplacement of successive intrusive phases and a wide variety of breccias. Compositions range from (alkalic) gabbro to syenite. The syenitic rocks vary from silica-undersaturated to saturated compositions. The most undersaturated nepheline normative rocks contain modal nepheline and, more commonly,

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

L03 - Porphyry Cu-Au: Alkalic

pseudoleucite. The silica-undersaturated suites are referred to as nepheline alkalic whereas rocks with silica near-saturation, or slight silica over saturation, are termed quartz alkalic (Lang *et al*., 1993). Coeval volcanic rocks are basic to intermediate alkalic varieties of the high-K basalt and shoshonite series and rarely phonolites.

DEPOSIT FORM: Stockworks and veinlets, minor disseminations and replacements throughout large areas of hydrothermally altered rock, commonly coincident wholly or in part with hydrothermal or intrusion breccias. Deposit boundaries are determined by economic factors that outline ore zones within larger areas of low-grade, laterally zoned mineralization.

TEXTURE/STRUCTURE: Veinlets and stockworks; breccia, sulphide and magnetite grains in fractures and along fracture selvages; disseminated sulphides as interstitial or grain and lithic clast replacements. Hydrothermally altered rocks can contain coarse-grained assemblages including feldspathic and calcsilicate replacements ('porphyroid' textures) and open space filling with fine to coarse, granular and rarely pegmatitic textures.

ORE MINERALOGY [Principal and *subordinate*]: Chalcopyrite, pyrite and magnetite; bornite, chalcocite and *rare galena, sphalerite, tellurides, tetrahderite, gold and silver*. Pyrite is less abundant than chalcopyrite in ore zones.

GANGUE MINERALOGY: Biotite, K-feldspar and sericite; garnet, clinopyroxene (diopsidic) and anhydrite. Quartz veins are absent but hydrothermal magnetite veinlets are abundant.

ALTERATION MINERALOGY: Biotite, K-feldspar, sericite, anhydrite/gypsum, magnetite, hematite, actinolite, chlorite, epidote and carbonate. Some alkalic systems contain abundant garnet including the Ti-rich andradite variety - melanite, diopside, plagioclase, scapolite, prehnite, pseudoleucite and apatite; rare barite, fluorite, sodalite, rutile and late-stage quartz. Central and early formed potassic zones, with K-feldspar and generally abundant secondary biotite and anhydrite, commonly coincide with ore. These rocks can contain zones with relatively high-temperature calcsilicate minerals diopside and garnet. Outward there can be flanking zones in basic volcanic rocks with abundant biotite that grades into extensive, marginal propylitic zones. The older alteration assemblages can be overprinted by phyllic sericite-pyrite and, less commonly, sericite-clay-carbonate-pyrite alteration. In some deposits, generally at depth in silica-saturated types, there can be either extensive or local central zones of sodic alteration containing characteristic albite with epidote, pyrite, diopside, actinolite and rarer scapolite and prehnite.

ORE CONTROLS: Igneous contacts, both internal between intrusive phases and external with wallrocks; cupolas and the uppermost, bifurcating parts of stocks, dike swarms and volcanic vents. Breccias, mainly early formed intrusive and hydrothermal types. Zones of most intensely developed fracturing give rise to ore-grade vein stockworks.

ASSOCIATED DEPOSIT TYPES: Skarn copper (K01); Au-Ag and base metal bearing mantos (M01, M04), replacements and breccias in carbonate and non-carbonate rocks; magnetite-apatite breccias (D07); epithermal Au-Ag : both high and low sulphidation types (H04, H05) and alkalic, Te and F-rich epithermal deposits (H08); auriferous and polymetallic base metal quartz and quartz-carbonate veins (I01, I05); placer Au (C01, C02).

COMMENTS: Subdivision of porphyry deposits is made on the basis of metal content, mainly ratios between Cu, Au and Mo. This is a purely arbitrary, economically based criterion; there are few differences in the style of mineralization between the deposits. Differences in composition between the hostrock alkalic and calcalkalic intrusions and subtle, but significant, differences in alteration mineralogy and zoning patterns provide fundamental geologically based contrasts between deposit model types. Porphyry copper deposits associated with calcalkaline hostrocks are described in mineral deposit profile L04.

L03 - Porphyry Cu-Au: Alkalic

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Alkalic cupriferous systems do not contain economically recoverable Mo (< 100 ppm) but do contain elevated Au (> 0.3 g/t) and Ag (>2 g/t). Cu grades vary widely but commonly exceed 0.5 % and rarely 1 %. Many contain elevated Ti, V, P, F, Ba, Sr, Rb, Nb, Te, Pb, Zn, PGE and have high CO_2 content. Leaching and supergene enrichment effects are generally slight and surface outcroppings normally have little of the copper remobilized. Where present, secondary minerals are malachite, azurite, lesser copper oxide and rare sulphate minerals; in some deposits native copper is economically significant (e.g. Afton, Kemess).

GEOPHYSICAL SIGNATURE: Ore zones, particularly those with high Au content, are frequently found in association with magnetite-rich rocks and can be located by magnetic surveys. Pyritic haloes surrounding cupriferous rocks respond well to induced polarization surveys. The more intensely hydrothermally altered rocks produce resistivity lows.

OTHER EXPLORATION GUIDES: Porphyry deposits are marked by large-scale, markedly zoned metal and alteration assemblages. Central parts of mineralized zones appear to have higher Au/Cu ratios than the margins. The alkalic porphyry Cu deposits are found exclusively in Later Triassic and Early Jurassic volcanic arc terranes in which emergent subaerial rocks are present. The presence of hydrothermally altered clasts in coarse pyroclastic deposits can be used to locate mineralized intrusive centres.

ECONOMIC FACTORS

GRADE AND TONNAGE:

- Worldwide according to Cox and Singer (U.S. Geological Survey Open File Report 88-46, 1988) 20 typical porphyry Cu-Au deposits, including both calcalkaline and some alkalic types, contain on average:
  160 Mt with 0.55 % Cu, 0.003 % Mo, 0.38 g/t Au and 1.7 g/t Ag.
- British Columbia alkalic porphyry deposits range from <10 to >300 Mt and contain from 0.2 to 1.5 % Cu, 0.2 to 0.6 g/t Au and >2 g/t Ag; Mo contents are negligible. Median values for 22 British Columbia deposits with reported reserves (with a heavy weighting from a number of small deposits in the Iron Mask batholith) are: 15.5 Mt with 0.58 % Cu, 0.3 g/t Au and >2 g/t Ag.

END USES: Production of chalcopyrite or chalcopyrite-bornite concentrates with significant Au credits.

IMPORTANCE: Porphyry deposits contain the largest reserves of Cu and close to 50 % of Au reserves in British Columbia; alkalic porphyry systems contain elevated Au values.

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L03 - Porphyry Cu-Au: Alkalic

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L04 - Porphyry Cu±Mo±Au

by Andre Panteleyev[1]

Panteleyev, A., 1995. Porphyry Cu±Mo±Au: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 87–91.

IDENTIFICATION

SYNONYM: Calcalkaline porphyry Cu, Cu-Mo, Cu-Au.

COMMODITIES (BYPRODUCTS): Cu. Mo and Au are generally present but quantities range from insufficient for economic recovery to major ore constituents. (Minor Ag in most deposits; rare recovery of Re from Island Copper mine.)

EXAMPLES (British Columbia - *Canada/International*):

- Volcanic type deposits (Cu + Au ± Mo) - Fish Lake (092O041), Kemess (094E021,094), Hushamu (EXPO, 092L240), Red Dog (092L200), Poison Mountain (092O046), Bell (093M001), Morrison (093M007), Island Copper (092L158); *Dos Pobres (USA); Far Southeast (Lepanto/Mankayan), Dizon, Guianaong, Taysan and Santo Thomas II (Philippines), Frieda River and Panguna (Papua New Guinea).*
- Classic deposits (Cu + Mo ± Au) - Brenda (092HNE047), Berg (093E046), Huckleberrry (093E037), Schaft Creek (104G015); *Casino (Yukon, Canada), Inspiration, Morenci, Ray, Sierrita-Experanza, Twin Buttes, Kalamazoo and Santa Rita (Arizona, USA), Bingham (Utah, USA),El Salvador, (Chile), Bajo de la Alumbrera (Argentina).*
- Plutonic deposits (Cu ± Mo) - Highland Valley Copper (092ISE001,011,012,045), Gibraltar (093B012,007), Catface (092F120); *Chuquicamata, La Escondida and Quebrada Blanca (Chile).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockworks of quartz veinlets, quartz veins, closely spaced fractures and breccias containing pyrite and chalcopyrite with lesser molybdenite, bornite and magnetite occur in large zones of economically bulk-mineable mineralization in or adjoining porphyritic intrusions and related breccia bodies. Disseminated sulphide minerals are present, generally in subordinate amounts. The mineralization is spatially, temporally and genetically associated with hydrothermal alteration of the hostrock intrusions and wallrocks.

TECTONIC SETTINGS: In orogenic belts at convergent plate boundaries, commonly linked to subduction-related magmatism. Also, in association with emplacement of high-level stocks during extensional tectonism related to strike-slip faulting and back-arc spreading following continent margin accretion.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level (epizonal) stock emplacement levels in volcano-plutonic arcs, commonly oceanic volcanic island and continent-margin arcs. Virtually any type of country rock can be mineralized, but commonly the high-level stocks and related dikes intrude their coeval and cogenetic volcanic piles.

AGE OF MINERALIZATION: Two main periods in the Canadian Cordillera: the Triassic/Jurassic (210-180 Ma) and Cretaceous/Tertiary (85-45 Ma). Elsewhere deposits are mainly Tertiary, but range from Archean to Quaternary.

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L04 - Porphyry Cu±Mo±Au

HOST/ASSOCIATED ROCK TYPES: Intrusions range from coarse-grained phaneritic to porphyritic stocks, batholiths and dike swarms; rarely pegmatitic. Compositions range from calcalkaline quartz diorite to granodiorite and quartz monzonite. Commonly there is multiple emplacement of successive intrusive phases and a wide variety of breccias. Alkalic porphyry Cu-Au deposits are associated with syenitic and other alkalic rocks and are considered to be a a distinct deposit type (see model L03).

DEPOSIT FORM: Large zones of hydrothermally altered rock contain quartz veins and stockworks, sulphide-bearing veinlets; fractures and lesser disseminations in areas up to 10 km^2 in size, commonly coincident wholly or in part with hydrothermal or intrusion breccias and dike swarms. Deposit boundaries are determined by economic factors that outline ore zones within larger areas of low-grade, concentrically zoned mineralization. Cordilleran deposits are commonly subdivided according to their morphology into three classes - classic, volcanic and plutonic (see Sutherland Brown, 1976; McMillan and Panteleyev, 1988):

- Volcanic type deposits (e.g. Island Copper) are associated with multiple intrusions in subvolcanic settings of small stocks, sills, dikes and diverse types of intrusive breccias. Reconstruction of volcanic landforms, structures, vent-proximal extrusive deposits and subvolcanic intrusive centres is possible in many cases, or can be inferred. Mineralization at depths of 1 km, or less, is mainly associated with breccia development or as lithologically controlled preferential replacement in hostrocks with high primary permeability. Propylitic alteration is widespread and generally flanks early, centrally located potassic alteration; the latter is commonly well mineralized. Younger mineralized phyllic alteration commonly overprints the early mineralization. Barren advanced argillic alteration is rarely present as a late, high-level hydrothermal carapace.
- Classic deposits (e.g., Berg) are stock related with multiple emplacements at shallow depth (1 to 2 km) of generally equant, cylindrical porphyritic intrusions. Numerous dikes and breccias of pre, intra, and post-mineralization age modify the stock geometry. Orebodies occur along margins and adjacent to intrusions as annular ore shells. Lateral outward zoning of alteration and sulphide minerals from a weakly mineralized potassic/propylitic core is usual. Surrounding ore zones with potassic (commonly biotite-rich) or phyllic alteration contain molybdenite ± chalcopyrite, then chalcopyrite and a generally widespread propylitic, barren pyritic aureole or 'halo'.
- Plutonic deposits (e.g., the Highland Valley deposits) are found in large plutonic to batholithic intrusions immobilized at relatively deep levels, say 2 to 4 km. Related dikes and intrusive breccia bodies can be emplaced at shallower levels. Hostrocks are phaneritic coarse grained to porphyritic. The intrusions can display internal compositional differences as a result of differentiation with gradational to sharp boundaries between the different phases of magma emplacement. Local swarms of dikes, many with associated breccias, and fault zones are sites of mineralization. Orebodies around silicified alteration zones tend to occur as diffuse vein stockworks carrying chalcopyrite, bornite and minor pyrite in intensely fractured rocks but, overall, sulphide minerals are sparse. Much of the early potassic and phyllic alteration in central parts of orebodies is restricted to the margins of mineralized fractures as selvages. Later phyllic-argillic alteration forms envelopes on the veins and fractures and is more pervasive and widespread. Propylitic alteration is widespread but unobtrusive and is indicated by the presence of rare pyrite with chloritized mafic minerals, saussuritized plagioclase and small amounts of epidote.

TEXTURE/STRUCTURE: Quartz, quartz-sulphide and sulphide veinlets and stockworks; sulphide grains in fractures and fracture selvages. Minor disseminated sulphides commonly replacing primary mafic minerals. Quartz phenocrysts can be partially resorbed and overgrown by silica.

ORE MINERALOGY (Principal and *subordinate*): Pyrite is the predominant sulphide mineral; in some deposits the Fe oxide minerals magnetite, and rarely hematite, are abundant. Ore minerals are chalcopyrite; molybdenite, lesser bornite and rare (primary) chalcocite. Subordinate minerals are *tetrahedrite/tennantite, enargite and minor gold, electrum and arsenopyrite*. In many deposits late veins commonly contain galena and sphalerite in a gangue of quartz, calcite and barite.

L04 - Porphyry Cu±Mo±Au

GANGUE MINERALOGY (Principal and *subordinate*): Gangue minerals in mineralized veins are mainly quartz with lesser *biotite, sericite, K-feldspar, magnetite, chlorite, calcite, epidote, anhydrite and tourmaline*. Many of these minerals are also pervasive alteration products of primary igneous mineral grains.

ALTERATION MINERALOGY: Quartz, sericite, biotite, K-feldspar, albite, anhydrite/gypsum, magnetite, actinolite, chlorite, epidote, calcite, clay minerals, tourmaline. Early formed alteration can be overprinted by younger assemblages. Central and early formed potassic zones (K-feldspar and biotite) commonly coincide with ore. This alteration can be flanked in volcanic hostrocks by biotite-rich rocks that grade outward into propylitic rocks. The biotite is a fine-grained, 'shreddy' looking secondary mineral that is commonly referred to as an early developed biotite (EDB) or a 'biotite hornfels'. These older alteration assemblages in cupriferous zones can be partially to completely overprinted by later biotite and K-feldspar and then phyllic (quartz-sericite-pyrite) alteration, less commonly argillic, and rarely, in the uppermost parts of some ore deposits, advanced argillic alteration (kaolinite-pyrophyllite).

WEATHERING: Secondary (supergene) zones carry chalcocite, covellite and other Cu~$_2$S minerals (digenite, djurleite, etc.), chrysocolla, native copper and copper oxide, carbonate and sulphate minerals. Oxidized and leached zones at surface are marked by ferruginous 'cappings' with supergene clay minerals, limonite (goethite, hematite and jarosite) and residual quartz.

ORE CONTROLS: Igneous contacts, both internal between intrusive phases and external with wallrocks; cupolas and the uppermost, bifurcating parts of stocks, dike swarms. Breccias, mainly early formed intrusive and hydrothermal types. Zones of most intensely developed fracturing give rise to ore-grade vein stockworks, notably where there are coincident or intersecting multiple mineralized fracture sets.

ASSOCIATED DEPOSIT TYPES: Skarn Cu (K01), porphyry Au (K02), epithermal Au-Ag in low sulphidation type (H05) or epithermal Cu-Au-Ag as high-sulphidation type enargite-bearing veins (L01), replacements and stockworks; auriferous and polymetallic base metal quartz and quartz-carbonate veins (I01, I05), Au-Ag and base metal sulphide mantos and replacements in carbonate and non-carbonate rocks (M01, M04), placer Au (C01, C02).

COMMENTS: Subdivision of porphyry copper deposits can be made on the basis of metal content, mainly ratios between Cu, Mo and Au. This is a purely arbitrary, economically based criterion, an artifact of mainly metal prices and metallurgy. There are few differences in the style of mineralization between deposits although the morphology of calcalkaline deposits does provide a basis for subdivision into three distinct subtypes - the 'volcanic, classic, and plutonic' types. A fundamental contrast can be made on the compositional differences between calcalkaline quartz-bearing porphyry copper deposits and the alkalic (silica undersaturated) class. The alkalic porphyry copper deposits are described in a separate model - L03.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Calcalkalic systems can be zoned with a cupriferous (± Mo) ore zone having a ‘barren’, low-grade pyritic core and surrounded by a pyritic halo with peripheral base and precious metal-bearing veins. Central zones with Cu commonly have coincident Mo, Au and Ag with possibly Bi, W, B and Sr. Peripheral enrichment in Pb, Zn, Mn, V, Sb, As, Se, Te, Co, Ba, Rb and possibly Hg is documented. Overall, the deposits are large-scale repositories of sulphur, mainly in the form of metal sulphides, chiefly pyrite.

GEOPHYSICAL SIGNATURE: Ore zones, particularly those with higher Au content, can be associated with magnetite-rich rocks and are indicated by magnetic surveys. Alternatively, the more intensely hydrothermally altered rocks, particularly those with quartz-pyrite-sericite (phyllic) alteration produce magnetic and resistivity lows. Pyritic haloes surrounding cupriferous rocks respond well to induced polarization (I.P.) surveys but in sulphide-poor systems the ore itself provides the only significant IP response.

L04 - Porphyry Cu±Mo±Au

OTHER EXPLORATION GUIDES: Porphyry deposits are marked by large-scale, zoned metal and alteration assemblages. Ore zones can form within certain intrusive phases and breccias or are present as vertical 'shells' or mineralized cupolas around particular intrusive bodies. Weathering can produce a pronounced vertical zonation with an oxidized, limonitic leached zone at surface (leached capping), an underlying zone with copper enrichment (supergene zone with secondary copper minerals) and at depth a zone of primary mineralization (the hypogene zone).

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE:

- Worldwide according Cox and Singer (1988) based on their subdivision of 55 deposits into subtypes according to metal ratios, typical porphyry Cu deposits contain (median values):
  Porphyry Cu-Au: 160 Mt with 0.55 % Cu, 0.003 % Mo, 0.38 g/t Au and 1.7 g/t Ag.
  Porphyry Cu-Au-Mo: 390 Mt with 0.48 % Cu, 0.015 % Mo, 0.15 g/t Au and 1.6 g/t Ag.
  Porphyry Cu-Mo: 500 Mt with 0.41 % Cu, 0.016 % Mo, 0.012 g/t Au and 1.22 g/t Ag.
  A similar subdivision by Cox (1986) using a larger data base results in:
  Porphyry Cu: 140 Mt with 0.54 %Cu, <0.002 % Mo, <0.02g/t Au and <1 g/t Ag.
  Porphyry Cu-Au: 100 Mt with 0.5 %Cu, <0.002 % Mo, 0.38g/t Au and 1g/t Ag. (This includes deposits from the British Columbia alkalic porphyry class, B.C. model L03.)
  Porphyry Cu-Mo: 500 Mt with 0.42 % Cu, 0.016 % Mo, 0.012 g/t Au and 1.2 g/t Ag.
- British Columbia porphyry Cu ± Mo ± Au deposits range from <50 to >900 Mt with commonly 0.2 to 0.5 % Cu, <0.1 to 0.6 g/t Au, and 1 to 3 g/t Ag. Mo contents are variable from negligible to 0.04 % Mo. Median values for 40 B.C. deposits with reported reserves are: 115 Mt with 0.37 % Cu, ~0.01 % Mo, 0.3g/t Au and 1.3 g/t Ag.

ECONOMIC LIMITATIONS: Mine production in British Columbia is from primary (hypogene) ores. Rare exceptions are Afton mine where native copper was recovered from an oxide zone, and Gibraltar and Bell mines where incipient supergene enrichment has provided some economic benefits.

END USES: Porphyry copper deposits produce Cu and Mo concentrates, mainly for international export.

IMPORTANCE: Porphyry deposits contain the largest reserves of Cu, significant Mo resources and close to 50 % of Au reserves in British Columbia.

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L04 - Porphyry Cu±Mo±Au

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L05 - Porphyry Mo (Low F-Type)

by W. David Sinclair[1]

Sinclair, W. D., 1995. Porphyry Mo (low F type): In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 93–95.

IDENTIFICATION

SYNONYMS: Calcalkaline Mo stockwork; Granite-related Mo; Quartz-monzonite Mo.

COMMODITIES (BYPRODUCTS): Mo (Cu, W)

EXAMPLES (British Columbia - *Canada/International*): Endako (093K 006), Boss Mountain (093A 001), Kitsault (103P 120), Adanac (104N 052), Carmi (082ESW029), Bell Moly (103P 234), Red Bird (093E 026), Storie Moly (104P 069), Trout Lake (082KNW087); *Red Mountain (Yukon, Canada), Quartz Hill (Alaska, USA), Cannivan (Montana, USA), Thompson Creek (Idaho, USA), Compaccha (Peru), East Kounrad (Russia), Jinduicheng (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockwork of molybdenite-bearing quartz veinlets and fractures in intermediate to felsic intrusive rocks and associated country rocks. Deposits are low grade but large and amenable to bulk mining methods.

TECTONIC SETTING(S): Subduction zones related to arc-continent or continent-continent collision.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres; multiple stages of intrusion are common.

AGE OF MINERALIZATION: Archean (e.g. Setting Net Lake, Ontario) to Tertiary; Mesozoic and Tertiary examples are more common.

HOST/ASSOCIATED ROCK TYPES: All kinds of rocks may be hostrocks. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusive rocks. Genetically related intrusive rocks range from granodiorite to granite and their fine-grained equivalents, with quartz monzonite most common: they are commonly porphyritic. The intrusive rocks are characterized by low F contents (generally <0.1 % F) compared to intrusive rocks associated with Climax-type porphyry Mo deposits.

DEPOSIT FORM: Deposits vary in shape from an inverted cup, to roughly cylindrical, to highly irregular. They are typically hundreds of metres across and range from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore is predominantly structurally controlled; mainly stockworks of crosscutting fractures and quartz veinlets, also veins, vein sets and breccias.

ORE MINERALOGY (Principal and *subordinate*): Molybdenite is the principal ore mineral*; chalcopyrite, scheelite, and galena are generally subordinate*.

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L05 - Porphyry Mo (Low F-Type)

GANGUE MINERALOGY: Quartz, pyrite, K-feldspar, biotite, sericite, clays, calcite and anhydrite.

ALTERATION MINERALOGY: Alteration mineralogy is similar to that of porphyry Cu deposits. A core zone of potassic and silicic alteration is characterized by hydrothermal K-feldspar, biotite, quartz and, in some cases, anhydrite. K-feldspar and biotite commonly occur as alteration selvages on mineralized quartz veinlets and fractures but may be pervasive in areas of intense fracturing and mineralization. Phyllic alteration typically surrounds and may be superimposed to various degrees on the potassic-silicic core; it consists mainly of quartz, sericite and carbonate. Phyllic alteration is commonly pervasive and may be extensive. Propylitic alteration consisting mainly of chlorite and epidote may extend for hundreds of metres beyond the zones of potassic-silicic and phyllic alteration. Zones of argillic alteration, where present, are characterized by clay minerals such as kaolinite and are typically overprinted on the other types of alteration; distribution of argillic alteration is typically irregular.

WEATHERING: Oxidation of pyrite produces limonitic gossans; oxidation of molybdenite produces yellow ferrimolybdite.

ORE CONTROLS: Quartz veinlet and fracture stockwork zones superimposed on intermediate to felsic intrusive rocks and surrounding country rocks; multiple stages of mineralization commonly present.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip Mo and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and in associated country rocks. Incursion of meteoric water during waning stages of the magmatic-hydrothermal system may result in late alteration of the hostrocks, but does not play a significant role in the ore-forming process.

ASSOCIATED DEPOSIT TYPES: Ag-Pb-Zn veins (I05), Mo-bearing skarns (K07) may be present.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mo, Cu, W and F may be anomalously high in hostrocks close to and overlying mineralized zones; anomalously high levels of Pb, Zn and Ag occur in peripheral zones as much as several kilometres distant. Mo, W, F, Cu, Pb, Zn and Ag may be anomalously high in stream sediments. Mo, W and Pb may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Magnetic anomalies may reflect presence of pyrrhotite or magnetite in hornfels zones. Radiometric surveys may be used to outline anomalous K in altered and mineralized zones. Induced polarization and resistivity surveys may be used to outline high-pyrite alteration zones.

OTHER EXPLORATION GUIDES: Limonitic alteration of pyrite can result in widespread gossan zones. Yellow ferrimolybdite may be present in oxidized zones. Ag-Pb-Zn veins may be present in peripheral zones.

L05 - Porphyry Mo (Low F-Type)

ECONOMIC FACTORS

GRADE AND TONNAGE: Typical size is 100 Mt at 0.1 to 0.2 % Mo. The following figures are for production plus reserves.
Endako (B.C.): 336 Mt at 0.087 % Mo; Boss Mountain (B.C.): 63 Mt. at 0.074 % Mo;
Kitsault (B.C.): 108 Mt at 0.115 % Mo; Lucky Ship (B.C.): 14 Mt at 0.090 % Mo;
Adanac (B.C.): 94 Mt at 0.094 % Mo; Carmi (B.C.): 34 Mt at 0.091 % Mo;
Mount Haskin (B.C.): 12 Mt at 0.090 % Mo; Bell Moly (B.C.): 32 Mt at 0.066 % Mo;
Red Bird (B.C.): 34 Mt at 0.108 % Mo; Storie Moly (B.C.): 101 Mt at 0.078 % Mo;
Trout Lake (B.C.): 50 Mt at 0.138 % Mo; Glacier Gulch (B.C.): 125 Mt at 0.151 % Mo;
Red Mountain (Yukon): 187 Mt at 0.100 % Mo; Quartz Hill (Alaska): 793 Mt at 0.091 % Mo;
Thompson Creek (Idaho): 181 Mt at 0.110 % Mo; Compaccha (Peru): 100 Mt at 0.072 % Mo;
East Kounrad (Russia): 30 Mt at 0.150 % Mo.

IMPORTANCE: Porphyry Mo deposits associated with low-F felsic intrusive rocks have been an important source of world molybdenum production. Virtually all of Canada’s Mo production comes from these deposits and from porphyry Cu-Mo deposits.

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L06 - Porphyry Sn

by W. David Sinclair[1]

Sinclair, W.D., 1995. Porphyry Sn: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 97–99.

IDENTIFICATION

SYNONYM: Subvolcanic Sn

COMMODITIES (BYPRODUCTS): Sn (Ag, W)

EXAMPLES (British Columbia - *Canada/International*): *Mount Pleasant (New Brunswick, Canada), East Kemptville (Nova Scotia, Canada), Catavi, Chorolque and Cerro Rico stock (Bolivia), Ardlethan and Taronga (Australia), Kingan (Russia), Yinyan (China), Altenberg (Germany).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Fine-grained cassiterite in veinlet and fracture stockwork zones, breccia zones, and disseminated in porphyritic felsic intrusive rocks and associated country rocks.

TECTONIC SETTING: Zones of weak to moderate extension in cratons, particularly post orogenic zones underlain by thick crust, possibly cut by shallow-dipping subduction zones.

GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres in cratons; multiple stages of intrusion may be present.

AGE OF MINERALIZATION: Paleozoic to Tertiary.

HOST/ASSOCIATED ROCK TYPES: Predominantly genetically related intrusive rocks and associated breccias, but may also include related or unrelated sedimentary, volcanic, igneous and metamorphic rocks. Genetically related felsic intrusive rocks are F and/or B enriched and are commonly porphyritic. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusions.

DEPOSIT FORM: Deposits vary in shape from inverted cone, to roughly cylindrical, to highly irregular. They are typically large, generally hundreds of metres across and ranging from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore is predominantly structurally controlled in stockworks of crosscutting fractures and quartz veinlets, or disseminated in hydrothermal breccia zones. Veins, vein sets, replacement zones may also be present.

ORE MINERALOGY (Principal and *Subordinate*): Cassiterite; *stannite, chalcopyrite, sphalerite and galena. Complex tin- and silver-bearing sulphosalts occur in late veins and replacement zones*.

GANGUE MINERALOGY: Pyrite, arsenopyrite, löllingite, topaz, fluorite, tourmaline, muscovite, zinnwaldite and lepidolite.

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[1] Geological Survey of Canada, Ottawa, Ontario, Canada

L06 - Porphyry Sn

ALTERATION MINERALOGY: In the Bolivian porphyry Sn deposits, sericite + pyrite ± tourmaline alteration is pervasive; in some deposits it surrounds a central zone of quartz + tourmaline. Sericitic alteration is typically bordered by weak propylitic alteration. In other deposits (*e.g.* Ardlethan, Yinyan), central zones are characterized by greisen alteration consisting of quartz + topaz + sericite; these zones grade outward to quartz + sericite + chlorite alteration.

WEATHERING: Oxidation of pyrite produces limonitic gossans. Deep weathering and erosion can result in residual concentrations of cassiterite in situ or in placer deposits downslope or downstream.

ORE CONTROLS: Ore minerals occur in fracture stockworks, hydrothermal breccias and replacement zones centred on 1-2 km^2, genetically related felsic intrusions.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip Sn and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and associated country rocks. Mixing of magmatic with meteoric water during waning stages of the magmatic-hydrothermal system may result in deposition of some Sn and other metals, particularly in late-stage veins.

ASSOCIATED DEPOSIT TYPES: Sn veins (I13), Sn-polymetallic veins (H07).

COMMENTS: Some of the deposits listed (*e.g.* Taronga, East Kemptville) are not "subvolcanic" but they are similar to some porphyry Cu deposits with regard to their large size, low grade, relationship to felsic intrusive rocks and dominant structural control (ie., mineralized veins, fractures and breccias).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sn, Ag, W, Cu, Zn, As, Pb, Rb, Li, F, B may be anomalously high in hostrocks close to mineralized zones and in secondary dispersion halos in overburden. Anomalously high contents of Sn, W, F, Cu, Pb and Zn may occur in stream sediments and Sn, W, F (topaz) and B (tourmaline) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Genetically related intrusions may be magnetic lows (ilmenite- rather than magnetite-dominant); contact aureole may be magnetic high if pyrrhotite or magnetite are present in associated skarn or hornfels zones. Radiometric surveys may be used to outline anomalous U, Th or K in genetically related intrusive rocks or in associated altered and mineralized zones.

OTHER EXPLORATION GUIDES: Sn (-Ag) deposits may be zoned relative to base metals at both regional (district) and local (deposit) scales.

ECONOMIC FACTORS

GRADE AND TONNAGE: Tens of millions of tonnes at grades of 0.2 to 0.5% Sn.

Mount Pleasant (New Brunswick): 5.1 Mt @ 0.79% Sn; East Kemptville (Nova Scotia): 56 Mt @ 0.165% Sn; Catavi (Bolivia): 80 Mt @ 0.3% Sn; Cerro Rico stock, Bolivia: averages 0.3% Sn; Ardlethan (Australia): 9 Mt @ 0.5% Sn; Taronga (Australia): 46.8 Mt @ 0.145% Sn; Altenberg, (Germany): 60 Mt @ 0.3% Sn; Yinyan (China): "large" (50 - 100 Mt?) @ 0.46% Sn

ECONOMIC LIMITATIONS: Low grades require high volumes of production which may not be justified by demand.

L06 - Porphyry Sn

IMPORTANCE: A minor source of tin on a world scale; when it was in production, East Kemptville was the major producer of tin in North America.

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L07 - Porphyry W

by W. David Sinclair[1]

Sinclair, W.D., 1995. Porphyry W: In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 101–104

IDENTIFICATION

SYNONYM: Stockwork W-Mo

COMMODITIES (BYPRODUCTS): W (Mo, Sn, Ag).

EXAMPLES (British Columbia - *Canada/International*): Boya (094M 021, 016; *Logtung (Yukon, Canada), Mount Pleasant (New Brunswick, Canada), Xingluokeng, Lianhuashan and Yanchuling (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockwork of W-bearing quartz veinlets and fractures in felsic intrusive rocks and associated country rocks. Deposits are low grade but large and amenable to bulk mining methods.

TECTONIC SETTING: Zones of weak to moderate extension in cratons, particularly post-collisional zones in areas of tectonically thickened crust.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres; multiple stages of intrusion are common.

AGE OF MINERALIZATION: Paleozoic to Tertiary, but Mesozoic and Tertiary examples are more common.

HOST/ASSOCIATED ROCK TYPES: Highly variable; mineralized rocks may be predominantly genetically related intrusive rocks, but may also be related or unrelated sedimentary, volcanic, igneous and metamorphic rocks. Genetically related felsic intrusive rocks are commonly F-rich (fluorite and/or topaz bearing) and porphyritic; unidirectional solidification features, particularly comb quartz layers, may also be present. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusions.

DEPOSIT FORM: Deposits vary in shape from inverted cup-shaped, to roughly cylindrical, to highly irregular. They are typically large, generally hundreds of metres across and ranging from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore minerals is structurally controlled; mainly stockworks of crosscutting fractures and quartz veinlets, also veins, vein sets, breccias, disseminations and replacements.

ORE MINERALOGY (Principal and *subordinate*): Main ore mineral is generally either scheelite or wolframite, although in some deposits both are present. *Subordinate ore minerals include molybdenite, bismuth, bismuthinite and cassiterite*.

GANGUE MINERALOGY: Pyrite, pyrrhotite, magnetite, arsenopyrite, löllingite, quartz, K-feldspar, biotite, muscovite, fluorite, topaz.

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[1] Geological Survey of Canada, Ottawa, Ontario, Canada

L07 - Porphyry W

ALTERATION MINERALOGY: Hydrothermal alteration is pervasive to fracture controlled and, at deposit scale, is concentrically zoned. It is commonly characterized by the presence of greisen alteration minerals, including topaz, fluorite and Li- and F-rich micas. At Mount Pleasant, for example, pervasive greisen alteration consisting of quartz + topaz ± sericite ± chlorite associated with high-grade W zones and grades laterally into fracture-controlled quartz-biotite-chlorite-topaz alteration associated with lower grade W zones. Propylitic alteration, mainly chlorite and sericite, extends as far as 1500 m beyond the mineralized zones. Potassic alteration, dominated by K-feldspar, occurs locally within the central areas of pervasive greisen alteration. Other deposits such as Xingluokeng (China) are characterized more by central zones of silicic and potassic alteration (K-feldspar and biotite); zones of weak greisen alteration consisting of muscovite and fluorite may be present. Sericitic alteration forms a broad aureole around the central potassic zone; irregular zones of argillic alteration may be superimposed on both the potassic and sericitic zones. In detail, alteration patterns may be complex; at Logtung, for example, different stages of mineralized veins and fractures are characterized by different assemblages of ore and alteration minerals.

WEATHERING: Oxidation of pyrite produces limonitic gossans; oxidation of molybdenite, if present, may produce yellow ferrimolybdenite.

ORE CONTROLS: Quartz veinlet and fracture stockwork zones surround or are draped over and are superimposed to varying degrees on small stocks (<1 km^2); multiple stages of mineralization commonly present; felsic intrusions associated with the deposits are typically F-rich.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip W, Mo and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and associated country rocks. Incursion of meteoric water during waning stages of the magmatic-hydrothermal system may result in late alteration of the hostrocks, but does not play a significant role in the ore forming process.

ASSOCIATED DEPOSIT TYPES: Porphyry W deposits may be part of a spectrum of deposits that include Climax-type Mo deposits (L08) as one end-member and porphyry Sn deposits as the other (L06). Vein/replacement W, Sn, Ag deposits may be associated (I05, H07), *e.g.* Logjam Ag-Pb-Zn veins peripheral to the Logtung W-Mo deposit. Skarn (contact metamorphic) zones associated with genetically related felsic intrusions may be mineralized, but are not typical skarn W (i.e. contact metasomatic) deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: W, Mo and Sn are anomalous in hostrocks close to mineralized zones; anomalously high contents of F, Zn, Pb and Cu occur in wallrocks up to several kilometres from mineralized zones. W, Sn, Mo, F, Cu, Pb and Zn may be anomalously high in stream sediments and W, Sn and F (topaz) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Genetically related intrusions may be magnetic lows (ilmenite rather than magnetite dominant); contact aureole may be magnetic high if pyrrhotite or magnetite are present in associated skarn or hornfels zones. Radiometric surveys may be used to outline anomalous U, Th or K in genetically related intrusive rocks or in associated altered and mineralized zones.

OTHER EXPLORATION GUIDES: The presence of scheelite can be detected with an ultraviolet lamp.

L07 - Porphyry W

ECONOMIC FACTORS

GRADE AND TONNAGE: Tens to more than 100 Mt at grades of 0.2 to 0.3 % W (Lianhushan is exceptional at 0.8 % W). Boya (British Columbia): limited size due to thrust fault truncation, no published resource data. Mount Pleasant (New Brunswick): Fire Tower zone: 22.5 Mt @ 0.21 % W, 0.10 % Mo, 0.08 % Bi, (includes 9.4 Mt @ 0.31 % W, and 0.12 % Mo), North zone: 11 Mt @ 0.2 % W, 0.1 % Mo. Logtung (Yukon): 162 Mt @ 0.10 % W, 0.03 % Mo. Xingluokeng (China): 78 Mt @ 0.18 % W. Lianhuashan (China): ~40 Mt @ 0.8 % W.

ECONOMIC LIMITATIONS: Low grades require high production volumes which may not be justified by current demand for tungsten.

IMPORTANCE: Not currently an important source of world W production; some W may be recovered from deposits in China (*e.g.* Lianhuashan), but none is recovered at present (1994) from deposits outside China. Mount Pleasant Tungsten in New Brunswick produced slightly more than 2000 t of concentrate grading 70% WO_3 from 1 Mt of ore mined from 1983 to 1985.

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L08 - Porphyry Mo (Climax-Type)

by W. David Sinclair[1]

Sinclair, W.D., 1995. Porphyry Mo (Climax-type): In: Selected mineral deposit profiles, volume 1 - metallics and coal, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1995-20, pp. 105–108.

IDENTIFICATION

SYNONYMS: Granite molybdenite; Climax Mo; granite-related Mo.

COMMODITIES (BYPRODUCTS): Mo (W, Sn; pyrite and monazite have also been recovered from the Climax deposit)

EXAMPLES (British Columbia - *Canada/International*): No unequivocal Climax-type porphyry Mo deposits occur in British Columbia *or other parts of Canada*; *Climax, Henderson, Mount Emmons and Silver Creek (Colorado, USA), Pine Grove (Utah, USA), Questa (New Mexico), Malmbjerg (Greenland), Nordli (Norway).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockworks of molybdenite-bearing quartz veinlets and fractures in highly evolved felsic intrusive rocks and associated country rocks. Deposits are low grade but large and amenable to bulk mining methods.

TECTONIC SETTING: Rift zones in areas of thick cratonic crust.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres; multiple stages of intrusion are common.

AGE OF MINERALIZATION: Paleozoic to Tertiary, but mainly Tertiary.

HOST/ASSOCIATED ROCK TYPES: Genetically related felsic intrusive rocks are high-silica (>75% SiO_2), F-rich (>0.1% F) granite/rhyolite; they are commonly porphyritic and contain unidirectional solidification textures (USTs), particularly comb quartz layers. Contents of Rb, Y and Nb are high; Ba, Sr and Zr are low. Mineralized country rocks may include sedimentary, metamorphic, volcanic, and older intrusive rocks. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusions.

DEPOSIT FORM: Deposits typically form an inverted cup or hemispherical shell; shapes may be modified by regional or local structures. They are typically large, generally hundreds of metres across and ranging from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore is structurally controlled; mainly stockworks of crosscutting fractures and quartz veinlets, also veins, vein sets and breccias; disseminations and replacements are less common.

ORE MINERALOGY (Principal and *Subordinate*): Molybdenite; *wolframite, cassiterite, sphalerite, galena, monazite*.

GANGUE MINERALOGY: Quartz, pyrite, topaz, fluorite and rhodochrosite.

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[1] Geological Survey of Canada, Ottawa, Ontario, Canada

L08 - Porphyry Mo (Climax-Type)

ALTERATION MINERALOGY: Potassic alteration (K-feldspar ± biotite) is directly associated with high-grade Mo (>0.2% Mo); pervasive silicic alteration (quartz ± magnetite) may occur locally in the lower parts of high-grade Mo zones. Quartz-sericite-pyrite alteration may extend hundreds of metres vertically above orebodies; argillic alteration may extend hundreds of metres beyond quartz-sericite-pyrite alteration, both vertically and laterally. Spessartine garnet occurs locally within quartz-sericite-pyrite and argillic alteration zones. Greisen alteration consisting of quartz-muscovite-topaz occurs as alteration envelopes around quartz-molybdenite veins below high-grade Mo zones. Propylitic alteration is widespread and may extend for several km.

WEATHERING: Oxidation of pyrite produces limonitic gossans; oxidation of molybdenite produces yellow ferrimolybdite.

ORE CONTROLS: Quartz veinlet and fracture stockwork zones surround or are draped over, and are superimposed to varying degrees on small, genetically related stocks (area <1 km^2); multiple stages of mineralization are commonly present; abundant comb quartz layers and other USTs characterize productive intrusions.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip Mo and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and associated country rocks. Incursion of meteoric water during waning stages of the magmatic-hydrothermal system may result in late alteration of the hostrocks, but does not play a significant role in the ore-forming process.

ASSOCIATED DEPOSIT TYPES: Ag-base metal veins (I05), fluorspar deposits. Some porphyry W-Mo deposits (*e.g.* Mount Pleasant) may be W-rich Climax-type deposits. Mo may also be present in adjacent skarn deposits (K07). Climax-type porphyry Mo deposits may be related to rhyolite-hosted Sn deposits (H07, USGS model 25h).

COMMENTS: This model is based mainly on descriptions of Climax and Climax-type deposits in Colorado. These deposits tend to have more complex igneous-hydrothermal systems and higher average Mo grades than low-F-type porphyry Mo deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mo, Sn, W, Rb, Mn and F may be anomalously high in hostrocks close to and overlying mineralized zones; Pb, Zn, F and U may be anomalous in wallrocks as much as several kilometres distant. Mo, Sn, W, F, Cu, Pb, Zn may be anomalous in stream sediments and Mo, Sn, W, and F (topaz) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Genetically related intrusions may be magnetic lows (ilmenite rather than magnetite dominant). Radiometric surveys may be used to outline anomalous U, Th or K in genetically related intrusive rocks or in associated altered and mineralized zones.

OTHER EXPLORATION GUIDES: Deposits occur in extensional tectonic settings in areas of thick continental crust. Genetically related felsic intrusive rocks generally have high contents of Nb (>75 ppm). Ag-Pb-Zn veins, topaz, fluorite and Mn-garnet may be present in peripheral zones. Yellow ferrimolybdite may be present in oxidized zones.

L08 - Porphyry Mo (Climax-type)

ECONOMIC FACTORS

GRADE AND TONNAGE: Deposits typically contain hundreds of millions of tonnes at 0.1 to 0.3% Mo. Following figures are production plus reserves (from Carten et al., 1993): Climax, Colorado: 769 Mt @ 0.216% Mo (mineable), Henderson, Colorado: 727 Mt @ 0.171% Mo (geological), Mount Emmons, Colorado: 141 Mt @ 0.264% Mo (mineable), Silver Creek, Colorado: 40 Mt @ 0.310% Mo (geological), Pine Grove, Utah: 125 Mt @ 0.170% Mo (geological), Questa, New Mexico: 277 Mt @ 0.144% Mo (mineable), Malmbjerg, Greenland: 136 Mt @ 0.138% Mo (geological), Nordli, Norway: 181 Mt @ 0.084% Mo (geological)

ECONOMIC LIMITATIONS: Economic viability of these deposits is affected by Mo production from other types of deposits such as porphyry Cu-Mo deposits, which produce Mo as a coproduct or byproduct.

IMPORTANCE: Porphyry Mo deposits of the Climax type have been a major source of world Mo production and contain substantial reserves.

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L09 - Plutonic-Related Au Quartz Veins & Veinlets

by David V. Lefebure[1] and Craig Hart[2]

Lefebure, D.V., and Hart, C., 2005. Plutonic-related Au quartz veins & veinlets: In: Yukon Mineral Deposit Profiles, Yukon Geological Survey, Energy, Mines and Resources, compiled by A. Fonseca and G. Bradshaw, YGS Open File 2005-5, pp. 121–125.

IDENTIFICATION

SYNONYMS: Intrusion-related gold systems, gold porphyries, plutonic-related gold quartz veins. Plutonic-related gold, Au-lithophile element deposits, Fort Knox-type Au, high arsenic and/or bismuth plutonic-related mesothermal gold deposits, intrusion-hosted gold vein and brittle shear zone deposits.

COMMODITIES (BYPRODUCTS): Au (Ag, W).

EXAMPLES: (British Columbia - *Canada/International*): Cam Gloria? (082M266), Ridge Zone, Rozan Property (082FSW179); *Dublin Gulch (106D 025), Clear Creek (115P 014), Scheelite Dome (115P 003), Brewery Creek (116B 160) (Yukon, Canada), Fort Knox, Cleary Hill (Alaska, USA), Mokrsko (Czech Republic), Timbarra (New South Wales, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold mineralization hosted by millimetre to metre-wide quartz veins hosted by equigranular to porphyritic granitic intrusions and adjacent hornfelsed country rock. The veins form parallel arrays (sheeted) and less typically, weakly developed stockworks; the density of the veins and veinlets is a critical element for defining ore. Native gold occurs associated with minor pyrite, arsenopyrite, pyrrhotite, scheelite and bismuth and telluride minerals.

TECTONIC SETTINGS: Most commonly found in continental margin sedimentary assemblages where intruded by plutons behind continental margin arcs. Typically developed late in orogeny or post-collisional settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Veins form in tensional fractures and shears within, and near, the apices of small (<3 km^2) granitoid intrusions at depths of 3-8 kilometres.

AGE OF MINERALIZATION: Any age, although they are best known (preserved?) in Paleozoic to Mesozoic rocks. Cenozoic deposits generally not yet exposed by erosion. Deposits in Alaska and the Yukon are Cretaceous age. Central Asian and European deposits are Carboniferous.

HOST/ASSOCIATED ROCK TYPES: The host rocks are granitic intrusions and variably metamorphosed sedimentary rocks. Associated volcanic rocks are rare. The granitoid rocks are lithologically variable, but typically granodiorite, quartz monzonite to granite. Most intrusions have some degree of lithological variation that appear as multiple phases that can include monzonite, monzogranite, albite granites, alkali syenite and syenite. The more differentiated phases commonly contain feldspar and quartz and less than 5% mafic minerals. Some deposits have abundant associated dykes, including lamprophyres, pegmatites, aplites and phases that have been fractionated from the main intrusion. Medium-to coarse-grained

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intrusions are commonly equigranular, but can contain megacrysts of potassium feldspar or porphyritic phenocrysts of quartz, plagioclase, or biotite. Biotite is common, hornblende is only locally observed, pyroxene is rare, and muscovite and tourmaline is common in more highly fractionated phases, aplites or pegmatites. The intrusions have a reduced primary oxidation state. Evidence of fluid saturation, such as miarolitic cavities, locally up to several centimetres, can be common; some intrusions exhibit much larger ones. Many of the granitoid intrusions have contact metamorphic aureoles that extend up to several km from the intrusion and can be much larger than the surface exposure of the intrusion. The stocks generally intrude variably metamorphosed sedimentary rocks (sandstone, shale, carbonate), however, some cut sequences which include metavolcanic rocks. In some cases the deposits are hosted by relatively high-grade metamorphic rocks including orthogneiss that may reflect the emplacement of the intrusions and veins at greater depths.

DEPOSIT FORM: Mineralization can be divided into intrusion-related, epizonal and shear-veins. Intrusion-related mineralization typically occurs widespread sheeted vein arrays. The arrays typically consist of numerous sheeted, or less commonly stockwork, veinlets and veins that form zones that are 10’s of metres wide, and continuous for several 10’s of metres. The veins are commonly hairline to centimetres wide, while some veins may be up to tens of metres thick. Epizonal mineralization is typically less focused, and may be disseminated, or occur as replacements. The thicker shear-veins veins are typically in fault zones outside of the pluton. The sheeted and stockwork zones extend up to a kilometre in the greatest dimension, while individual veins can be traced for more than a kilometre in exceptional cases.

TEXTURE/STRUCTURE: The sheeted veins are planar and often parallel to regional structures. The veins are generally extensional with no offset of walls, although some vein systems may also include shear-hosted veins. The veins may have minor vugs and drusy quartz. While most veins and structures are steeply dipping, shallowly dipping pegmatite and quartz bodies occur in some deposits, particularly those in the plutonic apices.

ORE MINERALOGY [Principal and S*ubordinate*]: Sulphide minerals are generally less than 3% and can be less than 1%. A number of deposits/intrusions have late and/or peripheral arsenopyrite, stibnite or galena veins. Native gold, sometimes visible, occurs with associated minor pyrite, arsenopyrite, loellingite, pyrrhotite, variable amounts of scheelite or more rarely wolframite, and sometimes *molybdenite, bismuthinite, native bismuth, maldonite, tellurobismuthinite, bismite, telleurides, tetradymite, galena and chalcopyrite*. Epizonal veins are arsenopyrite-pyrite rich and lack associated Bi, Te and W minerals. The thicker, solitary veins typically contain higher percentages (<20%) of sulphide minerals. Generally, sulphide mineral content is higher in veins hosted in the country-rocks.

GANGUE MINERALOGY: Quartz is the dominant gangue mineral with associated minor sericite, alkali feldspar, biotite, calcite and tourmaline. In some deposits the quartz veins grade into pegmatite dykes along strike - a relationship that has been referred to as vein-dykes or pegmatite veins. The pegmatites in some deposits can carry significant amounts of gold or scheelite, although they do not usually constitute ore. Many “veins” may lack gangue and are simply sulphide mineral coatings on fracture surfaces.

ALTERATION MINERALOGY: These deposits are characterized by relatively restricted alteration zones which are most obvious as narrow alteration selvages along the veins. The alteration generally consists of the same non-sulphide minerals as occur in the veins, typically albite, potassium feldspar, biotite, sericite, carbonate (dolomite) and minor pyrite. Pervasive alteration, dominated by sericite, only occurs in association with the best ore zones. The wall rocks surrounding the granitoid intrusions are typically hornfelsed and if carbonaceous, contain disseminated pyrrhotite. Alteration appears to be more extensive with shallow depths of emplacement or greater distances from the intrusion. Epizonal deposits may have clay alteration minerals.

WEATHERING: The quartz veins resist weathering and can form linear knobs. Since alteration zones are frequently weak and the veins often contain only minor sulphide minerals, associated gossans or colour anomalies are rare. However, oxidized sulphide-rich epizonal mineralization may yield gossans.

L09 - Plutonic-Related Au Quartz Veins & Veinlets

GENETIC MODELS: The veins are genetically related to proximal granitoid intrusions, which explains their association with tungsten, bismuth and other lithophile elements, and the transitional relationships with pegmatites seen in some deposits. Mineralization likely formed from late stage fluids that accumulated in late-stage melts of differentiating granitic intrusions at depths of 2 to 8 km below the surface. These fluids typically contain elevated PCO_2 and have lower salinities which enable them to transport gold and/or tungsten and only limited amounts of base metals. At some point following sufficient differentiation to concentrate anomalous concentrations of elements, such as Au and W, the fluids are released along fractures that developed in response to regional stresses and faults that accommodated pluton emplacement. Locally fluids infiltrate permeable or reactive rock units to form replacement mineralization or skarns. Stockwork mineralization is not common, but may have higher grades due to increased vein density. The deeper vein systems had little or no meteoric water input. In most deposits there are several other styles of mineralization, such as skarns and distal sulphide-rich veins that can be related to the same granitic intrusions but have different metallogenic signatures as they formed from rapidly evolving fluids. These characteristics are typical of an intrusion-centred mineralizing system, but are not characteristic of the shear-veins that do not show any metallogenic zonation or associated deposit types. The epizonal deposits may have evidence vectoring towards a higher-temperature zone, but typically form outside of the steep thermal gradients that are proximal to a cooling pluton.

ORE CONTROLS: The mineralization is strongly structurally controlled and spatially related to highly differentiated granitoid intrusion. Mineralization is commonly hosted by, or close to, the most evolved phase of the intrusion (differentiation index greater than 80).

ASSOCIATED DEPOSIT TYPES: W and Au skarns (K05, K04), W veins (I12), stibnite-gold veins (I09), Au-quartz veins (I01), disseminated gold sediment-hosted deposits (E03) and possibly polymetallic veins (I05). The veins commonly erode to produce nearby placer deposits (C01, C02).

COMMENTS: Differentiated reduced granites also host Sn greisens, but these may indicate too much fractionation to be a good gold mineralizer. Porphyry deposits, which may have associated tungsten mineralization and stibnite-base metal-gold veins are typically associated with oxidized magmas. Epizonal deposits, such as the Donlin Creek and Brewery Creek deposits have characteristics that include high sulphidation epithermal deposits. These granites are emplaced at relatively shallow depths (less than 2 kilometres) and can occur in the same regions as W-Au veins.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Placer gold in creeks draining plutons or hornfels is the best geochemical indicator. Analysis of heavy mineral or silt samples for W, Au, As and Bi is particularly effective. Elevated values of Au-W-Bi-As ± (Sn-Sb-Ag-Mo-Cu-Pb-Te-Zn) can be found in stream sediments, soils and rocks. Distal Sb and proximal Bi is a common association in the Yukon deposits.

GEOPHYSICAL SIGNATURE: Aeromagnetic data may be entirely flat as reduced granites have no magnetic signature. If the country rocks are reducing (e.g. carbonaceous), aeromagnetic signatures may produce “donut” anomalies with high magnetic values associated with pyrrhotite in the contact metamorphic zone fringing a non- magnetic intrusion.

OTHER EXPLORATION GUIDES: The number of deposits correlates inversely with the surface exposure of the related granitoid intrusion because stocks and batholiths with considerable erosion are generally less prospective. Evidence of highly differentiated granites and fluid-phase separation, such as pegmatites, aplites, unidirectional solidification textures (USTs) and leucocratic phases, indicates prospective settings. Lamprophyres indicate regions of high extension and potentially good structural sites for mineralization. Gold, wolframite, and scheelite in stream gravels and placer deposits are excellent guides. The associated deposit types (e.g. skarns) can also assist in identifying prospective areas.

L09 - Plutonic-Related Au Quartz Veins & Veinlets

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The bulk mineable, intrusion-hosted low grade sheeted vein deposits contain tens to hundreds of million tonnes of ~ 0.8 to 1.4 g/t Au. The epizonal deposits have slightly higher grades, 2-5 g/t Au and the shear veins have form high grade deposits contain hundreds of thousands to millions of tonnes grading ~10 to 35 g/t Au. Gold to silver ratios are typically less than 1. Some gold-producing veins have produced W when it was deemed a strategic metal or it reached unusually high commodity prices.

Intrusion-related

Fort Knox, Alaska - 143.5 M tonnes grading 0.82 g/t Au (cutoff of 0.39 g/t)
Dublin Gulch (Eagle Zone), Yukon - 100 Mt grading 1.2 g/t Au

Epizonal

Brewery Creek, Yukon - 13 Mt of 1.44 g/t Au
Donlin Creek, Alaska

Shear-veins

Pogo, Alaska - 9.05 Mt grading 17.83 g/t Au (cutoff of 3.43 g/t)
Ryan Lode, Alaska
Cleery Hill - ~1.36 Mt grading better than 34 g/t Au

ECONOMIC LIMITATIONS: The Fort Knox deposit has a low strip ratio and the ore is oxidized to the depths of drilling (greater than 300 m). A carbon-in-leach gold absorption with conventional carbon stripping process is used to recover the gold. The refractory nature of the arsenic-rich mineralization below the oxidation zone could render an otherwise attractive deposit sub-economic. Intrusion-hosted deposits may have a high work index.

IMPORTANCE: These deposits represent a potentially important gold resource which is found in regions that have seen limited gold exploration in recent years. A number of deposits are now known that contain more than a 100 tonnes of gold. In virtually all regions the production of gold from placers related to these deposits has exceeded the lode gold production.

ACKNOWLEDGEMENTS: This deposit profile draws heavily from presentations and related articles by Jim Lang, John Thompson, Jim Mortensen and Tim Baker summarizing research completed by the Mineral Deposits Research Unit of the University of British Columbia, Dan McCoy of Placer Dome and Moira Smith of Teck Exploration. Mike Cathro kindly reviewed the profile and provided constructive comments.

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M - Ultramafic / Mafic

Profile Title		Authors
M01*	Flood Basalt-Associated Ni-Cu	
M02*	Gabbroid Stocks Ni-Cu	
M03	Podiform chromite	C. Ash, 1996
M04	Magmatic Fe-Ti±V oxide deposits	G.A. Gross, C.F. Gower and D.V. Lefebure, 1999
M05	Alaskan-type Pt±Os±Rh±Ir	G.T. Nixon, 1996
M06	Ultramafic-hosted chrysotile asbestos	Z.D. Hora, 1999
M07	Ultramafic-hosted talc-magnesite	G.J. Simandl and D. Ogden, 1999
M08	Vermiculite deposits	G.J. Simandl, T. Birkett, and S. Paradis, 1999

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

M03 - Podiform Chromite

by Chris Ash[1]

Ash, C., 1996. Podiform chromite: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 109–112.

IDENTIFICATION

SYNONYMS: Alpine type; ophiolite hosted chromite.

COMMODITIES (BYPRODUCTS): Chromite (may contain platinum group elements Os, Ir and Ru).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Castle Mountain Nickel (082ESE091) and Scottie Creek (092INW001); *Guleman ore field (Turkey); Kalimash - Kukes-Tropoje district, Bulqize and Todo Manco - Bater-Martanesh district (Mirdita ophiolite, Albania); Tiébaghi ophiolite and Massif du Sud (New Caledonia), Acoje and Masinloc-Coto (Zambales range/ophiolite, Luzon, Phillipines); Batamshinsk, Stepninsk, Tagashaisai and Main SE ore fields (Kempirsai massif, Southern Urals, Russia); Xeraivado and Skoumtsa mines (Vourinos ophiolite, Greece); Semail ophiolite (Oman); Luobusa, Donqiao, Sartohay, Yushi, Solun, Wudu and Hegenshan deposits (China) all > 1.5 Mt*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits of massive chromitite occur as pods, lenses or layers within ophiolitic ultramafic rocks.

TECTONIC SETTING: Obducted fragments of oceanic, lower crustal and upper mantle ultramafic rocks within accreted oceanic terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Formed as a primary magmatic differentiate during early olivine and chrome-spinel crystal fractionation of basaltic liquid at an oceanic spreading centre; (1) as massive to disseminated pods and lenses of chrome-spinel surrounded by a dunite envelope within depleted mantle harzburgite; or (2) as massive to disseminated cumulate layers in dunite at the base of the crustal plutonic section.

AGE OF MINERALIZATION: Mesozoic and younger.

HOST/ASSOCIATED ROCK TYPES: Variably serpentinized peridotite; residual mantle harzburgite; cumulate dunite.

DEPOSIT FORM: Podiform, tabular lenses, irregular masses, cumulate layers. Pods and lenses typically occur in clusters of variable size.

TEXTURE/STRUCTURE: Massive to disseminated, nodular (*syn*. leopard, grape, bean or shot ore), chromite net, occluded silicate, orbicular.

ORE MINERALOGY: Chromite.

GANGUE MINERALOGY [Principal and *subordinate*]: Variably serpentinized olivine and orthopyroxene, magnetite, *iddingsite*.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

M03 - Podiform Chromite

WEATHERING: Black, no noticeable affects resulting from surface oxidation.

ORE CONTROLS: Proximity to the crust-mantle transition zone. Restricted to dunite bodies in tectonized harzburgite below this transition, or lower dunitic portions of ultramafic cumulate section above it.

GENETIC MODEL: Early fractional crystallization of chromite from a basaltic liquid either (1) just below the crust-mantle transition (syn. petrological MOHO) in small magma pockets or possibly conduits within the residual mantle harzburgite; or (2) immediately above the crust-mantle transition as cumulate layers within dunite at the base of the axial magma chamber. Pods and lenses in harzburgite obtain their diagonistic shape as a result subsolidus to hypersolidus ductile deformation due to mantle convection.

COMMENTS: Ophiolites of suprasubduction zone affinity with harzburgite mantle sections appear to be the only ophiolite type to host economic deposits of podiform chromite. A lack of any sizable chromite occurrence in British Columbia may reflect the fact that most ophiolitic complexes in the province are of mid-ocean ridge affinity. Occurrences of podiform chromite are found in ophiolitic ultramafic rocks in the Slide Mountain, Cache Creek and Bridge River terranes. Most of these known occurrences have been reviewed by Hancock (1990).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Cr

GEOPHYSICAL SIGNATURE: Gravity anomaly.

OTHER EXPLORATION GUIDES: Found in rocks formed near or within the ophiolitic crust-mantle transition zone.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grades range from 20 to 60% Cr_2O_3 and are a function of the texture of the chromite; *i.e.* amount of chromite relative to gangue serpentinite. Tonnages are variable, ranging from several thousand tonnes to several million tonnes.

ECONOMIC LIMITATIONS: The complex structure and irregular distribution make exploration and development difficult.

END USES: Chromium has a wide range of uses in the iron and steel industry which accounts for over 75% of its use. Chromite is also used in making refractory bricks for furnace linings.

IMPORTANCE: An important source of metallurgical-type chromite ores (45-60% Cr_2O_3: Cr/Fe = 2.8-4.3). Podiform chromite is the only source of refractory-type ore (min. 25% Al_2O_3: min. 60% $Cr_2O_3 + Al_2O_3$: max. 15% FeO). Historically podiform-type ore fields account for 57% of all chromite produced.

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M04 - Magmatic Ti-Fe+/-V Oxide Deposits

by G.A. Gross[1], C. F. Gower[2] and D.V. Lefebure[3]

Gross, G.A., Gower, C.F. and Lefebure, D.V., 1999. Magmatic Ti-Fe±V oxide deposits: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 57–60.

IDENTIFICATION

SYNONYMS: Mafic intrusion-hosted titanium-iron deposits.

COMMODITIES (BYPRODUCTS): Ti, Fe

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Bearpaw Ridge? (093I 028); *Methuen, Unfravile, Matthews-Chaffrey, Kingston Harbour (Ontario, Canada); Lac-du-Pin-Rouge, Lac Tio, Magpie (Quebec, Canada), Sanford Lake (New York, USA), Tellnes (Norway), Smaalands-Taberg (Sweden).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Ilmenite, hemo-ilmenite or titaniferous magnetite accumulations as cross-cutting lenses or dike-like bodies, layers or disseminations within anorthositic/gabbroic/noritic rocks. These deposits can be subdivided into an ilmenite subtype (anorthosite-hosted titanium-iron) and a titaniferous magnetite subtype (gabbro-anorthosite-hosted iron-titanium).

TECTONIC SETTING: Commonly associated with anorthosite-gabbro-norite-monzonite (mangerite)-charnockite granite (AMCG) suites that are conventionally interpreted to be anorogenic and/or extensional. Some of the iron-titanium deposits occur at continental margins related to island arc magmatism followed by an episode of orogenic compression.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Deposits occur in intrusive complexes which typically are emplaced at deeper levels in the crust. Progressive differentiation of liquids residual from anorthosite-norite magmas leads to late stage intrusions enriched in Fe and Ti oxides and apatite.

AGE OF MINERALIZATION: Mainly Mesoproterozoic (1.65 to 0.90 Ga) for the ilmenite deposits, but this may be a consequence of a particular combination of tectonic circumstances, rather than any a priori temporal control. The Fe-Ti deposits with titaniferous magnetite do not appear to be restricted in time.

HOST/ASSOCIATED ROCKS: Hosted by massive, layered or zoned intrusive complexes - anorthosite, norite, gabbro, diorite, diabase, quartz monzonite and hornblende pyroxenite. The anorthosites are commonly emplaced in granitoid gneiss, granulite, schist, amphibolite and quartzite. Some deposits associated with lower grade rocks.

DEPOSIT FORM: Lensoid, dike-like or sill-like bodies of massive ore, or disseminated in mafic host rocks. Some ore is disseminated as layers in layered intrusions. Typically the massive material has sharp, cross-cutting contacts with its anorthositic hosts, forming lenses tens to hundreds of metres wide and several hundred metres long. The massive ore may have apophyses cutting the host rock, be associated with intrusive breccias and contain anorthositic xenoliths. In layered deposits individual layers range in thickness from centimetres to metres and may be followed up to several thousand metres. Lean (disseminated) ore grades into unmineralized host rock. Lac Tio and Tellnes ore bodies are very large examples of the ilmenite subtype. Lac Tio is an irregular, tabular intrusive mass, 1100 m long and 1000 m wide. The Tellnes ore body, which is 400 m thick and 2.5 km long, is part of a 14 km long dike.

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[2] Newfoundland Department of Mines and Energy, St. John's, Newfoundland, Canada

[3] British Columbia Geological Survey, Victoria, British Columbia, Canada

M04 - Magmatic Ti-Fe+/-V Oxide Deposits

TEXTURE/STRUCTURE: Massive, disseminated or locally in layers. No zoning of ore minerals, but there may be variation in modal proportions of associated silicates. Medium or coarse grained, primary magmatic textures. Exsolution intergrowths of either ilmenite and hemo-ilmenite, or titanomagnetite, titaniferous magnetite or ilmenite in magnetite. Locally the massive ore, particularly near contacts with host rock, contains abundant xenoliths and xenocrysts derived from the associated intrusive.

ORE MINERALOGY (Principal and *subordinate*): Ilmenite, hemo-ilmenite, titaniferous magnetite and magnetite. Proportions of ilmenite and magnetite generally correlate with host rock petrology. Fe-sulphides such as *pyrrhotite, pentlandite and chalcopyrite.*

GANGUE MINERALOGY (Principal and *subordinate*): Silicate minerals, especially plagioclase, orthopyroxene, clinopyroxene and olivine, with apatite, minor *zircon and pleonaste spinel*. Orthopyroxene is rare to absent in the island arc-related titaniferous magnetite deposits.

ALTERATION MINERALOGY: Not normally altered.

WEATHERING: Rarely residual enrichment may occur in weathering zone.

ORE CONTROLS: The key control is the development of a late, separate Ti and Fe-rich liquid from a fractionating magma under stable conditions. Many deposits occur in elongate belts of intrusive complexes emplaced along deep-seated faults and fractures. Ilmenite deposits are associated with lower magnesian phases of anorthositic intrusions. Titaniferous magnetite deposits are commonly associated with magnesian, labradorite phases of anorthositic intrusions or gabbroic phases near the margins of the stock. In layered intrusions the titaniferous magnetite seams are commonly within the upper stratigraphic levels and in marginal zones of complex intrusive bodies.

GENETIC MODELS: Progressive differentiation of liquids residual from anorthosite-norite magmas leads to late enrichment in Fe and Ti. Typically plagioclase crystallization results in concentration of Fe and Ti in residual magmas which typically crystallize to form ferrodiorites and ferrogabbros. Layers form by crystal settling and accumulation on the floors of magma chambers and the disseminated deposits are believed to have formed in-situ. The origin of the discordant deposits, primarily associated with the Proterozoic anorthosites, is not well understood. Two genetic models have been suggested - remobilization of the crystal cummulates into cracks or fractures or emplacement as a Fe-Ti-oxide-rich immiscible melt with little silica.

ASSOCIATED DEPOSIT TYPES: Ni-Cu-Co magmatic sulphide deposits (M02), chromite deposits (e.g. Bushveld Complex), platinum group deposits (e.g. Stillwater Complex, Bushveld Complex), and placer ilmenite, magnetite, rutile and zircon (C01, C02).

COMMENTS: Titaniferous magnetite deposits associated with zoned ultramafic complexes in Alaska and British Columbia, such as Lodestone Mountain (092HSE034) and Tanglewood Hill (092HSE035), are included with Alaskan-type deposits (M05). Some authors would include them with magmatic Fe-Ti±V oxide deposits. In California in the San Gabriel Range occurrences of the ilmenite-subtype are hosted by anorthosite and ferrodiorite intrusions within a metamorphic complex composed of gneisses.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ti, Fe, V, Cr, Ni, Cu, Co geochemical anomalies.

GEOPHYSICAL SIGNATURE: Magnetic or EM response, although if the deposit is particularly ilmenite-rich it may exhibit either a subdued or a strong negative anomaly. Sometimes the subdued response displays characteristic irregular patterns of negative and positive anomalies that show broad smooth profiles or patterns.

M04 - Magmatic Ti-Fe=/-V Oxide Deposits

OTHER EXPLORATION GUIDES: Heavy mineral concentrations of ilmenite and titaniferous magnetite in placer deposits. Abundant apatite in some deposits. Association with anorthosite and gabbro intrusive complexes along deep fracture and fault zones.

ECONOMIC FACTORS

GRADE AND TONNAGE: Both grade and tonnage vary considerably. The ilmenite deposits are up to several hundreds of millions of tonnes with from 10 to 75% TiO_2, 32 to 45% Fe and less than 0.2% V. The Tellnes deposit comprises 300 Mt averaging 18% TiO_2. The Lac Tio deposit, largest of 6 deposits at Allard Lake, contains more than 125 Mt of ore averaging 32% TiO_2 and 36% FeO. Titaniferous magnetite deposits can be considerably larger, ranging up to a billion tonnes with grades between 20 to 45% Fe, 2 to 20% TiO_2 and less than 7% apatite with V contents averaging 0.25%.

ECONOMIC LIMITATIONS: The economic deposits are typically coarse, equigranular aggregates which are amenable to processing depending on the composition and kinds of exsolution textures of the Fe-Ti-oxide minerals.

USES: Titanium dioxide is a non-toxic, powdered white pigment used in paint, plastics, rubber, and paper. Titanium metal is resistant to corrosion and has a high strength-to-weight ratio and is used in the manufacturing of aircraft, marine and spacecraft equipment.

IMPORTANCE: Apart from placers, this type of deposit is the major source of TiO_2. These deposits were an important source of iron (pig iron) in the former Soviet Union. They have been mined for Fe in Canada, however, the grades are generally lower than those in iron formations and iron laterites. The only current iron production is as a co-product with TiO_2 in pyrometallurgial processing of ilmenite ore.

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M05 - Alaskan-Type Pt+/-Os+/-Rh+/-Ir

by Graham T. Nixon[1]

Nixon, G.T., 1996. Alaskan-type Pt±Os±Rh±Ir: In: Selected mineral deposit profiles, volume 2 - metallic deposits, British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 113–116.

IDENTIFICATION

SYNONYMS: Zoned ultramafic, Uralian-type.

COMMODITIES (BYPRODUCTS): Pt (Ir, Os, Rh, magnetite).

EXAMPLES (British Columbia - *Canada/International*): Tulameen Complex and associated placers; magnetite plus trace platinum group elements (PGE) -Lodestone Mountain (092HSE034), Tanglewood Hill (092HSE035); chromite - Grasshopper Mountain (092HNE011); olivine - Grasshopper Mountain Olivine (092HNE1890); *Red Mountain, Goodnews Bay (Alaska, USA), Tin Cup Peak (Oregon, USA), Ural Mountains and Aldan Shield (Russia), Fifield district (NSW, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Ultramafic intrusive complexes, commonly zoned, forming sills, stocks or intrusive bodies with poorly known external geometry. Subeconomic platinum group elements in lode occurrences are associated with:

1) thin (centimetre-scale), disrupted chromitite layers ,
2) thick (metre-scale) concentrations of cumulus magnetite or
3) clinopyroxenite.

Economic placer deposits appear to be derived predominantly from chromitite-hosted PGE occurrences.

TECTONIC SETTINGS: Traditionally subdivided into orogenic (unstable) and platformal (stable) environments. In British Columbia, Alaskan-type complexes were emplaced during an episode of Cordillera-wide, subduction-related arc magmatism followed by an episode of orogenic compression.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Zoned to crudely layered ultramafic-mafic intrusive complexes with rarely preserved (or poorly documented) metamorphic aureoles. Intrusive margins are commonly faulted. Traditionally viewed as deep-seated cumulates diapirically re-emplaced at high levels in the crust. In British Columbia, at least, most intrusions appear to represent cumulate deposition in upper crustal (subvolcanic?) magma chambers and the diapiric re-emplacement model lacks definitive supporting evidence.

AGE OF MINERALIZATION: Precambrian to late Mesozoic; most Alaskan-type complexes in British Columbia appear to be mid-Triassic to late Early Jurassic in age.

HOST/ASSOCIATED ROCK TYPES: Predominantly dunite, wehrlite, olivine clinopyroxenite, clinopyroxenite, hornblende clinopyroxenite, clinopyroxene hornblendite, hornblende- and/or clinopyroxene-bearing gabbro/diorite. Minor lithologies include chromitite, magnetitite, olivine-hornblende clinopyroxenite, and hornblendite. Associated feldspar-bearing lithologies include gabbro/diorite, monzonite, monzodiorite and minor alkali-feldspar syenite and hornblende-feldspar ± quartz ± biotite pegmatite.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

M05 - Alaskan-Type Pt±Os±Rh±Ir

DEPOSIT FORM: Lode occurrences of PGEs are primarily controlled by magmatic cumulate stratigraphy: 1) chromitites are restricted to dunites where they form thin discontinuous layers or schlieren, pods and nodular masses seldom more than a metre in length; 2) magnetitites and concentrations of cumulus magnetite form well bedded, locally continuous layers up to six m thick intercalated with hornblende clinopyroxenite; 3) lenses and vein-like bodies of relatively coarse-grained or "pegmatoid", biotite and magnetite-poor, PGE-bearing clinopyroxenites are enclosed by finer grained, biotite and magnetite-rich, PGE-poor clinopyroxenites.

TEXTURE/STRUCTURE: Cumulus and intercumulus textures are most common; poikilitic textures may predominate locally, especially in hornblende-bearing lithologies. Comparatively rare macroscopic layering. Euhedral to subhedral chromite concentrations form networks around olivine or discrete wispy or thin layers in dunite. Chromitites typically form schlieren and nodular masses due to syndepositional remobilization. Magnetite-rich accumulations usually form thin to thick bedded layers in hornblende clinopyroxenite. Tectonic deformation, commonly in the form of ductile shear fabrics, is locally superimposed on magmatic textures, and is especially prevalent at intrusive contacts.

ORE MINERALOGY (Principal and *subordinate*): Three types of PGE mineral (PGM) associations are recognized in lode occurrences: 1) chromitite-PGM association, principally chromite and Pt-Fe(-Cu-Ni) alloys (e.g. tetraferroplatinum, isoferroplatinum, rare *native platinum, tulameenite*) and minor *Os-Ir* and *Pt-Ir alloys, Rh-Ir sulpharsenides (hollingworthite-irarsite* series), *sperrylite* ($PtAs_2$), *geversite* ($PtSb_2$), and *laurite* (RuS_2); 2) magnetitite-PGM association (not well documented), principally magnetite (Ti-V-rich in certain cases) and Pt-Fe and Os-Ir alloys, and rare *cooperite* (PtS); 3) clinopyroxenite-PGM association (known from a single locality - Fifield, NSW, Australia), principally Pt-Fe alloys (isoferroplatinum-tetraferroplatinum), erlichmanite (OsS_2), cooperite, and sperrylite-geversite. Minor amounts of *base metal sulphides (chalcopyrite, pentlandite, pyrrhotite, pyrite, bornite, violarite, bravoite, millerite, heazlewoodite*) generally accompany the PGM in all three associations.

GANGUE MINERALOGY (Principal and *subordinate*): The principal gangue minerals include olivine, chrome spinel, clinopyroxene, and hornblende in ultramafic rocks; hornblende, clinopyroxene and plagioclase in gabbroic/dioritic rocks; and hornblende, quartz (rare) and alkali feldspar in leucocratic differentiates. Orthopyroxene is characteristically absent as a cumulus phase but may form very rare intercumulus grains. Accessory magnetite and apatite are generally common, and locally abundant in hornblende clinopyroxenite; sphene and zircon occur in felsic differentiates; phlogopite-biotite is particularly widespread as an accessory phase in British Columbia.

ALTERATION MINERALOGY: Secondary PGM are minor and closely associated with the primary PGM alloys. Remobilization of PGE is believed to be extremely limited and may be commonly related to postmagmatic serpentinizaton processes acting during regional metamorphism and deformation.

WEATHERING: It has been argued by some that the PGE found in placer occurrences may owe their origin to the hydromorphic dispersion and precipitation of PGE during normal weathering processes. The debate continues, but it is clear from a variety of textural, mineralogical and isotopic (Re-Os) data that the common placer PGE occurrences are the products of mechanical degradation of magmatic lode occurrences and not surficial remobilization processes.

ORE CONTROLS: The PGM appear to be restricted to chromitite, magnetite-rich or clinopyroxenite layers which formed by primary magmatic crystallization processes. The chromite is typically associated with dunite whereas the magnetite is found with clinopyroxenite.

GENETIC MODEL: The origin of the PGE in Alaskan-type deposits is magmatic with very limited low-temperature remobilization. A low sulphidation, relatively high oxidation magmatic environment (subduction-related?) appears to be an important genetic control. The chromitites in dunite and, to a much lesser extent, the magnetite-rich layers in clinopyroxenite, appear to be the ultimate source of the placer PGE.

M05 - Alaskan-Type Pt±Os±Rh±Ir

ASSOCIATED DEPOSIT TYPES: Placer deposits (C01, C02) are extremely important since they have been the only significant economically recoverable source of PGE associated with Alaskan-type complexes. Some lode deposits have been worked in Russia but their documentation is extremely poor.

COMMENTS: All of the world's most important Alaskan-derived placers appear to be related to concentrations of PGE in chromitites. Gold in these placers appears to have been derived from a separate source. Magnetite accumulations in clinopyroxenites of the Tulameen Complex have been explored for magnetite.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Primarily Pt, with subsidiary Os, Rh and Ir; other elements such as Cu, Ni, and Cr may be locally important. Geochemical pathfinder elements for PGE, such as As and Sb, may also be important.

GEOPHYSICAL SIGNATURE: Primarily magnetic; gravity may be important.

OTHER EXPLORATION GUIDES: Stream sediment sampling of heavy mineral concentrates for PGE is a key exploration tool; in favourable circumstances PGE geochemistry and platinum nugget mineralogy can uniquely distinguish an Alaskan-type heritage from all other common PGE environments.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: PGE concentrations in grab samples from lode deposits are extremely spotty such that reliable tonnages and grades are not available. The associated placer deposits are likewise extremely variable. Maximum grade of Pt from the Goodnews Mining Company records, Alaska (1957) was approximately “$37 per cubic yard” at February 1993 prices. Placers in the Tulameen district reportedly yielded some 620 kg of impure platinum between 1889 and 1936. Some of the placer deposits in the former Soviet Union have yielded exceptional platinum nuggets of up to 11.3 kg.

ECONOMIC LIMITATIONS: The chromitite-PGE association appears to be the most important in British Columbia; without exception, all of these chromitite occurrences are small, dispersed throughout a dunite host, and all have been remobilized soon after deposition within the high-temperature magmatic environment. A small open pit operation appears to be the only potentially economic method of PGE extraction. The occurrence of the PGE as small micrometre-size inclusions in refractory chromite poses problems for processing.

END USES: PGE are primarily used as high-temperature catalysts in a variety of industries, perhaps the most familiar being platinum for automobile catalytic converters. Other uses include medical and electronic (fuel cells, thermocouples), and platinum is used in jewelry.

IMPORTANCE: PGE are classed as a strategic commodity. The most important producers are South Africa and Russia.

M05 - Alaskan-Type Pt±Os±Rh±Ir

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M06 - Ultramafic-Hosted Chrysotile Asbestos

by Z.D. Hora[1]

Hora, Z.D., 1998. Ultramafic-hosted chrysotile asbestos: In: Selected mineral deposit profiles, volume 3 – industrial minerals and gemstones, Ministry of Energy and Mines, British Columbia Geological Survey, Open File 1999-10, p. 61-64.

IDENTIFICATION

SYNONYMS: Quebec-type asbestos, serpentine-hosted asbestos, ultramafic-intrusion hosted asbestos.

COMMODITIES (BYPRODUCTS): Chrysotile asbestos (nephrite jade at Cassiar).

EXAMPLES (British Columbia (MINFILE #) - *Canadian/International*): Cassiar (104P005), McDame (104P084), Letain (104I006), Ace (104K025), Asbestos (082 KNW075); *Thetford Mines, Black Lake, Asbestos (Quebec, Canada), Belvidere Mine (Vermont, USA), Coalinga (California, USA), Cana Brava (Brazil), Pano Amiandes (Cyprus), Bazhenovo (Russia), Barraba (New South Wales, Australia), Barberton (Transvaal, South Africa).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Chrysotile asbestos occurs as cross fibre and/or slip fibre stockworks, or as less common agglomerates of finely matted chrysotile fibre, in serpentinized ultramafic rocks. Serpentinites may be part of ophiolite sequence in orogenic belts or synvolcanic intrusions of Archean greenstone belts.

TECTONIC SETTINGS: Chrysotile deposits occur in accreted oceanic terranes, usually part of an ophiolite sequence, or within Alpine - type ultramafic rocks. They are also found in synvolcanic ultramafic intrusions of komatiitic affinity in Archean greenstone belts. In British Columbia the significant occurrences are found in the Slide Mountain, Cache Creek and Kootenay terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The serpentine host must have a nonfoliated texture and must be situated near a fault that is active during a change in the orientation of the regional stress from dip-slip to strike-slip fault motion. The serpentinite must be in the stability field of chrysotile when the change in orientation occurs. Subsequent deformation or temperature increase may destroy the fibre and result in a different mineralogy.

AGE OF MINERALIZATION: Precambrian to Tertiary. Deposits in British Columbia are considered Upper Cretaceous, deposits in southeastern Quebec formed during a relatively late stage of Taconic orogeny (late Ordovician to early Silurian), deposits in Ungava and Ontario are Precambrian. Chrysotile asbestos deposits are generally considered to be syntectonic and to form during the later stages of deformation.

HOST/ASSOCIATED ROCK TYPES: Serpentinite, dunite, peridotite, wehrlite, harzburgite, pyroxenite. Associated rocks are rodingite and steatite.

DEPOSIT FORM: In plan orebodies are equidimensional to somewhat oblate zones from 100 to 1000 metres in diameter within masses of serpentinized ultramafic rock. The vertical distribution of mineralized zones may be in the order of several hundreds of metres.

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M06 - Ultramafic-Hosted Chrysotile Asbestos

TEXTURE/STRUCTURE: Asbestos veins fill tension fractures in serpentinized ultramafic rocks or form a matrix of crushed and brecciated body of serpentinite. Usually, the orebodies grade from numerous stockwork veins in the centre to a lower number of crosscutting veins on the fringes. Cross-fibre veins, where the chrysotile fibres are at a high angle to the vein walls, are more abundant than slip fibre veins which parallel the vein walls. Individual veins are up to several metres in length and for the most part less than 1 cm thick, but may be up to 10 cm thick. In some deposits, powdery agglomerates of finely matted chrysotile form the matrix for blocks and fragments of serpentinite rock.

ORE MINERALOGY: Chrysotile.

GANGUE MINERALOGY: Gangue minerals in chrysotile veinlets are brucite and magnetite. Antigorite and lizardite may also be present in association with chrysotile veining.

ALTERATION MINERALOGY: Chrysotile and associated minerals are alteration products of ultramafic rocks. This process which starts as serpentinization, may be pervasive, but also fracture controlled and incomplete with serpentine surrounding peridotite (or other rock) cores. In relationship to changes in temperature, pressure and the fluid chemistry a variety of minerals from lizardite to talc and antigorite, or tremolite can be produced. Since the serpentinization of ultramafic rocks is frequently a multiple stage process, which can be either prograde or retrograde, many deposits contain minerals which do not form in the same stability field. Therefore, the alteration and gangue mineralogy are practically identical.

WEATHERING: In northern climates, only physical weathering of chrysotile and the serpentinized host rock takes place. Brucite and carbonates may be removed in solution and precipitated as hydromagnesite elsewhere. Lateritic soils should be expected in tropical climates.

ORE CONTROLS: Chrysotile veinlets are often best developed in massive serpentinite bodies with no schistose fabric. Chrysotile stability field; proximity to a fault that is active during change in the orientation of stress field; limited subsequent deformation and no subsequent medium to high grade metamorphism after the asbestos formation. Asbestos veins fill tension fractures in serpentinized ultramafic rocks or form a matrix of crushed and brecciated body of serpentinite.

GENETIC MODELS: Chrysotile asbestos deposits develop in nonfoliated, brittle ultramafic rocks under low grade metamorphic conditions with temperatures of 300 ± 50°C and water pressures less than 1 kbar. The chrysotile forms as the result of fluid flow accompanied by deformation where water gains access to partly or wholly serpentinized ultramafics along fault and shear zones.

ASSOCIATED DEPOSIT TYPES: Spatial association (but no genetic relationship) with podiform chromite deposits (M03) and jade (Q01) in ophiolitic sequences. Cyptocrystalline magnesite veins (I17), ultramafic-hosted talc-magnesite (M07) and anthophyllite asbestos deposits may be genetically related.

COMMENTS: Anthophyllite, a variety of amphibole, is another asbestiform mineral. Production of anthophyllite has been limited; Green Mountain mine in North Carolina is the only North American past producer.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: None.

GEOPHYSICAL SIGNATURE: Magnetite, which is a product of both sepentinization and the formation of chrysotile, can produce well defined, magnetic anomalies. Gravity surveys can distinguish serpentinite from the more dense (~20%) peridotite.

OTHER EXPLORATION GUIDES: Asbestos fibres found in soils. Massive, brittle and unsheared ultramafic bodies which are partly or fully serpentinized in proximity to faults and shears.

M06 - Ultramafic-Hosted Chrysotile Asbestos

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Total fibre content of commercial deposits is between 3 and 10%, the tonnage is between 500 000 to 150 million tons (in the asbestos industry fibre length is a critical parameter as well). In British Columbia, company reports indicate the Cassiar mine produced 31 Mt grading 7 to 10% fibre. There are however 25 Mt of tailings with 4.2% recoverable short fibre. Another 7.3 Mt geological reserves was left in the pit. The adjacent McDame deposit has measured reserves of 20 Mt @ 6.21% fibre and estimated geological reserves of 63 Mt. In the Yukon Clinton Creek produced 15 Mt @ 6.3% fibre. The following figures are from Duke (1996) and include past production plus reserves: Jeffrey, Quebec: 800 Mt @ 6% fibre, Bell-Wing-Beaver, Quebec: 250 Mt @ 6% fibre, British Canadian, Quebec: 150 Mt @ 6% fibre, Advocate, Newfoundland: 60 Mt @ 3% fibre. A relatively few deposits have been developed to mine agglomerates of finely matted chrysotile fibre which have much higher grades. The very large Coalinga deposit in California has reported short fibre recoveries in the order of 35 to 74%. The Stragari mine in Serbia is recovering 50-60% fibre.

ECONOMIC LIMITATIONS: Fibre lengths may vary significantly within and between deposits; stockwork mineralization is typically more economically attractive if the proportion of longer fibres is higher. Typically, the fibre value starts at CDN$180/ton for the shortest grade and reaches CDN$1750 for the longest (Industrial Minerals, 1997).

END USES: Asbestos-cement products; filler in plastics; break lining and clutch facings; asbestos textiles; gaskets; acoustic and electric and heat insulation.

IMPORTANCE: Ultramafic-hosted chrysotile is the only source of asbestos in North America and considered the least hazardous of commercial asbestos minerals. During the 1980s the market for asbestos in many countries declined due to health hazard concerns.

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M07 - Ultramafic-Hosted Talc-Magnesite

by G. J. Simandl[1] and D. Ogden[2]

Simandl, G.J., and Ogden, D., 1999. Ultramafic-hosted talc-magnesite: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 65–68.

IDENTIFICATION

SYNONYMS: Ultramafic-hosted magnesite/talc deposits, serpentinite-hosted talc.

COMMODITIES (BYPRODUCTS): Talc and magnesite (rarely nickel).

EXAMPLES (British Columbia - *Canada/International*): Rawhide (0921SW051), South Talc Lake Deposit (092ISW064), Gisby (092HNW002), J&J (092HNW047); *Deloro magnesite-talc deposit (Ontario, Canada), Luzcan mine of Thetford township and Van Reet mine, Ponton township, (Quebec, Canada), Windham (Vermont, USA), Lahnaslampi mine (Finland)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Ultramafic-hosted talc-carbonate deposits are located either along regional faults cutting ultramafic rocks or at contacts between ultramafic rocks and siliceous country rock. The ultramafic host rock is typically, but not necessarily of ophiolitic affiliation. Deposits related to regional fault systems cutting ultramafic host rock are commonly magnesite-rich. Deposits located within sheets of serpentinized peridotite, found along the periphery of ultramafic intrusions or near the borders of tectonically transported peridotite slices are typically talc-rich.

TECTONIC SETTINGS: These deposits are found typically in obducted, accreted or otherwise tectonically transported seafloor and ophiolite slices or lenses and in ancient greenstone belts. However, serpentinized ultramafic intrusions regardless of tectonic environment should be considered as a favourable host.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Faulted and metasomatized ultramafic rocks and tectonically-transported serpentinites in contact with siliceous rocks; the deposits are younger than the ultramafic protolith.

AGE OF MINERALIZATION: Precambrian or younger. Post or syn-tectonic.

HOST/ASSOCIATED ROCK TYPES: Talc-carbonate-bearing serpentinite, steatite, talc schist, talc-magnesite-dolomite schist that may contain serpentine/chlorite schist, dunite and serpentinite with associated, commonly at least partially serpentinized gabbro, pyroxenite, harzburgite and websterite or meta-komatiiate sills and lavas. Because many of the talc-bearing rocks are allochthonous there is a wide variety of associated lithologies.

DEPOSIT FORM: The fault-related deposits are irregular bodies having their largest dimensions parallel to the faults. In some cases only the hanging wall of the faults is mineralized. Small ultramafic lenses are commonly entirely serpentinized, while larger lenses consist of peridotite cores surrounded by serpentinite. Steatite and talc schists are most likely to be found at the contact of the serpentinite with siliceous rocks, however they may also form tabular or irregular bodies.

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M07 - Ultramafic-Hosted Talc-Magnesite

TEXTURE/STRUCTURE: Ore is massive or schistose, talc is fine to coarse flakes.

ORE MINERALOGY [Principal and *Subordinate*]: Talc, magnesite, rarely Ni-bearing minerals, such as pyrrhotite, pentlandite, melnikovite and bravoite.

GANGUE MINERALOGY [Principal and *Subordinate*]: Dolomite, serpentine, chlorite, ankerite (Fe-rich dolomite), breunerite (Fe-rich magnesite), *olivine, magnetite, quartz, pyrite, asbestos, rutile, calcite, chrome-mica*.

ALTERATION MINERALOGY: N/A. Talc and magnesite are alteration (metasomatic) products.

ORE CONTROLS: Primary control is the presence of a magnesium-rich silicate rock to act as a source of magnesium. Permeable fault zones or serpentinite-siliceous rock contacts control the sites of talc formation.

GENETIC MODELS: These deposits are commonly magnesite-rich and are linked to CO_2 and H_2O metasomatism (carbonatization and hydration) of ultramafic rocks by fluids following faults and contacts. The following reactions illustrate the concept:

1) 18 serpentine + magnetite + 30 CO_2 → 9 Talc + 30 breunerite + 27 H_2O + 1/2 O_2

2a) 2 olivine + 1 CO_2 + 1 H_2O → 1serpentine + 1 magnesite
2b) 2 serpentine + 3 CO_2 → 3 magnesite + 1 talc + 3 H_2O

3) 1 serpentine + 2 quartz → 1 talc + H_2O

The talc formed during metasomatism and/or regional metamorphism. Silica required for talc formation was derived from the country rock.

ASSOCIATED DEPOSIT TYPES: Chrysotile deposits (M06), magnesite veins and stockworks (I17) podiform chromite deposits (M03), famous "verde antique" dimension stone deposits and possibly, nephrite (Q01) and listwanite-related gold (I01) deposits.

COMMENTS: A similar origin has been proposed to explain the breunerite-talc assemblage in the Motherlode gold district in California. The hydration / carbonitization of ultramafic rocks differs from listwanite only by the lack of potassium metasomatism. Carbonitization products in some cases represent intermediate stage in formation of true listwanites (Halls and Zhao, 1995).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Talc is a relatively soft but inert mineral in most environments. It may be enriched in soils overlying talc-bearing zones. Ultramafic rocks are characterized by Mg, Fe, Cr, Ni, Co suite of elements. Under normal conditions, this signature may be reflected in soils, stream or lake sediments and in overburden.

GEOPHYSICAL SIGNATURE: Unserpentinized portions of the host ultramafic rocks commonly correspond to strong airborne and ground magnetic anomalies. Talc-rich zones corresponds commonly to airborne electromagnetic lows.

OTHER EXPLORATION GUIDES: Talc-rich zones coincide commonly with topographic lows and can be covered by lakes and swamps. Some deposits exhibit zoning from siliceous country rock (quartz-sericite-chlorite schist) into chlorite schist, then into the talc-bearing rocks (talc-carbonate-serpentine-bearing schists, steatite) with a serpentinite core. Deposits are located within sheets of serpentinized peridotite, along the periphery of ultramafic intrusions or thin, tectonically transported slivers, slices or lenses of peridotite. The ultramafic rocks and major faults may be detected by modern remote sensing technologies.

M07 - Ultramafic-Hosted Talc-Magnesite

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The grade and size of these deposits is highly variable. The Deloro deposit consists of 54% magnesite and 28% talc. It is about 1800 metres in length, 300 metres wide and has been drilled to the depth of 120 metres. An underground talc mine of Cyprus Minerals Co., located at Windham, Vermont consists of lenses exceeding 230 metres in length and 100 metres in width. The Lahnaslampi orebody in Finland contains over 30 million tonnes exceeding 50% talc and 0.1 to 0.2% Ni. Nickel concentrate is produced from the tailings at Lahnaslampi. There is the opportunity that talc could be a by-product from listwanite-hosted gold mines. The metallurgical tests suggest that in some cases, it is technically possible to produce a magnesite concentrate as talc by-product. However, economics of the process and exact technical specifications of the potential product are not well documented.

ECONOMIC LIMITATIONS: Steatite contains more than 90% talc. Flotation is required for most deposits to produce high-quality fillers for paint and plastic applications, the ceramic and pharmaceutical industries, and crayons. Underground mining is economically feasible to depths exceeding 300 metres. FeO content of magnesite from these deposits varies from 0.5 to 7%. Research is underway to chemically reduce iron content of magnesite, in order to achieve refractory grade magnesia products. Current restrictions placed on asbestos-bearing materials makes the ores from asbestos-free deposits easier to market.

END USES: Talc from these deposits is commonly used in paper, ceramic, paint, plastic, roofing and electrical applications. Massive talc and soapstone are used in electric insulation, refractory applications, as carving stone or as raw material for laboratory sinks.

IMPORTANCE: Ultramafic-hosted talc-magnesite deposits are important source of talc.

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M08 - Vermiculite

by G.J. Simandl[1], T. Birkett[2] and S. Paradis[3]

Simandl, G.J., Birkett, T., and Paradis, S., 1999. Vermiculite: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 69–72.

IDENTIFICATION

COMMODITY (BYPRODUCTS): Vermiculite (± apatite).

EXAMPLES (British Columbia - *Canadian/International*): Joseph Lake (093K 100), Sowchea Creek vermiculite (093K 101); *Libby (Montana, USA), Waldrop Pit, Enoreeq area (South Carolina, USA), Blue Ridge deposits (North Carolina, USA), Palabora deposit (Republic of South Africa)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: These near surface vermiculite deposits may also contain recoverable apatite. World-class vermiculite deposits occur mainly within zoned ultramafic complexes or carbonatites. Smaller or lower grade deposits are hosted by dunites, unzoned pyroxenites, peridotites or other mafic rocks cut by pegmatites and syenitic or granitic rocks.

TECTONIC SETTING: Deposits hosted by carbonatites and ultramafic complexes are commonly related to rifting within the continental platform or marginal to the platform in geosynclinal settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Mafic and ulramafic igneous or metamorphic rocks exposed to intense weathering and/or supergene, low temperature alteration.

AGE OF MINERALIZATION: Most deposits are derived from rocks of Precambrian to Jurassic age. Deposits post-date emplacement of intrusive host and regional metamorphism. Their age may be linked to periods of intense weathering which show up as erosional surfaces, paleo-regolith or unconformities.

HOST/ASSOCIATED ROCK TYPES: For major deposits the main hosts are biotitites, pyroxenites, phlogopite-serpentine rock, phlogopite-diopside±apatite rock and peridotites. Associated rock types are magnetite pyroxenites, foscorite, carbonatites, and variety of serpentinites that are in contact with alkali granites, syenites, fenites or pegmatites.

For smaller or marginal deposits located in highly metamorphosed settings the typical host rocks are amphibolite and biotite schists in contact with pyroxenites or peridotite dykes or lenses, sometimes cut by pegmatites.

DEPOSIT FORM: Variable shapes, a function of the geometry of the favourable protolith and zone of fluid access. Semi-circular surface exposures found with deposits associated with ultramafic zoned complexes or carbonatites, usually near the core of the intrusion. Lenticular or planar deposits of vermiculite are found along serpetinized contacts between ultramafic rocks and metamorphic country rocks. Individual lenses may be up to 7 metres thick and 30 metres in length. Smaller lenses may be found along fractures and the margins of pegmatites crosscutting ultramafic lenses within high grade metamorphic terranes. The degree of alteration and vermiculite grade generally diminishes with depth. Vermiculite grades of economic interest rarely extend more than 40 metres below the surface.

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[3] Geological Survey of Canada, Sidney, British Columbia, Canada

M08 - Vermiculite

TEXTURE/STRUCTURE: Vermiculite may be fine-grained or form books up to 20 cm across ("pegmatitic"). Serpentine can form pseudomorphs after olivine.

ORE MINERALOGY [Principal and *subordinate*]: Vermiculite ± hydrobiotite; ± *apatite*.

GANGUE MINERALOGY [Principal and *subordinate*]: Biotite, chlorite, phlogopite, clinopyroxene, *tremolite, augite, olivine, hornblende, serpentine*. In some of the deposits *acicular tremolite* and *asbestos* are reported.

ALTERATION MINERALOGY: Vermiculite is probably, in part, a low temperature alteration product of biotite.

WEATHERING: At least in some deposits, weathering is believed to play an important role in transformation of mafic minerals, mainly biotite, into vermiculite. Weathering also weakens the ore making blasting unnecessary; in extreme case it results in formation of semi- or unconsolidated, residual vermiculite deposits.

ORE CONTROLS: 1) The existence of a suitable protore, commonly dunite or pyroxenite rock containing abundant biotite or phlogopite which may be of late magmatic to hydrothermal origin. 2) Deposits occur mainly at surface or at shallow depths, but in some cases as a paleoregolith along an unconformity. 3) Vermiculite develops from periods of intense weathering or near surface alteration. 4) The maximum depth extent of the ore zone depends on the permeability, porosity, jointing and fracture system orientation which permit the circulation of meteoric fluids.

GENETIC MODELS: Vermiculite can form from variety of mafic minerals, but biotite or Fe-bearing phlogopite are deemed key components of the protore within economic deposits.

Most of the early studies suggest that vermiculite is a late magmatic, low temperature hydrothermal or deuteric alteration product. Currently, the most accepted hypothesis is that vermiculite forms by supergene alteration due to the combined effect of weathering and circulation of meteoric fluids.

ASSOCIATED DEPOSIT TYPES: Palabora-type complexes or other carbonatites (N01) contain vermiculite mineralization. Ultramafic-hosted asbestos (M06), ultramafic-hosted talc-magnesite (M07), nepheline-syenite (R13), Ni and platinoid showings, some sapphire deposits associated with so called “crossing line” pegmatites and placer platinoid deposits (C01 and C02) may be associated with the same ultramafic or mafic complexes as vermiculite deposits.

COMMENTS: In British Columbia, vermiculite is reported from surface exposures of granite, granodiorite and quartz diorite at the Joseph Lake and Sowchea Creek showings in the Fort Fraser/Fort St. James area (White, 1990). Low grades in combination with the preliminary metallurgical studies indicate that under current market conditions these occurrences are probably subeconomic (Morin and Lamothe, 1991). Similar age, or older, mafic or ultramafic rocks in this region may contain coarse-grained vermiculite in economic concentrations.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Vermiculite in soil.

GEOPHYSICAL SIGNATURE: Ultramafic rocks that host large vermiculite deposits are commonly characterized by strong magnetic anomalies detectable by airborne surveys. Since vermiculite is an alteration product of ultramafic rocks, vermiculite zones are expected to have a negative magnetic signature. However, no detailed geophysical case histories are documented.

M08 - Vermiculite

OTHER EXPLORATION GUIDES: The largest commercial deposits usually form in the cores of ultramafic or alkaline complexes (mainly pyroxenites and carbonatites). The roof portions of these complexes have the best potential because they may be biotite-rich. Deposits derived from biotite schist are typically much smaller. All these deposits are commonly associated with some sort of alkali activity, be it only alkali granite or syenite dykes. Vermiculite deposits may have a negative topographic relief.
A portable torch may be used to identify vermiculite in hand specimen since it exfoliates and forms golden flakes when heated. Therefore, an excellent time to prospect for vermiculite is after forest fires.
Fenitization halos associated with alkaline ultramafic complexes and carbonatites increases the size of the exploration target. Horizons of intense paleo-weathering that exposed mica-bearing ultramafic rocks are particularly favourable.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits with over 35% vermiculite (>65 mesh) are considered high grade. Most of the economic deposits contain from few hundred thousand to several million tonnes; although clusters of small, high-grade, biotite schist-hosted deposits ranging from 20 000 to 50 000 tonnes were mined in South Carolina.

ECONOMIC LIMITATIONS: World vermiculite production in 1995 was estimated at 480 000 tonnes. Major producing countries were South Africa (222 000 tonnes, mainly from Palabora), USA (170 000 tonnes) and Brazil (41 500 tonnes). In the early half of 1996 the prices of South African vermiculite imported to USA varied from US$127 to 209 per tonne. Deposits must be large enough to be amenable to open pit mechanized mining. Large flake size (more than 65 mesh) is preferred. Both wet and dry concentrating methods are in use. Crude vermiculite is moved in bulk to exfoliation plants that are typically located near the markets. In commercial plants expansion of 8 to 15 times the original volume is typical, but up to 20 times may be achieved. The higher the degree of expansion (without decrepitation) the better the concentrate. The concentrates from those deposits where vermiculite coexists with asbestos or “asbestiform” tremolite are difficult to market because of the concerns over related health risks.

END USES: Agriculture 40%, insulation 23%, light weight concrete aggregate 19%, plaster and premixes 13%, other 5% (USA statistics). Other applications include carrier substrate for predatory mites in pest extermination, additive to fish feed, removal of heavy metals from soils and absorbent in poultry litter.

IMPORTANCE: Some vermiculite is derived from laterite-type deposits. Vermiculite may be substituted in concrete applications by expanded perlite or by expanded shale. Recently the use of vermiculite in cement compounds has reduced due to substitution by polystyrene. In agricultural applications it may be substituted by peat, perlite, sawdust, bark, etc. In ion exchange applications it may be substituted by zeolites.

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N - Carbonatites, Kimberlites and Lamproites

	Profile Title	Authors
N01	Carbonatite-associated deposits	T. Birkett, and G.J. Simandl, 1999
N02	Kimberlite-hosted diamonds	J. Pell, 1999
N03	Lamproite-hosted diamonds	J. Pell, 1999

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

N01 - Carbonatite-Associated Deposits:Magmatic, Replacement and Residual

by T.C. Birkett[1] and G.J. Simandl[2]

Birkett, T., and Simandl, G.J., 1999. Carbonatite-associated deposits (magmatic, replacement and residual): In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 73–76.

IDENTIFICATION

SYNONYMS: Nephelinitic and ultramafic carbonatite-hosted deposits.

COMMODITIES (BYPRODUCTS): Niobium, tantalum, REE, phosphate, vermiculite (see also M08, this volume), Cu, Ti, Sr, fluorite, Th, U magnetite (hematite, Zr, V, nickel sulphate, sulphuric acid, calcite for cement industry).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*):
Magmatic: *Aley (REE, niobium, 094B 027), St. Honoré (niobium, Quebec, Canada), Mountain Pass (REE, California, USA), Palabora (apatite, South Africa).*
Replacement/Veins: Rock Canyon Creek (Fluorite, REE, 082JSW018); *Bayan Obo (REE, China), Amba Dongar (fluorite, India), Fen (Fe, Norway), Palabora (Cu, vermiculite, apatite, South Africa).*
Residual: *Araxa, Catalao and Tapira (niobium, phosphate, REE, Ti, Brazil), Cargill and Martison Lake (phosphates, Ontario, Canada).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Carbonatites are igneous rocks with more than 50% modal carbonate minerals; calcite, dolomite and Fe-carbonate varieties are recognized. Intrusive carbonatites occur commonly within alkalic complexes or as isolated sills, dikes, or small plugs that may not be associated with other alkaline rocks. Carbonatites may also occur as lava flows and pyroclastic rocks. Only intrusive carbonatites (in some cases further enriched by weathering) are associated with mineralization in economic concentrations which occur as primary igneous minerals, replacement deposits (intra-intrusive veins or zones of small veins, extra-intrusive fenites or veins) or residual weathering accumulations from either igneous or replacement protores. Pyrochlore, apatite and rare earth-bearing minerals are typically the most sought after mineral constituents, however, a wide variety of other minerals including magnetite, fluorite, calcite, bornite, chalcopyrite and vermiculite, occur in economic concentrations in at least one carbonatite complex.

TECTONIC SETTING: Carbonatites occur mainly in a continental environment; rarely in oceanic environments (Canary Islands) and are generally related to large-scale, intra-plate fractures, grabens or rifts that correlate with periods of extension and may be associated with a broad zones of epeirogenic uplift.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Carbonatites intrude all types of rocks and are emplaced at a variety of depths.

AGE OF MINERALIZATION: Carbonatite intrusions are early Precambrian to Recent in age; they appear to be increasingly abundant with decreasing age. In British Columbia, carbonatites are mostly upper Devonian, Mississippian or Eocambrian in age.

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[2] British Columbia Geological Survey, Victoria, British Columbia, Canada

N01 - Carbonatite-Associated Deposits

HOST/ASSOCIATED ROCK TYPES: Host rocks are varied, including calcite carbonatite (sovite), dolomite carbonatite (beforsite), ferroan or ankeritic calcite-rich carbonatite (ferrocarbonatite), magnetite-olivine-apatite ± phlogopite rock, nephelinite, syenite, pyroxenite, peridotite and phonolite. Carbonatite lava flows and pyroclastic rocks are not known to contain economic mineralization. Country rocks are of various types and metamorphic grades.

DEPOSIT FORM: Carbonatites are small, pipe-like bodies, dikes, sills, small plugs or irregular masses. The typical pipe-like bodies have subcircular or elliptical cross sections and are up to 3-4 km in diameter. Magmatic mineralization within pipe-like carbonatites is commonly found in crescent-shaped and steeply-dipping zones. Metasomatic mineralization occurs as irregular forms or veins. Residual and other weathering-related deposits are controlled by topography, depth of weathering and drainage development.

TEXTURE/STRUCTURE: REE minerals form pockets and fill fractures within ferrocarbonatite bodies. Pyrochlore is disseminated; apatite can be disseminated to semi-massive; bastnaesite occurs as disseminated to patchy accumulations; fluorite forms as veins and masses; hematite is semi-massive disseminations; and chalcopyrite and bornite are found in veinlets.

ORE MINERALOGY [Principal and *subordinate*]:

Magmatic: bastnaesite, pyrochlore, apatite, anatase, *zircon, baddeleyite, magnetite, monazite, parisite, fersmite*.

Replacement/Veins: fluorite, vermiculite, bornite, chalcopyrite and other sulphides, hematite.

Residual: anatase, pyrochlore and apatite, locally crandallite-group minerals containing REE.

GANGUE MINERALOGY [Principal and *subordinate*]: Calcite, dolomite, siderite, ferroan calcite, ankerite, hematite, biotite, titanite, olivine, *quartz*.

ALTERATION MINERALOGY: A fenitization halo (alkali metasomatized country rocks) commonly surrounds carbonatite intrusions; alteration mineralogy depends largely on the composition of the host rock. Typical minerals are sodic amphibole, wollastonite, nepheline, mesoperthite, antiperthite, aegerine-augite, pale brown biotite, phlogopite and albite. Most fenites are zones of desilicification with addition of Fe^{3+}, Na and K.

WEATHERING: Carbonatites weather relatively easily and are commonly associated with topographic lows. Weathering is an important factor for concentrating residual pyrochlore or phosphate mineralization.

ORE CONTROLS: Intrusive form and cooling history control primary igneous deposits (fractional crystallization). Tectonic and local structural controls influence the forms of metasomatic mineralization. The depth of weathering and drainage patterns control residual pyrochlore and apatite deposits, and vermiculite deposits.

GENETIC MODELS: Worldwide, mineralization within carbonatites is syn- to post-intrusion and commonly occurs in several types or stages:

1) REE-rich carbonatite and ferrocarbonatite, magmatic magnetite, pyrochlore
2) Fluorite along fractures
3) Barite veins
4) U-Th minerals + silicification
5) calcite veining and reprecipitation of Fe oxides (hematite)
6) Intense weathering may take place at any later time.

Magmatic mineralization may be linked either to fractional crystallization or immiscibility of magmatic fluids. Metasomatism and replacement are important Not all mineralization types are associated with any individual carbonatite intrusion. In general, it is believed that economic Nb, REE and primary magnetite deposits are associated with transgressive (late) igneous phases, but understanding of the majority of deposits is not advanced enough to propose any general relationship of timing. mineralization at St. Honoré, for example, is probably relatively early-formed.

N01 - Carbonatite-Associated Deposits

ASSOCIATED DEPOSIT TYPES: Nepheline syenite (R13) and nepheline syenite-related corundum deposits and sodalite. REE and zircon placer deposits (C01, C02) deposits can be derived from carbonatites. Wollastonite occurrences are in some cases reported in association with carbonatites. Fluorite deposits are known from the roof zones of carbonatite complexes (I11). Kimberlites and lamproites (common host-rocks for diamonds) may be along the same tectonic features as carbonatites, but are not related to the same magmatic event.

COMMENTS: Carbonatites should be evaluated for a variety of the mineral substances as exemplified by the exceptional Palabora carbonatite which provides phosphate (primary and possibly hydrothermal), Cu (hydrothermal), vermiculite (weathering) and also Zr, U and Th as byproducts. While extrusive carbonatite rocks are known to contain anomalous REE values, for example the Mount Grace pyroclastic carbonatite in British Columbia, they are not known to host REE in economic concentrations.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Resistant niobium or phosphate minerals in soils and stream sediments; F, Th and U in waters.

GEOPHYSICAL SIGNATURE: Magnetic and radiometric expressions and sometimes anomalous radon gas concentrations furnish primary targets.

OTHER EXPLORATION GUIDES: Carbonatites are commonly found over broad provinces, but individual intrusions may be isolated. Fenitization increases the size of target in regional exploration for carbonatite-hosted deposits. U-Th (radioactivity) associated with fluorite and barite within carbonatites are considered as indirect REE indicators. Annular topographic features can coincide with carbonatites.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Araxa deposit contains 300 million tonnes grading 3% Nb_2O_5; Cargill deposit consists of 60 million tonnes at 20% P_2O_5; Niobec deposit hosts 19 million tonnes grading 0.66 % Nb_2O_5; Alley has extensive zones exceeding 0.66% Nb_2O_5 and locally exceeding 2%.

ECONOMIC LIMITATIONS: Competitive markets are established for most of the commodities associated with carbonatites. In 1996, the world consumption was estimated at 22 700 tonnes of Nb_2O_5. Araxa mine, the largest single source of Nb_2O_5 in 1996, produced 18 300 tonnes of concentrate which was largely reduced into standard ferro-niobium. Brazil’s second largest producer, Catalao, produced 3 600 tonnes of ferroniobium. The largest North American producer is Niobec Mine which produced 3 322 tonnes of Nb_2O_5 which was also reduced to ferro-niobium. At the end of 1996 standard grade ferro-niobium sold at $US 15.2/kg, vacuum grade at $US 37.5/kg, nickel-niobium at US$ 39.7 - 55.1/kg of contained niobium. Demand for REE in 1996 was estimated at 65,000 tonnes/year contained rare earth oxides or US$ 650 million. Currently China accounts for nearly half of the world production due largely to heavy discounting, USA is the second largest producer. Separated rare earths account for 30% of the market by volume but 75% by value. Tantalum primary production for 1996 was estimated at 100.1 tonnes of Ta_2O_5 contained in tantalum-bearing tin slags (principally from smelters in Brazil, Thailand and Malaysia) and 426.0 tonnes of Ta_2O_5 in tantalite or other minerals.

END USES: Rare Earths - mainly as a catalyst in oil refining, catalytic converters, glass industry, coloring agents, fiber optics, TV tubes, permanent magnets, high strength alloys and synthetic minerals for laser applications. Phosphate: fertilizers, phosphorus, and phosphoric acid. Sr: Color TV screens, pyrotechnics and magnets. Nb: carbon stabilizer in stainless steel, niobium carbide used in cutting tools, Nb-containing temperature-resistant steel used in turbines, Nb-base alloys in reactors, super alloys for military and aerospace applications. Tantalum: in corrosion-resistant alloys; implanted prosthesis; nuclear reactors and electronic industry. Carbonates may be used in local portland cement industries. Vermiculite is exfoliated and used in agriculture, insulation, as lightweight aggregate, and other construction materials.

N01 - Carbonatite-Associated Deposits

IMPORTANCE: Carbonatites are the main source of niobium and important sources of rare earth elements, but have to compete for the market with placer deposits and offshore placer deposits (Brazil, Australia, India, Sri-Lanka). They compete with sedimentary phosphate deposits for a portion of the phosphate market.

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N02 - Kimberlite-Hosted Diamonds

by Jennifer Pell[1]

Pell, J., 1999. Kimberlite-hosted diamonds: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 77–80.

IDENTIFICATION

SYNONYMS: Diamond-bearing kimberlite pipes, diamond pipes, group 1 kimberlites.

COMMODITIES (BYPRODUCTS): Diamonds (some gemstones produced in Russia from pyrope garnets and olivine*)*.

EXAMPLES (British Columbia - Canada/International): No B.C. deposits, see comments below for prospects; *Koala, Panda, Sable, Fox and Misery (Northwest Territories, Canada), Mir, International, Udachnaya, Aikhal and Yubilenaya (Sakha, Russia), Kimberly, Premier and Venetia (South Africa), Orapa and Jwaneng (Botswana), River Ranch (Zimbabwe)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Diamonds in kimberlites occur as sparse xenocrysts and within diamondiferous xenoliths hosted by intrusives emplaced as subvertical pipes or resedimented volcaniclastic and pyroclastic rocks deposited in craters. Kimberlites are volatile-rich, potassic ultrabasic rocks with macrocrysts (and sometimes megacrysts and xenoliths) set in a fine grained matrix. Economic concentrations of diamonds occur in approximately 1% of the kimberlites throughout the world.

TECTONIC SETTING: Predominantly regions underlain by stable Archean cratons.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The kimberlites rise quickly from the mantle and are emplaced as multi-stage, high-level diatremes, tuff-cones and rings, hypabyssal dikes and sills.

AGE OF MINERALIZATION: Any age except Archean for host intrusions. Economic deposits occur in kimberlites from Proterozoic to Tertiary in age. The diamonds vary from early Archean to as young as 990 Ma.

HOST/ASSOCIATED ROCK TYPES: The kimberlite host rocks are small hypabyssal intrusions which grade upwards into diatreme breccias near surface and pyroclastic rocks in the crater facies at surface. Kimberlites are volatile-rich, potassic ultrabasic rocks that commonly exhibit a distinctive inequigranular texture resulting from the presence of macrocrysts (and sometimes megacrysts and xenoliths) set in a fine grained matrix. The megacryst and macrocryst assemblage in kimberlites includes anhedral crystals of olivine, magnesian ilmenite, pyrope garnet, phlogopite, Ti-poor chromite, diopside and enstatite. Some of these phases may be xenocrystic in origin. Matrix minerals include microphenocrysts of olivine and one or more of: monticellite, perovskite, spinel, phlogopite, apatite, and primary carbonate and serpentine. Kimberlites crosscut all types of rocks.

DEPOSIT FORM: Kimberlites commonly occur in steep-sided, downward tapering, cone-shaped diatremes which may have complex root zones with multiple dikes and “blows”. Diatreme contacts are sharp. Surface exposures of diamond-bearing pipes range from less than 2 up to 146 hectares (Mwadui). In some diatremes the associated crater and tuff ring may be preserved. Kimberlite craters and tuff cones may also form without associated diatremes (e.g. Saskatchewan); the bedded units can be shallowly-dipping. Hypabyssal kimberlites commonly form dikes and sills.

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N02 - Kimberlite-Hosted Diamonds

TEXTURE/STRUCTURE: Diamonds occur as discrete grains of xenocrystic origin and tend to be randomly distributed within kimberlite diatremes. In complex root zones and multiphase intrusions, each phase is characterized by unique diamond content (e.g. Wesselton, South Africa). Some crater-facies kimberlites are enriched in diamonds relative to their associated diatreme (e.g. Mwadui, Tanzania) due to winnowing of fines. Kimberlite dikes may display a dominant linear trend which is parallel to joints, dikes or other structures.

ORE MINERALOGY: Diamond.

GANGUE MINERALOGY (Principal and *subordinate*): Olivine, phlogopite, pyrope and eclogitic garnet, chrome diopside, magnesian ilmenite, enstatite, chromite, carbonate, serpentine; *monticellite, perovskite, spinel, apatite. Magma contaminated by crustal xenoliths can crystallize minerals that are atypical of kimberlites.*

ALTERATION MINERALOGY: Serpentinization in many deposits; silicification or bleaching along contacts. Secondary calcite, quartz and zeolites can occur on fractures. Diamonds can undergo graphitization or resorption.

WEATHERING: In tropical climates, kimberlite weathers quite readily and deeply to “yellowground” which is predominantly comprised of clays. In temperate climates, weathering is less pronounced, but clays are still the predominant weathering product. Diatreme and crater facies tend to form topographic depressions while hypabyssal dikes may be more resistant.

ORE CONTROLS: Kimberlites typically occur in fields comprising up to 100 individual intrusions which often group in clusters. Each field can exhibit considerable diversity with respect to the petrology, mineralogy, mantle xenolith and diamond content of individual kimberlites. Economically diamondiferous and barren kimberlites can occur in close proximity. Controls on the differences in diamond content between kimberlites are not completely understood. They may be due to: depths of origin of the kimberlite magmas (above or below the diamond stability field); differences in the diamond content of the mantle sampled by the kimberlitic magma; degree of resorption of diamonds during transport; flow differentiation, batch mixing or, some combination of these factors.

GENETIC MODEL: Kimberlites form from a small amount of partial melting in the asthenospheric mantle at depths generally in excess of 150 km. The magma ascends rapidly to the surface, entraining fragments of the mantle and crust, en route. Macroscopic diamonds do not crystallize from the kimberlitic magma. They are derived from harzburgitic peridotites and eclogites within regions of the sub-cratonic lithospheric mantle where the pressure, temperature and oxygen fugacity allow them to form. If a kimberlite magma passes through diamondiferous portions of the mantle, it may sample and bring diamonds to the surface provided they are not resorbed during ascent. The rapid degassing of carbon dioxide from the magma near surface produce fluidized intrusive breccias (diatremes) and explosive volcanic eruptions.

ASSOCIATED DEPOSIT TYPES: Diamonds can be concentrated by weathering to produce residual concentrations or within placer deposits (C01, C02, C03). Lamproite-hosted diamond deposits (N03) form in a similar manner, but the magmas are of different origin.

COMMENTS: In British Columbia the Cross kimberlite diatreme and adjacent Ram diatremes (MINFILE # - 082JSE019) are found near Elkford, east of the Rocky Mountain Trench. Several diamond fragments and one diamond are reported from the Ram pipes.

N02 - Kimberlite-Hosted Diamonds

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Kimberlites commonly have high Ti, Cr, Ni, Mg, Ba and Nb values in overlying residual soils. However, caution must be exercised as other alkaline rocks can give similar geochemical signatures. Mineral chemistry is used extensively to help determine whether the kimberlite source is diamondiferous or barren (see other exploration guides). Diamond-bearing kimberlites can contain high-Cr, low-Ca pyrope garnets (G10 garnets), sodium-enriched eclogitic garnets, high chrome chromites with moderate to high Mg contents and magnesian ilmenites.

GEOPHYSICAL SIGNATURE: Geophysical techniques are used to locate kimberlites, but give no indication as to their diamond content. Ground and airborne magnetometer surveys are commonly used; kimberlites can show as either magnetic highs or lows. In equatorial regions the anomalies are characterized by a magnetic dipolar signature in contrast to the “bulls-eye” pattern in higher latitudes. Some kimberlites, however, have no magnetic contrast with surrounding rocks. Some pipes can be detected using electrical methods (EM, VLF, resistivity) in airborne or ground surveys. These techniques are particularly useful where the weathered, clay-rich, upper portions of pipes are developed and preserved since they are conductive and may contrast sufficiently with the host rocks to be detected. Ground based gravity surveys can be useful in detecting kimberlites that have no other geophysical signature and in delineating pipes. Deeply weathered kimberlites or those with a thick sequence of crater sediments generally give negative responses and where fresh kimberlite is found at surface, a positive gravity anomaly may be obtained.

OTHER EXPLORATION GUIDES: Indicator minerals are used extensively in the search for kimberlites and are one of the most important tools, other than bulk sampling, to assess the diamond content of a particular pipe. Pyrope and eclogitic garnet, chrome diopside, picroilmenite, chromite and, to a lesser extent, olivine in surficial materials (tills, stream sediments, loam, etc.) indicate a kimberlitic source. Diamonds are also usually indicative of a kimberlitic or lamproitic source; however, due to their extremely low concentration in the source, they are rarely encountered in surficial sediments. Weathered kimberlite produces a local variation in soil type that can be reflected in vegetation.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: When assessing diamond deposits, grade, tonnage and the average value ($/carat) of the diamonds must be considered. Diamonds, unlike commodities such as gold, do not have a set value. They can be worth from a few $/carat to thousands of $/carat depending on their quality (evaluated on the size, colour and clarity of the stone). Also, the diamond business is very secretive and it is often difficult to acquire accurate data on producing mines. Some deposits have higher grades at surface due to residual concentration. Some estimates for African producers is as follows:

Pipe	Tonnage (Mt)	Grade (carats*/100 tonne)
Orapa	117.8	68
Jwaneng	44.3	140
Venetia	66	120
Premier	339	40

* one carat of diamonds weighs 0.2 grams

ECONOMIC LIMITATIONS: Most kimberlites are mined initially as open pit operations; therefore, stripping ratios are an important aspect of economic assessments. Serpentinized and altered kimberlites are more friable and easier to process.

END USES: Gemstones; industrial uses such as abrasives.

N02 - Kimberlite-Hosted Diamonds

IMPORTANCE: In terms of number of producers and value of production, kimberlites are the most important primary source of diamonds. Synthetic diamonds have become increasingly important as alternate source for abrasives.

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N03 - Lamproite-Hosted Diamonds

by Jennifer Pell[1]

Pell, J., 1999: Lamproite-hosted Diamonds: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 81-84.

IDENTIFICATION

COMMODITY: Diamonds.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): No B.C. examples; *Argyle, Ellendale (Western Australia), Prairie Creek (Crater of Diamonds, Arkansas, USA), Bobi (Côte d'Ivoire), Kapamba (Zambia), Majhgawan (India).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Diamonds occur as sparse xenocrysts and in mantle xenoliths within olivine lamproite pyroclastic rocks and dikes. Many deposits are found within funnel-shaped volcanic vents or craters. Lamproites are ultrapotassic mafic rocks characterized by the presence of olivine, leucite, richterite, diopside or sanidine.

TECTONIC SETTING: Most olivine lamproites are post-tectonic and occur close to the margins of Archean cratons, either within the craton or in adjacent accreted Proterozoic mobile belts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Olivine lamproites are derived from metasomatized lithospheric mantle. They are generally emplaced in high-level, shallow "maar-type" craters crosscutting crustal rocks of all types.

AGE OF MINERALIZATION: Any age except Archean. Diamondiferous lamproites range from Proterozoic to Miocene in age.

HOST/ASSOCIATED ROCK TYPES: Olivine lamproite pyroclastic rocks and dikes commonly host mineralization while lava flows sampled to date are barren. Diamonds are rarely found in the magmatic equivalents. Lamproites are peralkaline and typically ultrapotassic (6 to 8% K_2O). They are characterized by the presence of one or more of the following primary phenocryst and/or groundmass constituents: forsteritic olivine; Ti-rich, Al-poor phlogopite and tetraferriphlogopite; Fe-rich leucite; Ti, K-richterite; diopside; and Fe-rich sanidine. Minor and accessory phases include priderite, apatite, wadeite, perovskite, spinel, ilmenite, armalcolite, shcherbakovite and jeppeite. Glass and mantle derived xenocrysts of olivine, pyrope garnet and chromite may also be present.

DEPOSIT FORM: Most lamproites occur in craters which are irregular, asymmetric, and generally rather shallow (often the shape of a champagne glass), often less than 300 metres in depth. Crater diameters range from a few hundred metres to 1500 metres. Diamond concentrations vary between lamproite phases, and as such, ore zones will reflect the shape of the unit (can be pipes or funnel-shaped). The volcaniclastic rocks in many, but not all, lamproite craters are intruded by a magmatic phase that forms lava lakes or domes.

TEXTURE/STRUCTURE: Diamonds occur as discrete grains of xenocrystic origin that are sparsely and randomly distributed in the matrix of lamproites and some mantle xenoliths.

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N03 - Lamproite-Hosted Diamonds

ORE MINERALOGY: Diamond.

GANGUE MINERALOGY (Principal and *Subordinate*): Olivine, phlogopite, richterite, diopside, sanidine; *priderite, wadeite, ilmenite, chromite, perovskite, spinel, apatite, pyrope garnet*.

ALTERATION MINERALOGY: Alteration to talc ± carbonate ± sulphide or serpentine - septechlorite + magnetite has been described from Argyle (Jacques *et al*., 1986). According to Scott Smith (1996), alteration to analcime, barite, quartz, zeolite, carbonate and other minerals may also occur. Diamonds can undergo graphitization or resorption.

WEATHERING: Clays, predominantly smectite, are the predominant weathering product of lamproites.

ORE CONTROLS: Lamproites are small-volume magmas which are confined to continental regions. There are relatively few lamproites known world wide, less than 20 geological provinces, of which only seven are diamondiferous. Only olivine lamproites are diamondiferous, other varieties, such as leucite lamproites presumably did not originate deep enough in the mantle to contain diamonds. Even within the olivine lamproites, few contain diamonds in economic concentrations. Controls on the differences in diamond content between intrusions are not completely understood. They may be due to: different depths of origin of the magmas (above or below the diamond stability field); differences in the diamond content of the mantle sampled by the lamproite magma; differences in degrees of resorption of diamonds during transport; or some combination of these factors.

GENETIC MODEL: Lamproites form from a small amount of partial melting in metasomatized lithospheric mantle at depths generally in excess of 150 km (i.e., within or beneath the diamond stability field). The magma ascends rapidly to the surface, entraining fragments of the mantle and crust en route. Diamonds do not crystallize from the lamproite magma. They are derived from harzburgitic peridotites and eclogites within regions of the sub-cratonic lithospheric mantle where the pressure, temperature and oxygen fugacity allow them to form in situ. If a lamproite magma passes through diamondiferous portions of the mantle, it may sample them and bring diamonds to the surface provided they are not resorbed during ascent.

ASSOCIATED DEPOSIT TYPES: Diamonds can be concentrated by weathering to produce residual concentrations or by erosion and transport to create placer deposits (C01, C02, C03). Kimberlite-hosted diamond deposits (N02) form in a similar manner, but the magmas are of different origin.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Lamproites can have associated Ni, Co, Ba and Nb anomalies in overlying residual soils. However, these may be restricted in extent since lamproites weather readily and commonly occur in depressions and dispersion is limited. Caution must be exercised as other alkaline rocks can give similar geochemical signatures.

GEOPHYSICAL SIGNATURE: Geophysical techniques are used to locate lamproites, but give no indication as to their diamond content. Ground and airborne magnetometer surveys are commonly used; weathered or crater-facies lamproites commonly form negative magnetic anomalies or dipole anomalies. Some lamproites, however, have no magnetic contrast with surrounding rocks. Various electrical methods (EM, VLF, resistivity) in airborne or ground surveys are excellent tools for detecting lamproites, given the correct weathering environment and contrasts with country rocks. In general, clays, particularly smectite, produced during the weathering of lamproites are conductive; and hence, produce strong negative resistivity anomalies.

N03 - Lamproite-Hosted Diamonds

OTHER EXPLORATION GUIDES: Heavy indicator minerals are used in the search for diamondiferous lamproites, although they are usually not as abundant as with kimberlites. Commonly, chromite is the most useful heavy indicator because it is the most common species and has distinctive chemistry. To a lesser extent, diamond, pyrope and eclogitic garnet, chrome spinel, Ti-rich phlogopite, K-Ti-richterite, low-Al diopside, forsterite and perovskite can be used as lamproite indicator minerals. Priderite, wadeite and shcherbakovite are also highly diagnostic of lamproites, although very rare.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: When assessing diamond deposits, grade, tonnage and the average value ($/carat) of the diamonds must be considered. Diamonds, unlike commodities such as gold, do not have a set value. They can be worth from a few to thousands of $/carat depending on their quality (evaluated on the size, colour and clarity of the stone). Argyle is currently the only major lamproite-hosted diamond mine. It contains at least 75 million tonnes, grading between 6 and 7 carats of diamonds per tonne (1.2 to 1.4 grams/tonne). The Prairie Creek mine produced approximately 100 000 carats and graded 0.13 c/t. Typical reported grades for diamond-bearing lamproites of <0.01 to 0.3 carats per tonne are not economic (Kjarsgaard, 1995). The average value of the diamonds at Argyle is approximately $US 7/carat; therefore, the average value of a tonne of ore is approximately $US 45.50 and the value of total reserves in the ground is in excess of $US 3.4 billion.

END USES: Gemstones; industrial uses such as abrasives.

IMPORTANCE: Olivine lamproites have only been recognized as diamond host rocks for approximately the last 20 years as they were previously classified as kimberlites based solely on the presence of diamonds. Most diamonds are still produced from kimberlites; however, the Argyle pipe produces more carats per annum (approximately 38,000 in 1995), by far, than any other single primary diamond source. Approximately 5% of the diamonds are good quality gemstones.

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N03 - Lamproite-Hosted Diamonds

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O - Pegmatite

Profile Title		Authors
O01*	Rare element pegmatite - LCT family	
O02*	Rare element pegmatite - NYF family	
O03*	Muscovite pegmatite	
O04*	Feldspar-quartz pegmatite	

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

P - Metamorphic-Hosted

	Profile Title	Authors
P01	Andalusite hornfels	Z.D. Hora, 1999
P02	Kyanite, muscovite, garnet in metasediments	G.J. Simandl, S. Paradis, S., W.H. McCracken and K.D. Hancock, 1999
P03	Microcrystalline graphite	G.J. Simandl and W.M. Kenan, 1999
P04	Crystalline flake graphite	G.J. Simandl and W.M. Kenan, 1999
P05	Vein graphite in metamorphic terrains	G.J. Simandl and W.M. Kenan, 1999
P06	Corundum in aluminous metasediments	G.J. Simandl and S. Paradis, 1999

P01 - Andalusite Hornfels

By Z.D. Hora[1]

Hora, Z.D., 1999. Andalusite hornfels: In: Selected mineral deposit profiles, volume 3 – industrial minerals and gemstones, Ministry of Energy and Mines, British Columbia Geological Survey, Open File 1999-10, p. 85-87.

IDENTIFICATION

SYNONYM: Chiastolite hornfels.

COMMODITIES (BYPRODUCTS): Andalusite (staurolite, garnet).

EXAMPLES [BRITISH COLUMBIA (MINFILE #) - *Canada/International*]: Kootenay (082FSE099), Kwoiek Needle (092ISW052), Atna Peak (103H 040); *Kiglapait (Labrador, Canada), Canso (Nova Scotia, Canada), McGerrigle Pluton (Quebec, Canada), Groot Marico-Zeerust, Thamazimbi, Lydenburg (Tranvsaal, South Africa), Glomel (France), Tomduff (Ireland), Spargoville (Western Australia), Aktash (Uzbekistan)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Andalusite occurs in metamorphosed rocks of originally clay-rich composition (usually pelitic) in thermal aureoles formed in the proximity of igneous intrusions. Andalusite is formed under conditions of high temperature and low pressure.

TECTONIC SETTINGS: Mostly in orogenic belts, but also may occur in a platformal environment. Orogenic plutonism intruding pelitic sedimentary sequence.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Andalusite hornfels is a product of thermal recrystallization of rocks with high alumina and low calcium contents. The protolith is usually argillaceous sediment, but may also be hydrothermally altered volcanic or volcaniclastic rock. The whole spectrum of granitic to gabbroic igneous rocks can act as a source of heat. Metamorphic zonation of the contact aureole is characterized by distinct mineral assemblages and textural features, where andalusite may be major or minor component, fine grained or as crystal porphyroblasts several millimetres or even centimetres in size.

AGE OF MINERALIZATION: Precambrian to Tertiary. The largest producing deposits are related to intrusion of the Bushveld Igneous Complex (South Africa) about 1.95 billion years old. The deposit in France, the second largest producer in the world is related to granite of Hercynian age. The occurrences in British Columbia are Cretaceous and Eocene in age.

HOST/ASSOCIATED ROCK TYPES: The host rocks are chiastolite metapelite. The associated rocks are spotted slates, andalusite-cordierite hornfels, staurolite hornfels, spinel-corundum hornfels, silimanite hornfels, skarns and a variety of igneous intrusions.

DEPOSIT FORM: Large intrusions into pelitic sedimentary units may produce tabular deposits 20 to 60 metres wide and up to 6 kilometres long. Majority of occurrences are small and irregular in shape. Primary deposits may be associated with alluvial and eluvial accumulations.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

P01 - Andalusite Hornfels

TEXTURE/STRUCTURE: Andalusite forms euhedral crystals as porphyroblasts in a fine grained matrix. Individual crystals may reach the size of 60 millimetres in length. Randomly oriented minerals are characteristic of decussate texture. The chiastolitic rocks are characterized by fairly homogenous distribution and size of the andalusite crystals.

ORE MINERALOGY: (Principle and s*ubordinate*): Andalusite, *staurolite*, *garnet*.

GANGUE MINERALOGY (Principle and *subordinate*): Fine grained hornfels matrix - usually cordierite, biotite, muscovite, chlorite and quartz.

ALTERATION MINERALOGY: Retrograde metamorphism results in andalusite being altered to mica and staurolite or mica and chlorite. Such alteration (even partial) may render the andalusite unusable for industrial applications.

WEATHERING: Andalusite is not highly susceptible to chemical weathering and as such, may accumulate in alluvial sediments or as a residual deposit.

ORE CONTROLS: Andalusite development is a factor of the composition of the protolith and the high temperature/low pressure conditions adjacent to an igneous intrusion. The chemical nature and thickness of the original sedimentary layers and their respective distance from the intrusive contact are the main controls on the formation of andalusite hornfels orebodies. Although the metamorphic aureole may extend a large distance, typically only a few areas within the aureole satisfy the conditions necessary to produce economic accumulations of andalusite.

GENETIC MODELS: Andalusite deposits develop in pelitic rocks with high alumina and low calcium contents at temperatures of 550° to 600°C and low pressures of about two kilobars. Such conditions usually develop within the contact aureole of an intrusive. At higher temperatures, sillimanite or corundum and spinel would form at the expense of andalusite.

ASSOCIATED DEPOSIT TYPES: Wollastonite (K09) and garnet (K08) skarns form under similar circumstances from calcium-rich protoliths. Andalusite hornfels deposits can be the source for placer andalusite (C01, C02). Microcrystalline graphite (P03) and gem corundum (Q09) are also found in contact aureoles of igneous rocks.

COMMENTS: Under special conditions, regional, low pressure metamorphism can result in crystallization of sufficient andalusite to be a commercial grade. Some contact aureoles of large intrusive complexes, like the Bushveld Complex, are so extensive that they have features similar to regional low-pressure metamorphism.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: None.

GEOPHYSICAL SIGNATURE: None.

OTHER EXPLORATION GUIDES: Andalusite, corundum and spinel in alluvial deposits; geological contacts of pelitic sediments with plutonic rocks; sedimentary roof pendants in large plutonic complexes. Most deposits are found within one km of the related igneous intrusion. Economic deposits are more likely in prospective regions with well developed weathering profiles.

P01 - Andalusite Hornfels

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: South African deposits contain approximately 35 Mt of economically recoverable reserves. The Andafrax deposit is a 60 m thick zone with 5 to 20% andalusite crystals and with production of about 36 ktpy. The Grootfontein mine contains 15% andalusite with annual production capacity estimated at 140 kt. The Krugerspost deposit has an average width of 20 m with andalusite content 8 to 12% and annual mine production about 30 kt. The Havercroft mine has a 50 m thick hornfels ore zone with 7 to 8% andalusite and annual mine capacity about 50 kt. The Hoogenoeg mine ore contains between 8 and 12% andalusite; production capacity is 35 kt per year. The Kerphales deposit in France contains 15% andalusite crystals and is about 400 m thick. It has proven and possible reserves of 10 Mt and produces 65 kt per year.

ECONOMIC LIMITATIONS: Andalusite concentrate should contain from 57 to 61% Al_2O_3 and 0.6 to 0.9% Fe_2O_3 and is priced between US$180 and US$140 per tonne (Industrial Minerals, 1997). Because of extreme hardness, some fresh andalusite hornfels are uneconomic to process in spite of high andalusite content and only the weathered zones are mined (Hoogenoeg mine, South Africa). Andalusite recovery generally ranges from 50 to 60%, some production from primary deposits is supplemented from adjacent alluvial accumulations.

END USES: The most important use of andalusite is in monolithic refractories and unfired bricks for blast and glass furnaces, cement kilns and combustion chambers. Smaller quantities are used in specialty ceramics, like spark plugs, acoustic tiles, etc.

IMPORTANCE: Andalusite is a high quality raw material for high-alumina refractory products. It can be substituted by synthetic mullite, kyanite and sillimanite.

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P02 - Kyanite, Muscovite, Garnet in Metasediments

by G.J. Simandl[1], S. Paradis[2],
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Simandl, G.J., Paradis, S., McCracken, W.H., and Hancock, K.D., 1999. Kyanite, muscovite, garnet in metasediments: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 89–92.

IDENTIFICATION

SYNONYMS: Sillimanite deposits, kyanite deposits, muscovite schist deposits.

COMMODITIES (BYPRODUCTS): Kyanite or sillimanite (± muscovite, ± garnet; possibly staurolite and corundum). In some deposits garnet or mica may be considered as the principal commodity.

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Trail Bay and Dudevoir Passage showings also reffered to as Tsimpsean Peninsula (103J 024), Yellow Creek (083D 007), Hawkesbury Island kyanite (103H 058); *NARCO and Lac Croche kyanite deposits (Quebec, Canada), Willis Mountain kyanite, (Virginia, USA), Graves Mountain, (Georgia, USA). and sillimanite-corundum deposits of Sonapahar area (India) and Pella district (South Africa).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Kyanite and sillimanite occur as porphyroblasts or crystalline masses in schists, gneisses, quartzites and paragneisses formed by metamorphism from aluminous sedimentary rocks. Muscovite and garnet are often associated with kyanite and can be economically important. The host metamorphic sequences are deformed and often cut by pegmatites. Kyanite deposits are located in high pressure metamorphic terrains, while sillimanite occurs mainly in schists and gneisses affected by high-temperature and pressure metamorphism.

TECTONIC SETTINGS: Mainly in highly deformed metasedimentary belts where tectonic setting at the time of sedimentation is difficult or impossible to establish. Exposed catazone of the continental shield and core complexes along continental margin are good examples.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Host lithologies derived from high-alumina protoliths, such as high-alumina shale, paleo-regolith, paleo-placer or alteration zones. The kyanite and sillimanite deposits occur in metasedimentary belts, metasedimentary roof pendants and contact metamorphic zones.

AGE OF MINERALIZATION: Coincides with the age of metamorphism; most deposits are Precambrian.

HOST/ASSOCIATED ROCK TYPES: Kyanite- and/or sillimanite-bearing gneiss, schist and quartzite associated with marble, biotite and garnet paragneiss, mica schist, hornblende schist, orthogneiss, clinopyroxenite, amphibolite, pegmatite and variety of other intrusive rocks.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada
[2] Geological Survey of Canada, Sidney, British Columbia, Canada
[3] F.S. Alloys and Minerals Corporation, Pittsburgh, Pennsylvania, USA
[4] Spokane Resources Ltd., Vancouver, British Columbia, Canada

P02 - Kyanite, Muscovite, Garnet in Metasediments

DEPOSIT FORM: Stratabound; high-grade lenses, pockets and discordant planar or irregular zones may be present within low-grade stratiform mineralization. Mineable portions of the deposits are at least several metres in thickness and may be exposed over hundreds of metres along strike. Larger deposits are exposed over an area of several thousands of square metres.

TEXTURE/STRUCTURE: Kyanite and sillimanite-bearing rocks can be porphyroblastic or lepidoblastic and are commonly schistose or gneissic; size of porphyroblasts may increase near the contact with intrusive or pegmatite sweat-outs. Abundant solid inclusions within aluminum silicates.

ORE MINERALOGY [Principal and *Subordinate*]: Kyanite/ *± muscovite, ± garnet, ± staurolite or sillimanite/± corundum*.

GANGUE MINERALOGY [Principal and *Subordinate*]: Quartz*, biotite, ± muscovite, ± garnet, feldspar, ± staurolite, ± corundum, ± graphite, ± sulphides, ± oxides, ± amphiboles, ± sapphire, ± cordierite, ± andalusite, and ± rutile*.

ALTERATION MINERALOGY: Pyrophyllite, muscovite and sericite are common alteration products of kyanite.

WEATHERING: In general intense weathering facilitates separation of kyanite family minerals from gangue minerals.

ORE CONTROLS: Stratigraphy, chemical composition of the protolith and degree of metamorphism. High-grade zones within the mineralized units are commonly located in crests of folds, sheer zones and sweat-outs that were open to fluids at the time of the crystallization of anhydrous, aluminous silicates.

GENETIC MODEL: Kyanite, sillimanite, garnet and muscovite are metamorphic minerals. Kyanite deposits are hosted by quartzites, schists and paragneisses of high pressure metamorphic terrains. Sillimanite occurs mainly in schists and gneisses affected by high-temperature, high-pressure metamorphism.

ASSOCIATED DEPOSIT TYPES: Garnet-bearing paragneiss, some of the abyssal pegmatites (O04), crystalline flake graphite (P04) deposits. Secondary (C01) and primary (P06) sapphires, placer kyanite, sillimanite, andalusite and garnet or staurolite deposits (C02, C03) and corundum in aluminous metasediments occur in similar geological environments.

COMMENTS: In North America, kyanite is the most widely used Al_2SiO_3 polymorph. Sister polymorphs are andalusite and sillimanite. When calcined these minerals are converted to mullite, a highly refractory phase. Kyanite converts to mullite at 1370°C. This conversion is accompanied by a non reversible volume expansion of 18%. Because of this volume change, calcination of kyanite is required before it can be used in refractory shapes. For discussion on the andalusite see deposit model P01.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: N/A.

GEOPHYSICAL SIGNATURE: Regional geophysical data, such as EM, radiometric methods, etc. may be used as indirect tools to trace favourable metasedimentary units if marker horizons or igneous intrusions have distinctive signatures.

OTHER EXPLORATION GUIDES: Delimit areas where metamorphic conditions required to form anhydrous aluminum silicates were reached. Identify favorable lithologies and pay special attention to crests of folds and metasediment-intrusive rocks contacts. Panning along stream beds for heavy minerals is an effective exploration tool, since the density of aluminum silicates varies from 3.1 to 3.7 g/cm^3.

P02 - Kyanite, Muscovite, Garnet in Metasediments

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Graves Mountain has possible reserves of 30 Mt at 25% kyanite and Willis Mountain reports indicated reserves of 65 Mt at 25% kyanite.

ECONOMIC LIMITATIONS: Anhydrous aluminum silicate polymorphs are relatively low priced products. Transportation distance and processing required for specific end uses may limit the market area. Processing to mullite or precalcination does increase the market area for kyanite, assuming favourable energy costs near the mine site. Kyanite concentrates should contain a minimum of 56% Al_2O_3 and 42% SiO_2, with less than 1% Fe_2O_3, 1.2% TiO_2, 0.1% MgO and 0.1% CaO. In general, the coarse-grained concentrates command the highest prices; therefore, ores containing larger kyanite crystals with minor amounts of unwanted mineral inclusions are particularly attractive. Several large, high-grade deposits are not exploited because the kyanite incorporates deleterious mineral inclusions. Co-production of mica and garnet as part of hard-rock kyanite operations should be considered in modern feasibility studies.

Sillimanite concentrates are derived mainly as a byproduct of heavy mineral sand operations. The well-known sillimanite-corundum sources from Assam, India are nearly exhausted. Similar product was also mined in the Pella District, Republic of South Africa. Fibrolite sillimanite is not mined from gneisses because of processing difficulties. Occurrences with “matchstick”-sized crystals were mined in the past and are more amenable to upgrading.

END USES: These deposits represent low-cost raw materials for mullite-based, high-performance refractories characterized by high hot strength and resistance to chemically corrosive environments. Kyanite has applications in high-performance refractory products used in both brick and monolitic applications. Also utilized in steel and glass industries, cement kilns, heat treatment furnaces, ceramic and petrochemical industries. Kyanite has new applications in non-slip flooring, glazes and abrasives. Sillimanite-corundum boulders are cut directly into refractory shapes. Assuming comparable grades, sillimanite concentrate could compete with andalusite, both of these minerals are characterized by a relatively low volume increase during mullitization if compared to kyanite. However, currently there is a very limited market incentive to produce sillimanite concentrate.

IMPORTANCE: Kyanite derived from quartzites and schists is the most commonly used anhydrous aluminum silicate in North America. In Europe and in Japan, andalusite is the most preferred polymorph, because it does not require precalcination.

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P03 - Microcrystalline Graphite

G.J. Simandl[1] and W.M. Kenan[2]

Simandl, G.J., and Kenan, W.M., 1999. Microcrystalline graphite: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 93–95.

IDENTIFICATION

SYNONYM: "Amorphous graphite" is a technically incorrect but commonly used commercial term for the same product.

COMMODITY: Microcrystalline graphite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): *Kellog Mine in Moradillos (State of Sonora, Mexico), Kaiserberg, Styria region (Austria) and Velké Vrbno-Konstantin (Czech Republic)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Most amorphous graphite deposits are formed by contact or regional metamorphism of coal beds or other highly carbonaceous sedimentary rocks. Deposits may consist of several beds or lenses, each a few metres thick and up to several kilometres in length. Typical host rocks are quartzites, phyllites, schists and metagraywackes.

TECTONIC SETTINGS: Continental margin or intracratonic basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Near shore sedimentary rocks with intercalated coal seams, or other highly carbonaceous sedimentary beds, that are metamorphosed by nearby igneous intrusions or affected by regional metamorphism.

AGE OF MINERALIZATION: Most of the deposits are Mississippian to Cretaceous in age or younger.

HOST/ASSOCIATED ROCK TYPES: The host rocks are coal seams or other highly carbon-rich rock types and their low to medium grade metamorphic equivalents. Amorphous graphite deposits occur within sequences of chlorite and muscovite schists, phyllites, quartzites, metagraywackes, limestones, sandstones and conglomerates which may be cut by diabasic or granitic intrusions with associated andalusite-bearing hornfels.

DEPOSIT FORM: Stratiform or lens-shaped; beds may be deformed and/or repeated by folding and faulting. Pinching and swelling of beds is common. Deposits may consist of several beds, each one to few metres thick. They may be exposed for hundreds of metres to several kilometres in strike length.

TEXTURE/STRUCTURE: Graphite-bearing beds may contain lenses of hanging wall or footwall host rocks and are characterized by abundant slickensides. Graphite ore is schistose or massive.

ORE MINERALOGY [Principal and *subordinate*]: Microcrystalline graphite

GANGUE MINERALOGY [Principal and *Subordinate*]: Meta-anthracite ± anthracite ± quartz ± mica ± coke ± clay ± pyrite and other sulphides ± apatite ± gypsum.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada
[2] Asbury Graphite Mills Inc., Asbury, New Jersey, United States of America

P03 - Microcrystalline Graphite

ALTERATION MINERALOGY: N/A.

WEATHERING: Weathered outcrops of microcrystalline graphite are typically dull, porous and dark-gray to black.

ORE CONTROLS: Coal beds invaded by intrusive rocks or sedimentary sequences with coal seams or other carbon-rich rocks metamorphosed typically to greenschist facies. Size, grade and mineral impurities of the graphite deposit depend on the characteristics of the original coal seams and carbon-bearing or carbonaceous sediments. Degree of metamorphism controls the degree of graphitization. Graphite may grade into coal with increasing distance from the heat source. Temperatures required for graphitization are lower under shear conditions. Faults and folds may control the thickness or repetition of graphite beds.

GENETIC MODELS: Graphitization can be described as an extreme case of coal maturation. Coal maturation involves the following sequence: peat - lignite - bituminous coal - semi-anthracite - anthracite - meta-anthracite - microcrystalline graphite. Source of heat in contact-metamorphic environment may be plutons, dikes or sills adjacent to coal beds.

ASSOCIATED DEPOSIT TYPES: Coal deposits, (A03, A04, A05). Some coal beds may be only partially converted into graphite. Expending shale (R02) and bentonite deposits (E06) are commonly associated with coal. Andalusite deposits (P01) may be present in cases where graphite is formed by contact metamorphism.

COMMENTS: Although several areas appear favorable for the formation of amorphous graphite there are no known deposits in British Columbia. Meta-anthracite is reported at Guess Creek near Smithers and Flint Creek near Hazelton.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Graphite may be present in residual soils. Positive vanadium and nickel anomalies and negative boron anomalies associated with graphite beds were reported by Tichy and Turnovec (1978). This enrichment is probably related to the trace element content of the protolith, therefore, each deposit may have its own geochemical characteristics. It is unlikely that the chemical signature could be used effectively in grassroots mineral exploration

GEOPHYSICAL SIGNATURE: Graphite deposits have been located using induced polarization (IP), resistivity, ground and airborne electromagnetic (EM), spontaneous potential (SP) and audiomagnetotelluric (AMT) surveys. Outcrops may have associated radioactivity because of trace amounts of uranium.

OTHER EXPLORATION GUIDES: The most important regional exploration guides for high-grade amorphous deposits are: 1) coal beds within stratigraphic sequences invaded by igneous rocks or 2) coal seams traced across regional metamorphic isograds into low to medium-grade metamorphic areas.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The mean size of the deposits reported by Bliss and Sutphin (1992) is 4,900,000 tonnes. Major active mines contain over 80 per cent carbon, but the average grade of some of the European deposits may be as low as 55%. Some beds may be only partly graphitized.

ECONOMIC LIMITATIONS: Mines are mainly open pit, however underground mining is possible depending on the thickness and orientation of the ore. Prices of amorphous graphite are substantially lower than the prices of the crystalline flake graphite. The ore is commonly hand-sorted. Quantity and type of impurities and ash content are major concerns. The degree of graphitization varies from one deposit to an other and as a result, proportions of microcrystalline graphite to carbon also varies.

P03 - MICROCRYSTALLINE GRAPHITE

END USES: Microcrystalline graphite is used in brake linings, foundry applications, lubricants, pencils, refractories, and steel making. The graphite may contain several percent volatile material. In fact, some meta-anthracite from South Korea is marketed as microcrystalline graphite, but it may be due largely to export restrictions on energy exports from Korea.

IMPORTANCE: Metamorphosed coal beds are the main source of microcrystalline graphite. For most applications, synthetic graphite and crystalline graphite may be substituted for amorphous graphite but at increased cost.

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P04 - Crystalline Flake Graphite

by G.J. Simandl[1], and W.M. Kenan[2]

Simandl, G.J., and Kenan, W.M., 1999. Microcrystalline graphite: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 93–95.

IDENTIFICATION

SYNONYM: Disseminated flake graphite deposits.

COMMODITY: Crystalline flake graphite and crystalline graphite powder.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): AA prospect (092M 017), Black Crystal (82FNW260), Mon (093N 203); *Lac Knife deposit, Asbury Graphite mine and Peerless Mine (Quebec, Canada), Graphite Lake and Black Donald mines (Ontario, Canada); American Graphite Company mine (New York State, USA)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Disseminated flakes graphite deposits are commonly hosted by porphyroblastic and granoblastic marbles, paragneisses and quartzites. Alumina-rich paragneisses and marbles in upper amphibolite or granulite grade metamorphic terrains are the most favourable host rocks. Highest grades are commonly associated with rocks located at the contacts between marbles and paragneisses and deposits are thickest within fold crests. Minor feldspathic intrusions, pegmatites and iron formations also contain disseminated flake graphite.

TECTONIC SETTINGS: May be found in any setting with favourable paleo-environment for accumulation and preservation of organic materials, such as intracratonic or continental margin-type basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Metasedimentary belts of granulite or upper amphibolite facies invaded by igneous rocks.

AGE OF MINERALIZATION: Known deposits are mostly of Precambrian age, but could be of any age.

HOST/ASSOCIATED ROCK TYPES: Marbles, paragneisses, quartzites, magnetite-graphite iron formations, clinopyroxenites, amphibolites and pegmatites can host flake graphite deposits. Associated lithologies are orthogneisses, charnockites, orthopyroxenites, amphibolites, granulites and variety of intrusive rocks.

DEPOSIT FORM: Stratiform lens-shaped or saddle-shaped. Individual, economically significant deposits are several metres to tens of metres thick and hundreds of metres in strike length.

TEXTURE/STRUCTURE: Strong foliation, schistosity and lepidoblastic texture for paragneiss and schists. Granoblastic, equigranular or porphyroblastic textures in marbles.

ORE MINERALOGY [Principal and *Subordinate*]: Crystalline flake graphite ± *microcrystalline graphite*.

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[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Asbury Graphite Mills Inc., Asbury, New Jersey, United States of America

P04 - Crystalline Flake Graphite

GANGUE MINERALOGY [Principal and *Subordinate*]: In carbonate-hosted graphite deposits: calcite, clinopyroxene, pyrite and other sulphides ± *dolomite* ± *anorthite* ± *chlorite* ± *clinozoisite* ± *zoisite* ± *garnet*. In paragneiss-hosted graphite deposits: feldspar, quartz, biotite, ± clinopyroxene ± garnet ± sillimanite ± kyanite ± sulphides ± *clinozoisite* ± scapolite ± *secondary gypsum*.

ALTERATION MINERALOGY: Chlorite, prehnite, zoisite and clinozoisite are common retrograde minerals in porphyroblastic marbles.

WEATHERING: Jarosite is a common weathering product of disseminated pyrite-bearing, gneiss-hosted graphite deposits.

ORE CONTROLS: Low grade, large tonnage deposits are hosted mainly by paragneisses and are stratabound. Higher grade portions of these deposits are commonly located in fold crests; along paragneiss-marble, quartzite-marble and quartzite-paragneiss contacts; or along other zones that acted as channels for retrograde metamorphic fluids.

GENETIC MODELS: Low-grade, stratabound and stratiform deposits are believed to be a product of graphitization of the organic material within pre-metamorphic protolith (carbonates and shales). The crystallinity of graphite is linked to the degree of metamorphism. Higher grade portions of these deposits are usually structurally controlled, and were probably enriched during the retrograde phase of the regional or contact metamorphism. Late graphite precipitation (enrichment) may have been triggered by internal or external buffering or fluid mixing.

ASSOCIATED DEPOSIT TYPES: Commonly associated with vein-graphite deposits (P05).

COMMENTS: Can be spatially associated with kyanite, sillimanite, mica and garnet (P02), dimension stone (R03), high-calcium carbonate deposits (R09), wollastonite skarn (K09) and abyssal (ceramic) pegmatites (Q04).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Graphite concentrations in residual soils and stream beds. Geochemical trace element methods were pioneered in USSR although these methods do not rival with geophysical methods in effectiveness.

GEOPHYSICAL SIGNATURE: Effective methods for detecting high grade mineralization (where at least locally the individual flakes are touching) are airborne EM, ground VLF and other EM methods. Induced polarisation, applied potential and self potential are also used, although IP is considered relatively expensive and in many cases too sensitive.

OTHER EXPLORATION GUIDES: Graphite deposits commonly form clusters. Overall quality of graphite flake increases with the intensity of regional metamorphism. Metasedimentary rocks of upper amphibolite or granulite facies represent the best exploration ground. Traces of graphite within a metasedimentary sequence indicate that the oxidation-reduction conditions were favourable for the preservation of graphite deposits. High-grade ores are associated with fold crests and contacts between adjacent lithological units. In some regions, blue quartz is found in close spatial association with crystalline-flake graphite deposits and could be considered as an empirical indirect indicator of favourable environment for graphite exploration.

P04 - Crystalline Flake Graphite

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grade and tonnage of producing mines and developed prospects varies substantially. The median grade and size is 9.0% and 2 400 000 tonnes respectively (Bliss and Sutphin, 1992). Depending on market conditions, large deposits containing high proportions of easily liberated, coarse flakes can be economic with grades as low as 4%.

ECONOMIC LIMITATIONS: Price of the commercial concentrate is determined by flake size, degree of crystallinity (toughness), graphitic carbon content, ash content and type of the impurities. Crystalline flake graphite is commonly chemically-and heat-treated to enhance its properties. Depending on the applications, the most common limiting technical parameters are the carbon content, the diameter of the graphite flakes, the degree of crystallinity (which is related to the flake toughness), the type of impurities and the ash content. Metallurgical and consumer tests are therefore required to market flake graphite.

END USES: Main uses are in refractors, lubricants, brake linings, foundry moulds and dressings, crucibles, electrodes, pencils and others. Graphite use in non-traditional applications, such as expanded graphite and graphite foils, is increasing, while the demand for use in refractors is highly cyclical.

IMPORTANCE: Flake graphite can be substituted for in most of its applications, however substitute materials are more expensive and do not perform as well.

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P05 - Vein Graphite in Metamorphic Terrains

by G.J. Simandl[1] and W.M. Kenan[2]

Simandl, G.J., and Kenan, W.M., 1999. Vein graphite in metamorphic terrains: In: Selected mineral deposit profiles, volume 3 – industrial minerals and gemstones, Ministry of Energy and Mines, British Columbia Geological Survey, Open File 1999-10, p. 101-103.

IDENTIFICATION

SYNONYMS: Lump and chip graphite, epigenetic graphite.

COMMODITY: Crystalline lump and chip graphite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): *Calumet, Clot, Walker and Miller mines and St. Sauveur occurrences (Quebec, Canada), Dillon (Montana, USA), Bogala Mine (Sri Lanka), deposits of South Kerala (India)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Graphite veins currently mined are from few centimetres to a metre thick. Typically they cut amphibolite to granulite grade metamorphic rocks and/or associated intrusive rocks.

TECTONIC SETTING(S): Katazone (relatively deep, high-grade metamorphic environments associated with igneous activity; conditions that are common in the shield areas).

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Veins form in high-grade, dynamothermal metamorphic environment where metasedimentary belts are invaded by igneous rocks.

AGE OF MINERALIZATION: Any age; most commonly Precambrian.

HOST/ASSOCIATED ROCK TYPES: Hosted by paragneisses, quartzites, clinopyroxenites, wollastonite-rich rocks, pegmatites. Other associated rocks are charnockites, granitic and intermediate intrusive rocks, quartz-mica schists, granulites, aplites, marbles, amphibolites, magnetite-graphite iron formations and anorthosites.

DEPOSIT FORM: Veins are from a few millimetres to over a metre thick in places, although usually less than 0.3 meter thick. Individual veins display a variety of forms, including saddle-, pod- or lens-shaped, tabular or irregular bodies; frequently forming anastomosing or stockwork patterns. The mines in Sri Lanka are from 30 metres to 400 metres deep; individual veins rarely extend more than tens of metres.

TEXTURE/STRUCTURE: Rosettes, coarse flakes, "fibers" or "needles" oblique or perpendicular to wall rock, or in some cases schistosity subparallel to the vein walls.

ORE MINERALOGY [Principal and *subordinate*]: Crystalline and microcrystalline graphite.

GANGUE MINERALOGY [Principal and *Subordinate*]: Depends largely on the host-rock. In marble or skarn: *calcite ± wollastonite ±hedenbergite ± zoisite ± clinozoisite ± prehnite ± quartz ± titanite ± sulphides ± diopside ± scapolite ± prehnite*. In most of other rocks: feldspar *± apatite ± garnet ± scapolite ± biotite ± sillimanite ± secondary iron oxides*.

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[2] Asbury Graphite Mills Inc., Asbury, New Jersey, United States of America

P05 - Vein Graphite in Metamorphic Terrains

ALTERATION MINERALOGY: Most veins are not surrounded by macroscopically distinguishable alteration halos, while some veins have narrow (< 1cm thick) alteration halos that are not well documented. Sillimanite, graphite-sillimanite or graphite-tourmaline alteration is reported adjacent to the veins in Sri Lanka and New Hampshire. In Quebec, some of the veins cut rocks with contact metamorphic or skarn characteristics.

WEATHERING: In the near surface environments, graphite grades are enhanced by weathering out of gangue minerals.

ORE CONTROLS: Veins form along joints, breccia zones, crests of folds, decollements along geological contacts and foliations. Joints in brittle lithologies (such as hornfels or skarns in contact metamorphic aureoles associated with deep seated intrusive rocks) are particularly favourable. Relatively reducing conditions (within the graphite stability field).

GENETIC MODELS: The origin of graphite veins is controversial. The ultimate source of carbon may be vary from one deposit to other. Although most of the veins are hosted by high grade metamorphic rocks, the graphite precipitation may take place during the retrograde phase of the regional or contact metamorphism. This is suggested by coexistence of low temperature minerals such as prehnite with vein-graphite. Depending on the occurrence, the interaction of fluid with the host rock (internal or external buffering), such as oxidation of CH_4-bearing fluids by wall rock, cooling of a hot fluid nearly saturated with respect to graphite, or fluid mixing are the most probable causes of vein formation.

ASSOCIATED DEPOSIT TYPES: Commonly associated with disseminated crystalline flake graphite deposits (P04) and in some cases with wollastonite deposits (K09) and abyssal (ceramic) pegmatites (O04).

COMMENTS:

1) Crystalline graphite veins hosted by ultramafic rocks are relatively uncommon and are not covered by this profile.

2) Portions of the AA crystalline flake graphite deposit, located near the southern tip of Bentick Arm, British Columbia, contain microscopic graphite veinlets, suggesting that graphite veins may also occur in the metasedimentary roof pendants of the Coast Plutonic Complex.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Veins may have in some cases narrow (< 1cm thick) alteration halos that are not well documented and are to thin to be of use in exploration. The chemical composition of ore is influenced mainly by the composition of gangue minerals.

GEOPHYSICAL SIGNATURE: Ground electromagnetic methods (VLF in initial exploration stage, horizontal or vertical loupe at later stages) and resistivity are the most appropriate methods to locate large graphite veins. "Mise a la masse" is useful in vein delineation.

OTHER EXPLORATION GUIDES: Graphite veins are most common in highly metamorphosed terrains and in several cases are associated with crystalline flake graphite deposits. Because graphite is inert in the weathering environment, boulder tracing and use of electomagnetic mats may be effective.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Veins contain 40 to 90% graphitic carbon before hand sorting. No reliable data is available on the tonnages for individual veins.

P05 - Vein Graphite In Metamorphic Terrains

ECONOMIC LIMITATIONS: Since the deposits are relatively narrow veins, the mines are typically small scale, labour intensive and underground. The ore is hand sorted, washed and screened. Where possible, consumers substitute the less expensive and readily available crystalline flake graphite for vein graphite. The main technical parameter of the vein-graphite concentrate is its ability to mould to any shape and flow when exposed to extreme pressures.

END USES: Graphite from veins is used mainly in: powder metals, special refractories, copper graphite and carbon graphite brushes for electrical applications.

IMPORTANCE: The only current source of crystalline lump graphite is Sri Lanka; it is exported world-wide.

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P06 - Corundum in Alumina-Rich Metasediments

by G.J. Simandl[1] and S. Paradis[2]

Simandl, G.J., and Paradis, S., 1999. Corundum in alumina-rich metasediments: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 105–108.

IDENTIFICATION

SYNONYMS: Corundum-bearing schists and paragneisses; corundum in metapelites and metabauxites are covered by this model.

COMMODITIES (BYPRODUCTS): Industrial-grade corundum (gem corundum) and emery.

EXAMPLES (British Columbia - *Canada/International*): Blu Star (082FNW259); *Elk Creek, Bozeman and Bear Trap deposits (Montana, USA), Gangoda and Tannahena occurrences (Sri Lanka).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Corundum occurs as porphyroblasts or idiomorphic, xenomorphic or skeletal crystals within high grade, regionally metamorphosed belts. It is confined to specific metamorphic layers and concordant lenses of alumina-rich gneisses and schists. It is rarely of gem quality. Emery is a fine-grained, black, granular rock composed of intergrowths of corundum, magnetite, hercinite or hematite that commonly forms in medium to high grade metamorphic environments.

TECTONIC SETTINGS: Corundum in gneisses occurs mostly in fold belts or deep cratonic (catazonal) environments exhumed in thrust belts or by erosion. Emery and related meta-bauxites may be found in wide variety of tectonic environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Most of these deposits form in high-grade, mainly granulite facies, dynamothermal metamorphic (catazonal) environments. Metasedimentary belts containing aluminous strata or lenses, in some cases intruded by igneous rocks, are particularly favourable. Emery deposits are also known to occur in similar and lower grade metamorphic environments.

AGE OF MINERALIZATION: Corundum is considered syn-metamorphic. The protolith may be Precambrian or younger. Rocks that were exposed at the surface during periods of extreme chemical weathering are particularly favourable

HOST/ASSOCIATED ROCK TYPES: Corundum-bearing gneisses and schists are associated with sillimanite-garnet-biotite gneisses, kyanite-mica schists, quartzites, clinopyroxenites, pegmatites, syenites or alkaline intrusions, anorthosites, charnockites, migmatites, granitic and intermediate intrusive rocks, quartz-mica schists, granulites, aplites, marbles, cordierite-bearing gneisses, amphibolites and wollastonite-scapolite rocks. The lithologies hosting metasedimentary emery lenses are commonly lower metamorphic grade equivalents of above listed rocks.

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P06 - Corundum in Alumina-Rich Metasediments

DEPOSIT FORM: Corundum-bearing, stratabound and discontinuous layers and lenses in gneisses are from 20 centimetres to a few metres in thickness and may be traced for tens to hundreds of metres along strike. These layers are commonly strongly deformed, with coarse-grained "sweat outs" which may cut across the gneissic texture. Emery may form lenses from 5 to more than 50 metres thick and more than 100 metres in length.

TEXTURE/STRUCTURE: Gneissosity and schistosity is generally parallel to the compositional layering and corundum mineralization; however, if migmatization or granitization was involved, corundum zones may be irregular or vein-like. The texture of corundum-bearing rocks varies from fine-grained, equigranular to coarse-grained (approaching pegmatitic), locally displaying pseudo-orbicular texture. Corundum crystals may be idiomorphic, xenomorphic or skeletal and may vary from near gem quality to those with abundant solid inclusions. Emery deposits in the low metamorphic grade areas, may contain corundum pseudomorphs after diaspore.

ORE MINERALOGY (Principal and *subordinate*): Industrial grade corundum is a dominant constituent of corundum-bearing gneiss. Same gneiss may also contain specimen quality materials and exceptionally near gem quality stones. Corundum is also the essential constituent of emery ores.

GANGUE MINERALOGY (Principal and *subordinate*): In corundum-bearing schists and gneisses: feldspar, quartz, ± sillimanite, ± muscovite, ± biotite, ± *rutile,* ± *titanite,* ± *zircon,* ± *apatite,* ± *tourmaline,* ± *magnetite,* ± kyanite, ± *calcite,* ± *dolomite,* ± *chlorite,* ± *prehnite,* ± *amphibole,* ± *pleonaste,* ± *cordierite,* ± sapphirine, ± *chloritoid.*
In emery-type deposits: magnetite, spinel (typically hercinite), ± hematite are the most common impurities. Diaspore, staurolite, kyanite ± hydrargite, ± garnet, ± mica, ± chloritoid, ± chlorite, ± calcite, ± epidote may be also present.

ALTERATION MINERALOGY: Corundum crystals commonly alter to muscovite along fractures and twinning planes. Retrograde corundum alteration to diaspore and margarite is also known. Vermiculite-rich layers may form at the contact between corundum-bearing and mafic rocks or marbles.

WEATHERING: Post-depositional exposure of rocks to intense weathering produces high-alumina protolith required to form isochemical metamorphic emery and corundum deposits. Corundum is resistant to chemical and mechanical weathering. Weathering facilitates crystal recovery from the hardrock deposits. Corundum may be enriched in residual soils or eroded and deposited as placer-type deposits. A large proportion of alluvial gem corundum is sometimes interpreted to be derived from corundum layers within garnet-sillimanite-biotite gneisses (Dahanayake and Ranasinghe, 1981).

ORE CONTROLS: The principal controls are the chemical composition (high alumina and low silica content) of the protolith and a high regional metamorphic grade, typically granulite facies. On the other hand, emery deposits may form at temperatures as low as 420°C.

GENETIC MODELS: In most cases, coarse corundum-bearing metasediments are believed to form by the isochemical metamorphism of alumina-rich regoliths, including bauxite protoliths formed under conditions of tropical weathering. Hydrothermal alteration zones containing clays, alunite and diaspore and igneous rocks, such as nepheline syenites and anorthosites, are also considered as favourable, premetamorphic protoliths. Alternatively, some of the deposits are interpreted to have formed by preferential concentration of alumina in restites associated with extreme metamorphism, migmatization and granitization.

ASSOCIATED DEPOSIT TYPES: Sillimanite deposits (P02). Corundum and garnet placer deposits (C01 and C02) are sometimes derived from these corundum deposits. Crystalline flake graphite (P04), vein graphite deposits (P05), and muscovite (Q03) and quartz feldspar pegmatites (Q04) may occur in the same geological settings.

P06 - Corundum in Alumina-Rich Metasediments

COMMENTS: Corundum occurrences formed in shallow, low pressure hydrothermal environments, such as the Empress porphyry deposit, British Columbia and the Semiz-Buru deposit in Kazakhstan, are not covered by this model. In most of geological environments, corundum occurs in silica-undersaturated rocks. Corundum may coexist with quartz at unusually high pressures (Shaw and Arima, 1988).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Corundum and associated minerals, such as sillimanite, ± garnet, ± sapphirine and ± pyroxene in heavy mineral concentrates from stream, lake, till and residual soils. Emery may be also detected in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Magnetite-bearing emery deposits may be detected by magnetometer surveys.

OTHER EXPLORATION GUIDES: Aluminous lithologies within metasedimentary sequences in high grade metamorphic belts. These aluminous lithologies commonly contain high alumina silicate assemblages. Contacts between silica-deficient intrusions and alumina-rich metasediments.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Typical, individual corundum-bearing lenses and layers contain 5 to 28% corundum and most contain less than 7 500 tonnes of ore. In emery rock, the corundum content may reach 70%. The emery is crushed, but in most cases the corundum is not separated from gangue minerals.

ECONOMIC LIMITATIONS: Most of the gneiss-hosted corundum deposits contain industrial grade corundum with little or no high quality gem-quality stones. Mining is typically by open cast, because of relatively low prices of industrial grade corundum (U.S.$150.00 to 275.00 per tonne). Residual and placer deposits are not only less expensive to exploit, but typically contain a higher proportion of gem-quality material due to the break-up of micro-fractured stones during stream transport. Synthetic corundum competes with natural corundum in gem applications and has replaced it in most high technology industrial applications.

END USES: Corundum materials are used as abrasives, in refractory applications, as hardener for heavy-duty concrete floors and as anti-skid material on bridges and entrances to toll booths.

IMPORTANCE: In industrial applications both emery and corundum have to compete with a number of higher-performance synthetics, such as silicon carbide and fused alumina, or lower priced natural materials, such as garnet. Natural and synthetic diamond are also competing for the same market. As a result, combined consumption of corundum and emery in the USA is estimated in order of 10 000 tonnes per year. The U.S. Bureau of Mines considers corundum deposits as a possible substitute for bauxite in high-alumina refractories. The United States imports over 90% of refractory grade bauxite. Unlike bauxite, corundum does not require thermal processing. Preliminary flotation studies of corundum-bearing gneisses were successful in producing refractory grade materials (Smith and Liewellyn, 1987).

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P06 - Corundum in Alumina-Rich Metasediments

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Q - Gems and Semi-Precious Stones (diamonds Under N)

	Profile Title	Authors
Q01	Jade	Z.D. Hora, 2007
Q02	Rhodonite	Z.D. Hora, 2009
Q03*	Agate	
Q04*	Amethyst	
Q05*	Jasper	
Q06	Columbia-type emeralds	G.J. Simandl, S. Paradis, and T.Birkett, 1999
Q07	Schist-hosted emeralds	G.J. Simandl, S. Paradis, and T.Birkett, 1999
Q08	Sediment-hosted precious opal	S. Paradis, J. Townsend and G.J. Simandl, 1999
Q09	Ultramafic-Related Corundum (Contact Metamorphic/Metasomatic)	G.J. Simandl and S. Paradis, 1999
Q10	Alkali basalt/lamprophyre-hosted sapphire and ruby	G.J. Simandl and S. Paradis, 1999
Q11	Volcanic-hosted precious opal	S. Paradis, G.J. Simandl and A. Sabina, 1999

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

Q01 - Jade (Nephrite)

By Z.D.Hora[1]

Hora, Z.D., 2007. Jade (nephrite): mineral deposit profile Q01, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 4 pp.

IDENTIFICATION

SYNONYMS: Nephrite, nephrite jade, jadestone, greenstone (in New Zealand).

COMMODITY: Jade

EXAMPLES (British Columbia - *Canada/International*): Jade King (092HSW097), Birkenhead (092JNE063), Marshall Creek (092JNE064), Noel Creek (092NE118), O`Ne-ell Creek (093K 005), Mt. Sidney Willians (093K 043), Mt.Ogden (093N 157,165), Wheaton Creek (104I 082,085,104), Provencher Lake (104I 064,065,066,078,111), Cassiar (104P 005); *Yukon, Alaska, Wyoming, California, China, Taiwan, New Zealand, Australia, Siberia, Transvaal.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Nephrite is an exceptionally tough, bright green to nearly black massive aggregate of fine grained fibrous amphibole – tremolite or actinolite. Nephrite jade occurs as lenticular bodies. They are associated with serpentinites that are intrusive into or in fault contact with suites of greenstones, chert, pelite and limestone.

TECTONIC SETTING(S): Alpine type serpentinites, ophiolite complex preceding a formation of island arc. In British Columbia the significant occurrences are found in Bridge River, Southern Cache Creek, Slide Mountain, and Northern Cache Creek terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The initial geological setting requires the formation of ultramafic rocks that form in proximity of ribbon chert and argillites or are structurally emplaced next to these types of sediments. The ultramafic rocks are frequently associated with regional fault systems where serpentinites are in contact with cherts and siliceous sediment or siliceous intrusive rocks. Subsequent geological processes, in particular serpentinization, is the main factor in forming nephrite jade.

AGE OF MINERALIZATION: Globally, nephrite occurrences are hosted by Precambrian serpentinites in Zimbabwe to Tertiary ultramafic rocks in New Zealand. In B.C. jade is hosted by mid-Pennsylvanian oceanic crustal rocks and Permo-Triassic sediments. Deformation with resulting greenschist metamorphism took place during Middle to Late Jurassic time and was followed by further deformation and dextral strike slip in Late Cretaceous to Early Tertiary. It is thought that the jade formation occurred during the later stages of deformation. At least on some sites, nephrite is contemporary with origin of rodingite.

HOST/ASSOCIATED ROCK TYPES: Serpentinized ultramafic rocks (harzburgite, dunite, pyroxenite) in contact with argillite and cherty sediments. Associated rocks are rodingite and similar heterogeneous calc-silicate rocks (in British Columbia frequently called “whiterock”).

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Q01 - Jade (Nephrite)

DEPOSIT FORM: Lenticular nephrite bodies typically less than 10 metres wide, 100 metres long at surface occur near contact of major serpentinite mass or in smaller satellite serpentinite slices. In general parallel to the contact with sediments or granitic intrusives and along shear zones.

TEXTURE/STRUCTURE: Massive, very fine grained rock that is light to dark green or almost black in colour. Under the microscope nephrite is characterized by microfibrous tremolite that occurs as interlocking, twisted and felted bundles, tufts and sheaf-like aggregates. Accessory minerals, like magnetite, picotite or garnet, are frequently present in the otherwise fine grained amphibole matrix.

ORE MINERALOGY [Principal and *Subordinate*]: Actinolite – tremolite; *chromite, magnetite, picotite, uvarovite (chromium garnet)*.

GANGUE MINERALOGY [Principal and *Subordinate*]: Rodingite – a heterogeneous mixture of zoisite/clinozoisite, serpentine, actinolite/tremolite, wollastonite, prehnite and garnet) / *talc, chlorite, sphene, magnetite*

ALTERATION MINERALOGY: Nephrite jade is an alteration product resulting from a metasomatic reaction between serpentinite and a source of silica, usually cherty metasediments.

WEATHERING: Jade is resistant to weathering in contrast to the common host rocks, serpentine and metasediments, and frequently forms boulder trains along its outcrops. Jade may be a common component in alluvial and colluvial deposits.

ORE CONTROLS: Serpentinization of ultramafic rocks in contact with high silica and calcium rocks to produce the formation of tremolite. Key element is large volumes of fluids moving through the serpentinized ultramafics capable to produce the metasomatic reaction with chemically right environment.

GENETIC MODELS: The studies on serpentinites indicate, that nephrite is a result of the desilication and calcium metasomatism produced in contact of serpentinites with sedimentary rocks under close to the blueschist metamorphic conditions.The reaction zone develop at a time when larger masses of ultramafic mantle are tectonically emplaced into the base of the crust or moved tectonically higher into it. This may produce a metasomatic reaction resulting in nephrite lenses surrounded by tremolite/chlorite alteration zone (usually called "whiterock"). Ultramafic rock must be below olivine stability field for the reaction to occur. Monomineralic and fine grained jade is stable in a variety of thermodynamic conditions. Evidence is pointing to conclusion, that nephrite jade forms during highly dynamic tectonic activity with fast changing local conditions in temperature, pressure and circulating fluids. Formation of nephrite is considered to occur at temperatures between 500ºC and 290ºC with pressure between 4 and 8 Kb where the water pressure was nearly equal to the total pressure.

ASSOCIATED DEPOSIT TYPES: Ultramafic hosted talk-magnesite (M07), ultramafic hosted asbestos (M06). The Cassiar asbestos deposit produced jade periodically as a by-product.

COMMENTS: There are two types of jade - nephrite and jadeite. While nephrite jade is mineralogically a variety of amphibole, jadeite is a variety of pyroxene. All known Canadian jade occurrences are the nephrite variety.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Not normally used.

GEOPHYSICAL SIGNATURE: Magnetic highs can be used to identify ultramafic and serpentinite bodies.

OTHER EXPLORATION GUIDES: Prospecting for boulder trains and boulders in creeks. The boulders typically have a smooth surface and need to be broken or drilled to see the jade quality. Presence of “whiterock” or rodingite in serpentine outcrop.

Q01 - Jade (Nephrite)

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grades depend on colour, impurities, and presence of fractures. The highest quality jade has a uniform bright green translucent colour (emerald) with little or no impurities and limited fractures. Also the stone`s fabric, i.e. orientation of individual grains is important. In situ deposits range in size from a few tonnes to more than 4,000 tonnes, although not all of the deposit will be commercial jade. Jade cobbles and boulders are also exploited and can be up to tens of tones in weight.

ECONOMIC LIMITATIONS: Top grade jade (without flaws and of good colour) is routinely flown out to the nearest good road, otherwise road access is required. Non-standard colours can come into vogue at times.

END USES: Semiprecious stone used for carving, tiles and ornamental applications. In primitive cultures, jade has been used for weapons, tools and gemstones. Some cultures particularly value jade as a precious stone like Chinese, Maori in New Zealand or Maya Indians in Mexico and Guatemala.

IMPORTANCE: Annual exports of B.C. jade are approximately 100 to 200 tonnes. In 1991, a 32 tonne jade boulder was sold for $CDN 350,000 to be carved into a Buddha statue in Thailand. In 1996 the best quality raw jade sold for $100 per kilogram. Most of the jade produced in British Columbia is regularly exported to Far East countries, some to New Zealand. BC is leading world exporter of nephrite jade.

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Q02 - Rhodonite

by Z.D. Hora[1]

Hora, Z.D., 2009. Rhodonite: mineral deposit profile Q02, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 5 pp.

IDENTIFICATION

SYNONYMS: Manganese spar, manganolite (pyroxmangite).

COMMODITIES (BYPRODUCTS): Rhodonite (jasper).

EXAMPLES (British Columbia - *Canada/International*): Hill 60 (092B 027), Hollings (092B 074), Rocky (092C 113), Arthur Point (092M 015), Clearcut (082ESE241), OrofinoMtn (082ESW009), Olalla (082ESW017), Ashnola Pinky (082ESW208), Joseph Creek (092P 148), Snowy Creek (104P 067); *Evelyn Creek (Yukon, Canada).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Lenses of bedded or massive rhodonite hosted by laminated cherts and cherty tuffs at the base of turbiditic sandstone, siltstone and argillite sequences, usually in proximity to mafic volcanics or greywackes. Red jasper beds with laminated hematite, pyrite and magnetite are sometimes associated with deposits of rhodonite.

TECTONIC SETTINGS: Island arcs, back arc basins, sea floor spreading areas. Epicratonic or continental margin marine basins associated with oceanic faults or rifts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Deep to shallow marine basins. The widespread soft-sediment structures present in the host rock and within the rhodonite bodies suggest deposition of an unstable, gel-like sediment. Submarine hydrothermal activity in mafic environment, abundant silica to feed radiolarian population in the area. Similar modern environments have been described from the Galapagos, southwest Pacific island arc, Gulf of Aden and Mid-Atlantic Ridge.

AGE OF MINERALIZATION: In British Columbia described as mostly Mississippian, Carboniferous or Permian in age, also Upper Triassic. Recently found in a Lower Cretaceous unit. Globally, this type probably may occur in oceanic units of any age.

HOST/ASSOCIATED ROCK TYPES: Ribbon cherts, laminated cherts and cherty tuffs with argillite interbeds; pillow basalts, mafic tuffaceous sediments and greywacke turbidites in the lower part of sequence; sandstone, argillite, calcarenite and limestone in the upper part. Rhodonite is also found in the metamorphosed equivalents of these rocks; typically prehnite-pumpellyite to greenschist grade.

DEPOSIT FORM: Stratiform lenses of rhodonite that are metres thick and intermittently extend laterally some hundreds of metres. Frequently discontinuous and pinching out over tens of metres or less. Thin rhodonite bands less than 10 centimetres across often pinch out over several metres. Thicker rhodonite layers can be followed for distances of more than 50 metres.

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Q02 - Rhodonite

TEXTURE/STRUCTURE: The texture of rhodonite varies from laminated to patchy. Massive rose-pink layers alternate with darker bands and minor yellow and grey chert. Soft sediment deformation features are frequent, particularly along the hanging wall of major rhodonite lenses. Embedded fragments of roof sediment in cherty rhodonite and small “ghost” radiolarians infilled by microcrystalline quartz are common. Crosscutting and bedding parallel rhodonite veinlets up to a few millimeters thick are typical. Some rhodonite lenses adjacent to footwall contain layers and round shaped metallic, black nodules of braunite $(Mn,Si)_2O_3$ from 5 to 10 millimetres in diameter that are overgrown with concentric pink rhodonite rims. The predominant minerals in massive rhodonite-rich zones are usually microcrystalline quartz interbedded with disseminated, mottled and banded rhodochrosite and rhodonite, interlayered with hematite and garnet-rich bands. Manganese oxide is invariably present lining hairline fractures and as surface coatings. Rhodonite occurs as intergrowths with massive or crystalline rhodochrosite as euhedral elongate tabulate crystals, stellated crystal masses or sheath-like bundles enclosed within and encroaching upon a microcrystalline quartz matrix. Rhodonite also forms spongy porphyroblasts up to 500 microns in length. Some rhodonite exhibits mammillary growth textures. Rhodochrosite ranges from a massive carbonate to a mixture of with microcrystalline quartz, rhodonite or disseminated hematite. At higher metamorphic grades the rhodonite exhibits more granoblastic to porphyroblastic texture.

ORE MINERALOGY [Principal and *Subordinate*]: Rhodonite, rhodochrosite, pyroxmangite / *microcrystalline silica, barite, spessartine garnet***,** *bustamite, tephroite, palenzonaite, penninite*, *clinochlore*, *stilpnomelane*, *adularia*.

GANGUE MINERALOGY [Principal and *Subordinate*]: Jasper, chert and manganese oxide / *argillite interbeds.*

ALTERATION MINERALOGY: Effects of metamorphism: amphibole, graphite, phlogopite, garnet, plagioclase in higher metamorphic grades; garnet - tremolite – adularia – prehnite - epidote quartz association in lower metamorphic grades.

WEATHERING: Widespread development of oxidized manganese secondary products.

ORE CONTROLS: The primary control on rhodonite deposits are a favourable stratigraphic package of deep water marine sedimentary and volcanic rocks with a significant sequence of cherts containing manganese-rich layers. Secondary controls are synsedimentary and later deformation that can create thicker or thinner lenses and later processes, such as cross-cutting veinlets, that reduce the value of the rhodonite or rhodochrosite.

GENETIC MODELS: Manganese is deposited as a distal member of volcanogenic products from hydrothermal solutions generated in rifting environment where the thermal fluids percolated through sea-floor basalts and associated rocks of similar chemical composition. These solutions would be hot, slightly acid, strongly reducing, and enriched in Mn, Fe, Si, Ba, Ca, K, Li, Rb and trace metals. Separation of Fe from Mn may occur within the seafloor at depth with the formation of sulphides like pyrite and on the seafloor when the hydrothermal solution mixed with cold, alkaline and oxygenated seawater and precipitates chemical sediments. Nucleation and precipitation kinetics of Mn and Si oxides are sluggish; therefore, they are often distributed distally from the hydrothermal vent. At lower temperatures the manganese precipitates as amorphous oxyhydroxides and Mn^{4+} oxides, moderately higher temperatures could promote syndepositional Mn silicate and carbonate. The hydrothermal sediments can form mounds and retain level of semi-plasticity for extended time which can lead to synsedimenatary deformation and slumping. Alternatively, Mn silicate and carbonate may form during subsequent diagenetic or metamorphic episodes.

ASSOCIATED DEPOSIT TYPES: Red jasper with taconite iron mineralization (G01), all manganese oxide deposits associated with volcanogenic origin (G02) and volcanogenic massive sulphides (G04, G05, G06).

Q02 - Rhodonite

COMMENTS: The name “Rhodonite” is rather a misnomer. The rock is a mixture of pink manganese silicates and a carbonate with fine grained silica. There are many manganese deposits described from all parts of world that are considered of volcanogenic origin. Deposits of rhodonite outside of the Canadian Cordillera are rather uncommon. One possible explanation is that glaciation may have exposed primary deposits which could be deeply weathered with a thick zone of manganese oxides in non-glaciated areas.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalous in manganese, enriched in base metals, barium and strontium.

GEOPHYSICAL SIGNATURE: Not used, probably reflecting the small size of the orebodies and similarities to the associated chert.

OTHER EXPLORATION GUIDES: Oceanic terrains, chert beds, particularly with red jasper, and black staining.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Lenses from up to 3 meters thick and 15 meters long on surface. In most economic deposits, rhodonite and rhodochrosite account for at least 45% of the lens. However, rock hounds often contribute some supply from lenses with lower contents of the semi-precious stone. Two properties in Western Canada were active producers for 20 years – one in Yukon and the other on the British Columbia coast. After the initial major production period, both have been largely inactive for more than 10 years.

ECONOMIC LIMITATIONS: Physical/chemical properties affect the end use. Brighter colours due to rhodochrosite and attractive dendrite black veining increase aesthetic value. Dense fracturing decreases the value and uncemented microfractures restrict carving of larger statues. The relatively high unit value for rough rhodonite allows for processing far away from the original source, frequently overseas.

END USES: Semiprecious stone used in lapidary, jewellery and carvings.

IMPORTANCE: The North American market is very small - only a few tonnes annually. Semi-precious stone used to produce jewellery and carvings. The industry considers rhodonite as a potential substitute for pink coral when environmental considerations prevent its production.

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Q02 - Rhodonite

Hora, Z.D., Langrova, A. and Pivec, E. (2005): Contribution to the Mineralogy of the Arthur Point Rhodonite Deposit, Southwestern British Columbia; *in* Geological Fieldwork 2004, *BC Ministry of Energy, Mines and Petroleum Resources*, Paper 2005 – 1, pages 177-185.

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Q06 - Colombia-Type Emeralds

G.J. Simandl[1], S. Paradis[2] and T. Birkett[3]

Simandl, G.J., Paradis, S., and Birkett, T., 1999. Columbia-type emeralds: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 109–112.

IDENTIFICATION

SYNONYMS: Emerald veins, Muzo and Chivor-type emerald deposits.

COMMODITIES (BYPRODUCTS): Emeralds (pale-green and colorless beryl gemstones).

EXAMPLES (British Columbia - *Canada/International*): No Colombia-type emerald deposits are known in British Columbia. *Chivor, La Mina Glorieta, Las Cruces, El Diamante, El Toro, La Vega de San Juan, Coscuez and Muzo (Colombia)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Colombia-type emerald deposits consist mainly of carbonate-pyrite-albite quartz veins forming “en échellon” or conjugate arrays and cementing breccias. So called “stratiform tectonic breccias” may also contain emeralds. Emeralds are disseminated in the veins as clusters, single crystals or crystal fragments; however, the best gemstones are found in cavities. Country rocks are black carbonaceous and calcareous shales.

TECTONIC SETTING: Probably back arc basins (shales deposited in epicontinental marine anoxic environments spatially related to evaporites) subjected to a compressional tectonic environment.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The deposits are controlled by deep, regional decollements, reverse or thrust faults; hydraulic fracture zones, intersections of faults and by permeable arenite beds interbedded with impermeable black shales.

AGE OF MINERALIZATION: Colombian deposits are hosted by Cretaceous shales. Ar/Ar laser microprobe studies of Cr-V-K-rich mica, believed to be penecontemporaneous with the emerald mineralization, indicate 32 to 38 Ma for Muzo area and 65 Ma for Chivor district. It is not recommended to use these age criteria to constrain the exploration programs outside of Columbia.

HOST/ASSOCIATED ROCK TYPES: Emerald-bearing veins and breccias are hosted mainly by black pyritiferous shale, black carbonaceous shale and slate. Claystone, siltstone, sandstone, limestone, dolomite, conglomerate and evaporites are also associated. Two special lithologies described in close association with the deposits are albitite (metasomatized black shale horizons) and tectonic breccias (“cenicero”). The latter consist of black shale and albitite fragments in a matrix of albite, pyrite and crushed black shale.

DEPOSIT FORM: The metasomatically altered tectonic blocks may be up to 300 metres in width and 50 km in length (Beus, 1979), while individual productive zones are from 1 to 30 metres in thickness. Emeralds are found in en échelon and conjugate veins that are commonly less than 10 centimetres thick, in hydraulic breccia zones and in some cases in cenicero.

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Q06 - Colombia-Type Emeralds

TEXTURE/STRUCTURE: Emeralds are found disseminated in veins as clusters, single crystals or crystal fragments, however, the best gemstones are found in cavities. Quartz is cryptocrystalline or forms well developed hexagonal prisms, while calcite may be fibrous. In some cases, emerald may be found in black shale adjacent or close to the veinlets or “cenicero”.

ORE MINERALOGY [Principal and *subordinate*]: Emerald; *beryl specimens and common beryl.*

GANGUE MINERALOGY [Principal and *subordinate*]: Two vein stages are present and may be superimposed, forming composite veins. A barren stage 1 consisting mainly of fibrous calcite and pyrite and a productive second stage with associated rhombohedral calcite and dolomite, albite or oligoclase, pyrite, ± quartz and minor ± *muscovite,* ± *parisite,* ± *fluorite,* ± *barite,* ± *apatite,* ± *aragonite,* ± *limonite and anthracite/graphite-like material*. Some pyrite veins also contain emeralds. Cavities within calcite-rich veins contain best emerald mineralization.
Solid inclusions within emerald crystals are reported to be black shale, anthracite/graphite-like material, calcite, dolomite or magnesite (?), barite, pyrite, quartz, albite, goethite and parisite.

ALTERATION MINERALOGY: Albitization, carbonatization, development of allophane by alteration of albite, pervasive pyritization and development of pyrophyllite at contacts between veins and host rocks has also been reported.

WEATHERING: In Columbia the intense weathering and related alteration by meteoric water of stratiform breccias and albitites are believed to be responsible for the formation of native sulfur, kaolinite and gypsum. Albite in places altered to allophane.

ORE CONTROLS: Deep, regional fault systems (reverse or thrust); intersections of faults; breccia zones; permeable arenites interbedded with impermeable shales.

GENETIC MODELS: The hypotheses explaining the origin of these deposits are fast evolving. The most recent studies favor a moderate temperature, hydrothermal-sedimentary model. Compressional tectonics result in formation of decollements that are infiltrated by alkaline fluids, resulting in albitization and carbonatization of shale and mobilization of Be, Al, Si, Cr, V and REE. The alkaline fluids are believed to be derived from the evaporitic layers or salt diapirs. As the regional compression continues, disharmonic folding results in the formation of fluid traps and hydrofracturing. A subsequent decrease in fluid alkalinity or pressure could be the main factor responsible for emerald precipitation. Organic matter is believed to have played the key role in emerald precipitation (Cheilletz and Giuliani, 1996, Ottaway *et al*., 1994).

ASSOCIATED DEPOSIT TYPES: Spatially associated with disseminated or fracture-related Cu, Pb, Zn, Fe deposits of unknown origin and barite and gypsum (F02) deposits.

COMMENTS: Colombia-type emerald deposits differ from the classical schist-hosted emerald deposits (Q07) in many ways. They are not spatially related to known granite intrusions or pegmatites, they are not hosted by mafic/ultramafic rocks, and are emplaced in non-metamorphosed rocks. Green beryls, where vanadium is the source of colour, are described at Eidsvoll deposit (Norway) where pegmatite cuts bituminous schists. Such deposits may be better classified as pegmatite-hosted.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Black shales within the tectonic blocks are depleted in REE, Li, Mo, Ba, Zn, V and Cr. The albitized zones contain total REE<40 ppm while unaltered shales have total REE values of 190 ppm. Stream sediments associated with altered shales have low K/Na ratio. Soils overlying the deposits may have also low K/Na ratio.

GEOPHYSICAL SIGNATURE: Geophysics may be successfully used to localize major faults where outcrops are lacking. The berylometer, has applications in ground exploration.

Q06 - Colombia-Type Emeralds

OTHER EXPLORATION GUIDES: Regional indicators are presence of beryl showings, available sources of Cr and Be and structural controls (decollement, reverse faults, fault intersections). In favourable areas, exploration guides are bleached zones, albitization and pyritization. White metasomatic layers within black shale described as albitites, and stratiform polygenetic breccias consisting of black shale fragments cemented by pyrite, albite and shale flour are closely associated with the mineralization.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Distribution of emeralds within the mineralized zones is erratic; therefore, pre-production tonnage estimates are difficult to make. The official grade reported for Colombian deposits is approximately 1 carat/m^3. All stones are valued according to size, intensity of the green colouration and flaws, if present. Tonnages for individual deposits are unknown; however, Chivor reportedly produced over 500,000 carats between 1921 and 1957.

ECONOMIC LIMITATIONS: The earliest developments were by tunneling. To reduce mining costs benching, bulldozing and stripping of mountainsides were introduced. Recently, apparently to reduce environmental pressures, underground developments have been reintroduced at Muzo. Physical and chemical properties of high-quality synthetic emeralds match closely the properties of natural stones. There is currently uncertainty if synthetic emeralds can be distinguished from the high-quality, nearly inclusion-free natural specimens. Recent attempts to form an association of emerald producers may have a similar effect on emerald pricing as the Central Selling Organization has on diamond pricing.

END USES: Highly-valued gemstones.

IMPORTANCE: Currently, world production of natural emeralds is estimated at about $US 1 billion. In 1987 ECONOMINAS reported emerald production of 88,655,110 carats worth US$ 62,910,493. Colombia is the largest producer of natural emeralds by value; most of the gemstones come from the Muzo and Chivor districts. The other major producing countries are Brazil, Zambia, Zimbabwe, Pakistan, Afghanistan, Russia and Madagascar which have schist-hosted emerald deposits (Q07). Brazil is the world's largest producer of emeralds by weight.

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Q07 - Schist-Hosted Emeralds

G.J. Simandl[1], S. Paradis[2] and T. Birkett[3]

Simandl, G.J., Paradis, S., and Birkett, T., 1999, Schist-Hosted Emeralds: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, p. 113–117.

IDENTIFICATION

SYNONYMS: Emerald deposits commonly described as “suture zone-related”, “pegmatite-related schist-hosted” or “exometamorphic”, “exometasomatic”, “biotite schist-type”, “desilicated pegmatite related” and “glimerite-hosted” are covered by this model.

COMMODITIES (BYPRODUCTS): Emerald (industrial grade beryl, other gemstones, such as aquamarine, chrysoberyl, phenakite, tourmaline).

EXAMPLES (British Columbia - *Canada/International*): *Socoto and Carnaiba deposits (Brazil), Habachtal (Austria), Perwomaisky, Mariinsky, Aulsky, Krupsky, Chitny and Tsheremshansky deposits (Russia), Franqueira (Spain), Gravelotte mine (South Africa), Mingora Mines (Pakistan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Emerald deposits principally related to mafic and ultramafic schists or unmetamorphosed ultramafic rocks in contact with felsic rocks, either pegmatoid dykes, granitic rocks, paragneisses or orthogneisses. Such contacts may be either intrusive or tectonic.

TECTONIC SETTINGS: Found in cratonic areas as well as in mobile belts. In many cases related to major Phanerozoic or Proterozoic suture zones that may involve island arc-continent or continent-continent collision zones. The lithological assemblages related to suture zones commonly form a “tectonic mélange” and in some areas are described as “ophiolitic melange”.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Mainly in greenstone belts, but also in other areas where Cr-bearing rocks may be adjacent to pegmatites, aplites, granites and other felsic rocks rich in beryllium. Metamorphic grade is variable; however, it typically reaches green schist to amphibolite facies.

AGE OF MINERALIZATION: The deposits are hosted by Archean age rocks or younger. The age of mineralization is typically linked to either a period of tectonic activity or a time of pegmatoid emplacement.

HOST/ASSOCIATED ROCK TYPES: Biotite schists (“biotites”, “phlogopitites” and “glimerites”) are a particularly favourable host. Other favourable hosts are metamorphosed mafic volcanic rocks, such as epidote-chlorite-actinolite-bearing rock, chlorite and chlorite-talc schists, talc and talc-carbonate schists, white mica schists, mafic schists and gneisses and amphibolites. Less commonly emeralds occur in unmetamorphosed mafic or ultramafic rocks and possibly listwaenites. Pegmatites or quartz veins in the contact zone between granitic rocks and mafic rocks may in some cases host emeralds. A wide variety of rocks can be associated with schist-hosted emerald deposits, including granite, syenite, tonalite, granodiorite, a variety of orthogneisses, marbles, black phyllites, white mica schists, mylonites, cataclasites and other metasedimentary rocks.

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DEPOSIT FORM: Most of the mineralization is hosted by tabular or lenticular mafic schists or "blackwall zones". Favourable zones are a few metres to tens of metres wide and follow the contacts between felsic and mafic/ultramafic lithologies for distances of tens to hundreds of metres, but economically minable portions are typically much smaller. For example, minable bodies in the Urals average 1 metre in thickness and 25 to 50 metres in length. Pegmatoids, where present, may form horizontal to steeply dipping pods, lens-shaped or tabular bodies or anastomosing dykes which may be zoned.

TEXTURE/STRUCTURE: In blackwall or schists lepidoblastic texture predominates. The individual, discrete emerald-bearing mafic layers within the favourable zones may be complexly folded, especially where the mineralization is not spatially associated with pegmatites. Emeralds are commonly zoned. They may form porphyroblasts, with sigmoidal orientation of the inclusion trails; beryl may form the rims separating phenakite form the surrounding biotite schist; or emerald crystals may be embedded in quartz lenses within the biotite schist. Chrysoberyl may appear as subhedral porphyroblasts or skeletal intergrowths with emerald, phenakite or apatite.

Where disseminated beryl crystals also occur within pegmatites, they are short, commonly fractured, prismatic to tabular with poor terminations; but may be up to 2 metres in length and 1 metre in cross section. Long, prismatic, unfractured crystals occur mainly in miarolitic cavities.

ORE MINERALOGY [Principal and *Subordinate*]: Emerald and other beryls (*in some cases aquamarine or morganite*), *± chrysoberyl and industrial grade beryl. Spodumene gems (in some cases kunzite) may be found in related pegmatites*.

GANGUE MINERALOGY [Principal and *Subordinate*]: In the schist: biotite and/or phlogopite, talc, actinolite, plagioclase, serpentine, ± fuchsite, ± quartz, ± carbonates, ± chlorite, ± muscovite, ± pyrite, *epidote, ± phenakite, ± milarite and other beryllium species, ± molybdenite, ± apatite, ± garnet, ± magnetite, ± ilmenite, ± chromite, ± tourmaline, ± cassiterite.*

In the pegmatoids: feldspars (commonly albite), quartz, micas; ± *topaz,* ± *phenakite* , ± *molybdenite, ± Sn and W-bearing minerals, ± bazzite, ± xenotime, ± allanite, ± monazite, ± phosphates, ± pollucite, ± columbite-tantalite, ± kyanite, zircon, ± beryllonite, ± milarite and other beryllium species.* Emerald crystals may contain actinolite-tremolite, apatite, biotite, bityite, chlorite, chromite, columbite-tantalite, feldspar, epidote, fuchsite, garnet, hematite, phlogopite, pyrrhotite, rutile, talc, titanite and tourmaline inclusions.

ALTERATION MINERALOGY: Limonitization and pyritization are reported in the host rocks. Kaolinite, muscovite, chlorite, margarite, bavenite, phenakite, epidimyte, milarite, bityite, bertrandite, euclase are reported as alteration products of beryl.

WEATHERING: Weathering contributes to the economic viability of the deposits by softening the matrix, and concentrating the beryl crystals in the overlaying soil or regolith.

ORE CONTROLS:

1) The principal control is the juxtaposition of beryllium and chromium-bearing lithologies along deep suture zones. Emerald crystals are present mainly within the mafic schists and in some cases so called "blackwall zones" as described ultramafic-hosted talc deposits (M07). In this settings it may be associated with limonite zones.

2) This often occurs near the contacts of pegmatoids with mafic schists. Emerald crystals are present mainly within the mafic schists, although in some cases some of the mineralization may be hosted by pegmatoids.

3) Another prospective setting is along fracture-controlled glimmerite zones.

4) Mineralization may be concentrated along the planes of regional metamorphic foliation, especially in cores of the folds where the relatively high permeability favors chemical exchange and the development of synmetamorphic reaction zones between chromium and beryllium-bearing lithologies.

5) Serpentinite roof pendants in granites are prospective.

Q07 - Schist-Hosted Emeralds

GENETIC MODELS: The origin of schist-hosted emerald deposits is controversial as is the case with many deposits hosted by metamorphic rocks. All emerald deposits require special geological conditions where chromium (± vanadium) and beryllium coexist. Where pegmatoids or plagioclase-rich lenses occur within ultramafic rocks, the crystalization of emeralds is commonly explained by interaction of pegmatites or pneumatolytic-hydrothermal, Be-bearing fluids with Cr-bearing mafic/ultramafic rocks. In other cases, emeralds in schists form by syn- or post-tectonic regional metamorphic chemical exchange (metasomatism) between felsic rocks, such as felsic gneisses, garnet mica schists or pre-metamorphic pegmatoids, with the adjacent Cr-bearing rocks such as schists, gneisses or serpentinites. Contacts between Cr- and Be-bearing source rocks may be tectonic, as is the case for “suture zone-related” deposits.

ASSOCIATED DEPOSIT TYPES: Feldspar-quartz and muscovite pegmatites (O03, O04). Mo and W mineralization may be associated with emeralds. Some porphyry W deposits (L07) have associated beryl. Tin-bearing granites are in some cases associated with emeralds. Gold was mined at Gravelotte Emerald Mines (no information about the gold mineralization is available).

COMMENTS: Recently, microprobe studies have shown that the green color of some beryls is due to vanadium rather than chrome. In most cases both Cr and V were detected in the beryl crystal structure. There are two schools of gemmologists, the first believes that strictly-speaking the vanadium-rich beryls are not emeralds. The second school believes that gem quality beryls should be named based on their physical, and more particularly, color properties. It is possible that pegmatoid-related or suture zone-related emerald deposits hosted by black shales or other chromium and/or vanadium-bearing rocks will be discovered. In those cases it will be difficult to decide if these deposits are schist-hosted or Columbia-type (Q06) emeralds.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: The presence of beryl in eluvial and alluvial deposits is good pathfinder. The distribution of beryllium in stream sediments proved to be useful in Norway when coupled with identification of the individual drainage basins and knowledge of the geological environ-ment.

GEOPHYSICAL SIGNATURE: A portable field detector that uses ^{124}Sb as a gamma radiation source, the berylometer, is used to detect Be in outcrop. The instrument should be held less than 4 cm from the sample. Radiometric surveys may be useful in detecting associated radioactive minerals where pegmatites are involved. Magnetic and electromagnetic surveys may be useful in tracing suture zones where ultramafic rocks and felsic rocks are faulted against each other.

OTHER EXPLORATION GUIDES: Any Be occurrences in a favorable geological setting should be considered as positive indicators. If green, chromium and/or vanadium-bearing beryls are the main subject of the search then ultramafic rocks, black shales or their metamorphic equivalents represent the most favorable host rocks. If exploration is focused on a variety of gem-quality beryls (not restricted to emerald), or if the targeted area is not mapped in detail, then Be occurrences without known spatial association with Cr- or V-bearing lithologies should be carefully considered. Minerals associated with emeralds in the ores may be considered as indirect indicators. A wide variety of field-tests based on fluorescence, alkalinity, staining, density and refractive index have been used in the past to distinguish beryl.

Q07 - Schist-Hosted Emeralds

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The grade and tonnage of these deposits is difficult to estimate due to erratic emerald contents (gram/tonne), episodic nature of the mining activity which often results in high grading, and variability in the quality of gemstones (value/carat). For example, at the Mingora mines in Islamia Trench two, 15 to 30 centimetres thick layers of talc-rich rock surrounding quartz lenses contained 1000 to 5000 carats of good stones up to 30 carats in size. Some of the individual pits in the area produced less than 1000 carats. The cumulative production of the Mingora emerald mines was reported between 20 000 to over 50 000 carats/year between 1979 and 1988. At Gravelotte Emerald Mine, at least 23 000 kg of

emeralds of varying grades have been produced since 1929 from several zones. For the same mine promotional literature states that " conservative estimates" of ore within the Cobra pit are 1.69 million tonnes that could result in production of 17 000 kg of emeralds (approximately 1gram /tonne). It is estimated that about 30% of the emeralds could be sold, but only 2-3% of these are believed to be gem quality. In the Urals the Mariinsky deposit was explored to a average depth of 500 metres by boreholes and underground workings. To determine emerald content, bulk samples as large as 200 tonnes are taken systematically at 100 metres interval along the favourable zone. No grade and tonnage are available.

ECONOMIC LIMITATIONS: Mining of precious stones in underdeveloped countries and smaller deposits is done using pick and shovel with limited use of jackhammers and bulldozers. Larger schist-hosted emerald deposits, may be successfully exploited by a combination of surface and underground mining. The Mariinsky deposit was mined by open pit to the depth of 100 metres and is exploited to the depth of 250 metres by underground methods. "Low impact" explosives, expanding plastics or hydraulic wedging are used to break the ore. The ore is milled, screened and manually sorted.

END USES: Transparent and colored beryl varieties, such as emerald, morganite and aquamarine, are highly valued gemstones. Industrial grade beryls commonly recovered as by-products are a source of Be oxide, Be metal alloys used in aerospatial and defence applications, Be oxide ceramics, large diameter beryllium-copper drill rods for oil and gas, fusion reactors, electrical and electronic components. Berylium metal and oxides are strategic substances, and may be substituted for by steel, titanium and graphite composites in certain applications. Phosphor bronze may replace beryllium-copper alloys. However, all known substitutes offer lower performance than Be-based materials.

IMPORTANCE: Schist-hosted deposits are the most common source of emeralds, although the largest and most valuable gemstones are most frequently derived from the Colombia-type deposits. Besides schist-hosted deposits and pegmatites, beryl for industrial applications may be also be present in fertile granite and syenite complexes that may be parent to pegmatites. A major portion of the beryl ore used in the U.S.A. as raw material for beryllium metal is recovered as a byproduct of feldspar and quartz mining from pegmatites.

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Q08 - Sediment-Hosted Precious Opal

by: S. Paradis[1], J. Townsend[2] and G J. Simandl[3]

Paradis, S., Townsend, J., and Simandl, G.J., 1999. Sediment-hosted precious opal: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 119–122.

IDENTIFICATION

SYNONYMS: Australian opal deposits.

COMMODITY: Gem quality opal (precious and common).

EXAMPLES (British Columbia - *Canadian/International*): *Lightning Ridge and White Cliffs (New South Wales, Australia), Mintabie, Coober Pedy, Lambina and Andamooka (South Australia), Yowah, New Angledool (Queensland, Australia)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Most of the Australian opal occurs in cracks, partings, along bedding planes, pore spaces and other cavities in strongly weathered sandstones generally underlain by a subhorizontal barrier of reduced permeability. The barriers consist mainly of claystones, siltstones and ironstone strata.

TECTONIC SETTINGS: The tectonic setting at the time of deposition and lithification of the opal-bearing lithologies is not indicative of favourable environment for opal. However, the presence of a terrestrial (non-marine) environment at the time of intense weathering is essential.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Clastic sediments were deposited in the shallow inland basins. Subsequently, these areas were affected by climatic/paleo-climatic changes (transformation into desert environment) that resulted in rapid fluctuation in water table levels and entrapment of silica-rich waters.

AGE OF MINERALIZATION: In Queensland, Australia the host rocks are Cretaceous or Paleozoic and have been affected by deep weathering during the Early Eocene and Late Oligocene. The latter period is believed to be related to opal precipitation. Similar conditions favourable for opal deposition could have prevailed in different time periods in other parts of the world.

HOST/ASSOCIATED ROCKS: Sandstones, conglomerate, claystone and silty claystone. Associated lithologies are feldspathic rocks weathered to kaolinite, silcrete and siliceous duricrust, shales and shaley mudstones, limestones, dolostones and ironstones. Exceptionally, precious opal may be found in weathered crystalline basement rocks stratigraphically underlying the lithologies described above.

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Q08 - Sediment-Hosted Precious Opal

DEPOSIT FORM: Opal occurrences are stratabound. Favorable subhorizontal, precious opal-bearing intervals can exceed 10 m in thickness, and are known to persist for distances of one to over 100 km. The distribution of individual precious opal occurrences within favorable areas is erratic. Veins are subhorizontal to subvertical and locally up to 10 cm thick. They pinch and swell, branch or terminate abruptly. A single vein can contain chalky to bony to blue, gray or milky common opal and precious opal.

TEXTURE/STRUCTURE: Opal occurs as veinlets, thin seams in vertical and horizontal joints, desiccation cracks in ironstone layers, lenses and concretions, and replacing fossils (shell and skeletal) and wood fragments. Opal also forms pseudomorphs after glauberite[5] . In places opal seems to follow cross bedding. In unusual cases opal pieces eroded from the original host are incorporated into younger sediments. Precious opal may form the cement around detrital quartz grains in silicified sandstone. Opal may also be cut by gypsum or alunite-filled fractures. The lithologies above the opal may contain characteristic red-brown, gypsiferous silt-filled tubules.

ORE MINERALOGY: Precious opal.

GANGUE MINERALOGY [Principal and *subordinate*]: Host rock, common opal, gypsum and gypsum-shot opal, alunite, hematite, limonite/goethite.

ALTERATION MINERALOGY: N/A.

WEATHERING: Feldspathic rocks strongly altered to kaolinite typically overly the Australian precious opal-bearing deposits. Opal exposed to arid weathering environments may desiccate, crack and lose its value; however, gem quality opal may be preserved at depth.

ORE CONTROLS:

1) Regional configuration of impermeable layers permitting groundwater pooling.
2) Local traps within regional sedimentary structure, such as bedding irregularities, floored by impermeable layers, porous material (e.g. fossils) or voids where opal can precipitate.

GENETIC MODELS: Australian opal is hosted mainly by strongly weathered sandstones which are underlain by claystone, siltstone and ironstone that form relatively impermeable barriers. Periods of intense weathering are evidenced by indurated crust horizons. Silica-transporting solutions derived from intense weathering of feldspar within sandstones percolated downward to the contact between the porous sandstone and the underlying impermeable layers. During a subsequent dehydration (dry) period silica was progressively concentrated by evaporation. The last, most concentrated solutions or colloidal suspensions were retained within bedding irregularities at the permeable/impermeable rock interface, in joints and in other traps. Gem-quality opal was formed by ordered settling and hardening of silica microspheres of uniform dimensions. Disordered arrangement of silica microspheres or variability in microsphere size results in formation of common opal.

ASSOCIATED DEPOSIT TYPES: Possibly clay deposits (B05).

COMMENTS: There is good reason to believe that a similar mode of opal formation could also take place in porous terrestrial and waterlain pyroclastic rocks, assuming favorable geological and paleo-climatic setting.

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[5] Glauberite: $4[Na_2Ca(SO_4)_2]$, widespread as a saline deposit formed as a precipitate in salt lake environments, also occurs under arid conditions as isolated crystals embedded in clastic sediments.

Q08 - Sediment-Hosted Precious Opal

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: N/A

GEOPHYSICAL SIGNATURE: Most opal fluoresces brightly if exposed to ultraviolet light. Limited success was achieved using magnetic field and resistivity to find ironstone and ironstone concretions that commonly contain precious opal in Queensland.

OTHER EXPLORATION GUIDES: Unmetamorphosed or weakly metamorphosed areas known for:

1) prolonged periods of deep chemical paleoweathering characterized by rock saturation and dehydration cycles;
2) broad sedimentary structures permitting shallow underground solution pooling;
3) local traps where opal could precipitate from nearly static, silica-bearing ground waters; and
4) presence of common opal.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: No reliable estimates of grade or tonnage are available for individual deposits. Until 1970 the only records of production were annual returns submitted by opal buyers. Miners fear that reporting the true production would be used for taxation purposes. As with other gemstones, reporting the grades in terms of grams or carats per tonne may be strongly misleading. Large and exceptional quality stones command very high prices. Precious opal may be transparent, white, milky-blue, yellow or black. It is characterized by the internal play of colors, typically red, orange, green or blue. The best opal from Lightning Ridge was worth as much as $A 10 000.00 per carat in cut form and Mintabie opal varied from $A 50.00 to 10 000.00 per ounce of rough. Most of the white to milky colored opal from Coober Pedy was worth $A 10.00 to 100.00 per ounce of rough, but the prices of top quality precious black and crystal opals exceeded $A 5 000.00 per ounce. The value-added aspect of the gem industry is fundamental. An opal miner receives 1 to 50% of the value of cut and polished stone.

ECONOMIC LIMITATIONS: Opal production in Australia is largely mechanized, either underground or on surface. Opal-bearing seams are generally found at shallow depths (< 30 metres). Opal is still recovered from old tailings by hand sorting over conveyer belts using ultraviolet light. Large and exceptional quality stones command very high prices and the unexpected recovery of such stones may change an operation from losing money to highly profitable. Stones from sediment-hosted deposits are believed to have better stability under atmospheric conditions than opal from most volcanic-hosted deposits.

END USES: A highly priced gemstone that is commonly cut into solid hemispherical or *en cabochon* shapes. If the precious opal is too thin, a slice of common opal or other support is added to the back with plastic cement to form “doublets”.

IMPORTANCE: Australian sedimentary-hosted opal deposits account for most of the world’s opal production. This situation is likely to continue since these deposits recently attracted important Japanese investment. In 1990, the Coober Pedy, Andamooka and Mintabie deposits produced opal worth over $Aus. 47 million. Total production estimates for Australia are in the order of $Aus. 100 million annually.

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Q09 - Ultramafic-Related Corundum (Contact Metamorphic/Metasomatic)

by G.J. Simandl[1] and S. Paradis[2]

Simandl, G.J., and Paradis, S., 1999. Ultramafic-related corundum (contact metamorphic /metasomatic): In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, p. 123–127.

IDENTIFICATION

SYNONYMS: Plumasite and marundite deposits, contact-metamorphic corundum and emery, “desilication” or metasomatic sapphire.

COMMODITIES (BYPRODUCTS): Rubies, sapphires, industrial grade corundum and emery.

EXAMPLES (British Columbia - *Canada/International*): *Corundum Hill (North Carolina, USA), Emery Hill (New York, USA), Natal and Birdcage camp (South Africa), Umba (Tanzania), Kinyiki Hill and Penny Lane ruby mine (Kenya).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sapphire, ruby and industrial grade corundum occur within, or adjacent to, aplite, pegmatite, albitite, plumasite or marundite dykes, sills and rarely plugs cutting mafic and ultramafic rocks and their metamorphosed equivalents. Industrial grade corundum is also found commonly along contacts of mafic/ultramafic intrusions with metapelites or other felsic country rocks. It may occur both within country rock and the intrusion.

TECTONIC SETTINGS: These deposits occur in orogenic belts where felsic rocks are thrust against silica-undersaturated rocks and within the stable cratons.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Corundum is commonly found in quartz-free reaction zones located along contacts of silica-deficient rocks, such as ultramafic and mafic rocks, with pegmatite, paragneiss, syenite gneiss or other felsic rocks. Country rocks are typically affected by medium to high grade regional metamorphism.

AGE OF MINERALIZATION: Archean or younger. Abrasive-grade corundum deposits are commonly contemporaneous with contact metamorphism, while gem-quality corundum may post-date metamorphism and the peak of the tectonic activity.

HOST/ASSOCIATED ROCK TYPES: Common host rocks are vermiculite ± chlorite ± asbestos-bearing rocks, plumasite (coarse grained rock consisting of anhedral corundum crystals in an oligoclase matrix), marundite (corundum in margarite matrix), syenite, pegmatite, aplite or hornfels. Associated rocks are ultramafics, a variety of mafic lithologies including gabbro, amphibolite, anorthosite, serpentinite, anthophyllite-chlorite-talc schist, peridotite and dunite and peraluminous orthogneisses or paragneisses.

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Q09 - Ultramafic-Related Corundum

DEPOSIT FORM: Most of the dyke-associated or fracture-controlled deposits that crosscut ultramafic and mafic rocks are planar or lens-shaped; rarely forming vertical plugs. They are less than a metre to 10 metres in thickness and may extend from few metres to several tens of metres along strike. These deposits exhibit several types of mineralogical zoning from the center of the deposit outwards:

a) Corundum-chlorite > spinel - chlorite > enstatite > talcose rock > friable dunite > dunite;
b) plumasite > biotitite > pegmatite > serpentinite;
c) aplite> plumasite>spinel-magnetite rock > vermiculite and/or chlorite > actinolite > talc>serpentinite;
d) barren pegmatite> marundite > talc-chlorite zone>amphibolite (pegmatite may not be present).

Lenticular or irregularly shaped, corundum-bearing pockets may be also present along the tectonic contacts between gneiss and serpentinite. Some of the gem-quality and most of the industrial grade corundum and emery deposits occur near the contacts of mafic and ultramafic intrusions with country rocks. Emery may form veins, layers and irregular or lens-shaped masses within both endo- and exometamorphic reaction zones. Most of the corundum is typically found in metapelites adjacent to such intrusions.

TEXTURE/STRUCTURE: Sapphire and ruby may form rhombohedral or hexagonal prisms or they may occur as clear portions of large, poikilitic corundum crystals that may exceptionally reach over a metre in length. In South African plumasites the corundum crystals commonly vary from 3 millimetres to 10 centimetres. In marundite, corundum occurs as coarse hexagonal crystals embedded in scaly or rosette-shaped aggregates of margarite. Emery rock is typically equigranular, fine-grained (<1mm). It may form layers, veinlets or lenses and irregular zones of massive ore in intrusive and country rock.

ORE MINERALOGY [Principal and *subordinate*]: In plumasite and marundite: sapphires, rubies, specimen- quality or industrial grade corundum.
Within contact metamorphic zones of mafic and ultramafic intrusions: mostly emery or silimanite-corundum rock or coarse industrial-grade corundum.
Along tectonic contacts: rubies, sapphires, specimen and industrial grade corundum.

GANGUE MINERALOGY [Principal and *subordinate*]: In plumasites: mainly plagioclase, ± *biotite*, ± *amphibole*, ± *fuchsite*, ± *tourmaline*. Some of the solid inclusions identified within sapphires and rubies are zircon, rutile, apatite, boehemite, monazite, hematite, mica, calcite, pyrrhotite and graphite.
In marundites: margarite, ± feldspar, ± *biotite*, ± *apatite*, ± *garnet*, ± *tourmaline*, ± *fuchsite*, ± *kyenite* (?), ± *talcose material and possibly anthophyllite.*
In metasomatic zones cross-cutting ultramafic rocks without plumasite core: vermiculite, ± chlorite. The main solid inclusion in gem corundum is vermiculite.
In contact metamorphic deposits: a) In emery ores: Hercinite, pleonaste, magnetite, hematite/ *ilmenite, ilmenohematite. hypersthene, sapphirine, sillimanite, cordierite, garnet, biotite, feldspar, staurolite, gahnite. Some of the minor constituents in emery ore may be due to hostrock inclusions.* b) In sillimanite-corundum rock: *rutile and ilmenite are trace constituents.*

ALTERATION MINERALOGY: Corundum may retrograde into diaspore or mica. In marundites it is commonly partially replaced by gibbsite and margarite.

WEATHERING: Some uneconomical primary gemstone and industrial grade deposits may form viable residual or placer deposits.

ORE CONTROLS: There are three major spatial controls: 1) fracture zones control metasomatic and plumasite mineralization within the mafic/ultramafic rocks; 2) tectonic contacts control mineralization pockets located between gneisses and serpentinites; and 3) contact metamorphic zones around mafic intrusions are also favourable.

Q09 - Ultramafic-Related Corundum

GENETIC MODELS: A number of theories explaining the origin of these deposits have been proposed over the years. The three models that appear the most likely are:

a) Desilication of granitic pegmatites or pegmatitic fluids by interaction with silica-undersaturated country rocks. This is particularly popular theory to explain the origin of fracture-controlled mineralization associated with marundite, plumasite, vermiculite rock, pegmatite or aplite crosscutting ultramafic country rocks.

b) In the contact metamorphic/metasomatic settings, the high ratio of $Al_2O_3/(CaO+Na_2O+K_2O)$ and low silica content that favor corundum formation may be achieved by magmatic interaction of mafic or ultramafic rocks with metapelites or by partial melting of the pelitic country rocks.

c) Where the felsic rocks were thrust against ultramafic rocks, reaction zones may have formed under open system conditions during regional metamorphism.

ASSOCIATED DEPOSIT TYPES: Placer-type corundum deposits (C01 and C02) and corundum-bearing residual soils. Vermiculite (M08), nepheline syenite (R16) and pegmatites (O01, O02, O03 and O04) may be genetically related to some of the corundum deposits covered by this profile. Corundum-bearing metapelites (P06) may also be present in the same geological setting.

COMMENTS: Emery is a black granular rock formed by intergrowths of corundum with magnetite, hercinite or hematite. Emery deposits may also form during regional metamorphism of aluminous sediments, such occurrences are described in the profile P06 (this volume). It is used mainly as an abrasive or for anti-skid surfaces. “Anolite”, a highly-priced ornamental stone formed from a famous ruby-bearing zoisite amphibolite from Longido (Tanzania), is closely associated with serpentinites (Keller, 1992). Due to the lack of outcrops, it is not clear if this deposit belongs to the metasomatic type of mineralization described in this profile. Marble and skarn-hosted ruby/sapphire deposits, such as those described by Okrush *et al.* (1976), also may be similar in origin. Some of these deposits may have formed by essentially isochemical regional metamorphism, while others may be pegmatite and aplite-related metasomatic zones. Marble hosted deposits should be considered as a distinct deposit type.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Corundum-bearing lithologies are silica-undersaturated and characterized by their high $Al_2O_3/(CaO+Na_2O+K_2O)$ ratio. Saphire, ruby, corundum or emery may be found in heavy mineral concentrates from stream sediments or tills. As well, the solid inclusions within corundum crystals, corundum texture, and associated minerals in the concentrates may be indicative of the type of primary source, such as gem corundum hosted by alkalic rocks (Q10), corundum in aluminous metasediments (P16) and gem corundum in marbles.

GEOPHYSICAL SIGNATURE: Ultramafic rocks associated with this deposit type may be detected and possibly delimited by magnetic or electromagnetic surveys. Magnetite-bearing emery deposits may be detected using a magnetometer.

OTHER EXPLORATION GUIDES: Some vermiculite occurrences may be worth examining for gem corundum.

Q09 - Ultramafic-Related Corundum

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grades are rarely reported for hard rock-hosted sapphire and ruby deposits. They are difficult to determine as these deposits are often high-graded and mined sporadically. A substantial proportion of the production is sold on the black market. Grades of up to 2000 carats of rough gems per ton are reported from the weathered extension of sapphire and ruby rock occurrences at Umba (Tanzania). In another portion of the same property 100 000 carats were recovered from soil above apparently barren veins, but the grade is not reported. In South Africa, plumasites contain 5 to 80% corundum with typical grades around 30 to 40%. Larger deposits may contain 5 to 10 thousand tonnes, but average tonnage is more likely less than 2 thousand tonnes. These deposits were mined in the first half of the 19th century to about 40 metres. Typical content of eluvial deposits associated with plumasites varies from 10 to 20% by volume. The emery deposits of Emery Hill (Peekskill area) consisted of veins (some less than 2cm thick), pods and thin layers parallel to the schistosity. The emery consisted of varying proportions of spinel (0 to 65%), magnetite (20-30%) and corundum (15 to 65%).

ECONOMIC LIMITATIONS: Together with emerald, red beryl and diamond, ruby and sapphire are the most valuable gemstones. The most valuable rubies are dark purplish red (“pigeon's blood red”). The most desirable color for sapphire is “Kashmir blue”. Star rubies and sapphires exhibit asterism better than any other gems. The color of many natural corundum gems is artificially enhanced by heat treatment. Due to the highly variable grades and relatively small deposit size, these hard rock deposits are commonly mined by open-cast methods and in some cases by primitive underground methods.

END USES: Depending on quality, corundum may be used as a gemstone, abrasive or friction material on non-slip surfaces. Sillimanite-corundum rock is a relatively highly priced material for refractory applications. Some corundum-bearing rocks are used as ornamental stones.

IMPORTANCE: Most corundum gems are recovered from regoliths, residual soils or gravels, and as byproducts of placer mining (C01, C02). They may be also found in alkali basalts, lamprophyres (Q10) and rarely in aluminous metamorphic rocks (P06) and marbles. However, deposits of this type, remain worthwhile targets for prospectors and small exploration companies. Clear, nearly inclusion-free corundum crystals are produced synthetically, and compete with natural gems. Silicon carbide and artificial corundum manufactured from bauxite has largely replaced corundum and emery in most industrial abrasive applications. Today, the combined consumption of industrial grade corundum and emery in the USA is estimated to be less than 10,000 tonnes/year.

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Q10 - Alkali Basalt and Lamprophyre-Hosted Sapphire and Ruby

by G.J. Simandl[1] and S. Paradis[2]

Simandl, G.J., and Paradis, S., 1999. Alkali basalt and lamprophyre-hosted sapphire and ruby: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 129–132.

IDENTIFICATION

SYNONYMS: Alkali basalt-hosted, lamprophyre-hosted or volcaniclastic-hosted gem corundum deposits.

COMMODITIES (BYPRODUCT): Sapphire and ruby (zircon).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Mark diatreme (082N 089); *Yogo Gulch (Montana, USA), Braemar, Stratmore and Kings Plains Creek (New South Wales, Australia), Changle (China)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sapphires and rubies are found as xenocrysts in some hypabyssal or eruptive alkalic rocks. The residual soil or regolith overlying these rocks can be enriched in sapphires and rubies due to intense weathering which liberates the megacrysts from the matrix.

TECTONIC SETTINGS: Host rocks occur in continental and pericontinental settings related to rifts, deep faults and/or hot-spots. In some cases they are interpreted to be subduction zone-related.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Corundum gems are brought to the surface by alkali basalt eruptions. The highest grades are associated with diatreme and base surge lithologies that erode quickly unless capped by weathering-resistant rocks, such as lava flows. Significant corundum can also be present in lava flows and hypobysal equivalents of these corundum-rich volcanic pulses.

AGE OF MINERALIZATION: Post-dates tectonic and metamorphic events. Typically hosted by Cenozoic or younger rocks. Oligocene and Miocene in New South Wales, Australia.

HOST/ASSOCIATED ROCK TYPES: Lava flows, hypabyssal intrusions and volcaniclastic rocks of alkali basalt, lamprophyre, nephelinite, basanite or phonolite composition. Highly altered and/or weathered volcaniclastic rocks, including reworked lahar flows and base surge and ash-fall deposits commonly have the highest gem corundum content. Mantle and crustal rock xenoliths, including lherzolites, peridotites and in some cases corundum-bearing gneiss, occur in the above lithologies. There are little or no restrictions as to the lithology of the wallrock.

DEPOSIT FORM: With the exception of diatremes and volcanic necks, host igneous rocks are generally tabular bodies (dykes, lava flows, pyroclastic flows). The flows and their erosional remnants vary from less than a metre to several metres in thickness and extend from hundreds of metres to more than several kilometres. Extensive, thin, heavy minerals-enriched layers can carry higher grades. They form volcaniclastic aprons

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Q10 - Alkali Basalt and Lamprophyre-Hosted Sapphire and Ruby

around diatremes and are possibly produced by base surges. High grade zones may also form thin blankets associated with unconformities or recent erosional surfaces. The lamprophyre dykes, such as Yogo, may consist of several en echelon segments from less than a metre to several metres thick and hundreds of metres in length.

TEXTURE/STRUCTURE: In extrusive rocks, sapphire and ruby occur as megacrysts that are typically bi-pyramidal, stepped and tapering or barrel shaped. The corundum crystals can be corroded and etched. Some crystals are zoned, contain a variety of solid inclusions and can be intergrown with other minerals. They may have spinel reaction rims. In New South Wales they are typically less than 1 carat in weight (about 5 mm or less). In Thailand the typical size of sapphires from alluvial sediments is 3-6 mm, but crystals up to 9.5 x 6 x 5.5 cm are also reported. Rubies of about 1-1.5 cm in diametre were found in some localities. In Yogo lamprophyre dykes, most of the sapphire occurs as subhedral to anhedral grains. The most common shape is a wafer with etched surfaces and a thin spinel crust. The host lithologies may contain numerous mantle or crust xenoliths, some of them corundum-bearing gneisses.

ORE MINERALOGY [Principal and *Subordinate*]: Sapphire, ruby; ± *zircon.*

GANGUE MINERALOGY [Principal and *Subordinate*]: In alkali volcanic rocks the gangue minerals are feldspar (mainly anorthoclase), pyroxene, ± analcime, ± olivine, amphiboles, such as kaersutite, ilmenite, ± magnetite, ± spinel, ± garnet, with minor biotite/phlogopite*, spinel and chrome diopside and zircon* ± rutile. Vesicles may contain amorphous silica, andesine and zeolites.

In lamprophyre hypabyssal rocks, pyroxene, phlogopite, ± calcite (mainly in veins), ± olivine, ± analcime are major constituents. Minor constituents are *magnetite, apatite, chlorite, serpentine, amphibole, brucite and feldspar.*

The main solid inclusions reported within the corundum in volcanic rocks are: spinels (hercynite, gahnite), ilmenite, rutile, ilmeno-rutiles, columbite, uranopyrochlore-betafite, zircon, akali feldspar, plagioclase, mica, thorite, sulphides and glass.

ALTERATION MINERALOGY: Volcaniclastic rocks that host gem corundum are commonly clay-altered and ferruginized due to combination of alteration and weathering.

WEATHERING: Palagonitic clasts and “clast in clast” structures are visible in weathered volcaniclastic rocks that host gem corundum. Weathering can greatly enhance the gem corundum grade and transform a low grade occurrence into a deposit of economic interest. The near surface portion of Yogo dike was weathered to a yellowish clay. Ore from the Yogo Gulch deposit was left on surface to weather for few months to reduce the need for crushing.

ORE CONTROLS: Primary controls are sapphire and ruby-bearing alkali basalt, lamprophyre, nephelinite, basanite or phonolite dikes, flows, pyroclastics or possibly diatremes. Unconformities, paleoregoliths or current erosional surfaces intersecting sapphire/ruby-bearing lithologies provide a vector for identifying secondary deposits.

GENETIC MODEL: Several hypotheses have been proposed to explain the origin of the sapphire-bearing lithologies. Most of proposed models involve alkali volcanic or hypabyssal rocks incorporating previously formed sapphires and/or rubies as xenocrysts and transporting them to the surface in a similar way to diamonds in kimberlites (N02). Any volcanic rock type with the potential to host sapphires (alkali basalts, kimberlites, lamproids, lamprophyres) must originate at greater depth than that required for the formation of sapphire. There is no consensus about the source lithology or magma for gem corundum. Corundum gems may have formed by metamorphism of aluminous sediments; crystallization in deep-seated syenitic melts or from undersaturated fractionated felsic melts; contact reactions between ultramafic/mafic intrusions and alumina-rich metasediments in deep continental crust; metamorphism of aluminous sediments contained in subducting oceanic crust, etc.

ASSOCIATED DEPOSIT TYPES: Can be the source for placer corundum ± zircon ± diamond deposits (C01, C02, C03, C04) and corundum-bearing regolith.

Q10 - Alkali Basalt and Lamprophyre-Hosted Sapphire and Ruby

COMMENTS: Syenite-hosted corundum deposits, such as the Blue Mountain deposit (Ontario, Canada), may also be a source of corundum. These occurrences are described as nepheline syenite deposits (R13). Corundum is also known to occur as discrete crystals in diatremes of carbonatitic and kimberlitic affinity.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: “Zircospilian” association (zircon-corundum-spinel-ilmenite-anorthite) can be considered characteristic of these deposits. Corundum gemstones and indirect indicator minerals, such as kaersutite and chrome diopside (derived from lherzolite xenoliths), in heavy mineral concentrates from stream and lake sediments or from tills. Blue-green-yellow zoned corundum is particularly characteristic of Australian and Asian deposits. These corundums contain up to 0.04 wt% Ga_2O_3 and have low Cr/Ga and Ti/Ga ratios.

GEOPHYSICAL SIGNATURE: Electromagnetic and magnetic surveys may be effectively used in delimiting sapphire/ruby-bearing host rocks, assuming good contrast with surrounding lithologies.

OTHER EXPLORATION GUIDES: Pipes, dikes, plugs and diatremes of alkali lithologies are positive indicators. In some localities there appears to be a positive correlation between the abundance of mantle-derived xenoliths and corundum (Guo and O’Reilly,1996). Unexplained sapphire, ruby or corundum occurrences in favourable tectonic settings warrant follow-up.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: No reliable grades in terms of carats recovered or dollars per metric tonne are available for most of the hard rock-hosted gem deposits. In New South Whales, corundum is typically present as trace constituent in basalts, but volcaniclastic sediments may contain as much as 12 kg of corundum per cubic metre of material (Peacover, 1994). The Yogo dike yielded about 10 carats/ton between 1897 and 1929. The grade varied probably from 0 to 70 carats/tonne. It supplied about 16 million carats valued in the rough at about $2.5 US million. About 2.25 million carats were gem quality. Approximately 675 000 carats of cut sapphires, worth $ US 20-30 million were obtained (Claubaugh, 1952). More recently, the production for 1984 was 4 000 carats with $US 3 million in sales for finished jewelry (Voynock, 1985). According to Brownlow and Komorowski (1988), the weight of average stone is less than 1 carat.

ECONOMIC LIMITATIONS: Red beryl, emerald, diamond, ruby and sapphire are the most valuable gemstones. The colors of corundum reflect variations in trace element contents. The most valuable rubies are dark purplish red ("pigeon's blood red"). The most desirable color for sapphire is Kashmir blue. The color and clarity of many natural corundum crystals is commonly artificially enhanced by heat treatment to increase the proportion of stones suitable for faceting (Turnovec, 1987). For example, the treatment of material from Laos can increase the proportion of stones suitable for faceting by 20 % by weight. Star rubies and sapphires exhibit asterism better than any other gems. Synthetic corundum competes with natural crystals in gem applications and has replaced natural corundum crystals in most high technology applications. Nevertheless, the "magic" of the natural stones persist in the gem industry.

END USES: Gemstones, specimen samples, industrial grade abrasives and friction surfaces.

IMPORTANCE: Primary (hard rock) sapphire-bearing deposits of this type are relatively rare. Most of the corundum gems are recovered from associated residual soils or placer deposits. Sapphire-bearing, alkali volcanic rocks are source rocks for some of the large alluvial sapphire deposits, such as the Kings Plain deposits in the Inverell-Glen Innes and Anakie districts of Eastern Australia, Pailin gem fields in Cambodia and Bo Rai deposits of Thailand. In 1993-94, the sapphire production in eastern Australia was estimated at A$ 20 to 25 million (65-75 million carats).

Q10 - Alkali Basalt and Lamprophyre-Hosted Sapphire and Ruby

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Q11 - Volcanic-Hosted Precious Opal

S. Paradis[1] , G.J. Simandl[2] and A. Sabina[3]

Paradis, S., Simandl, G.J., and Sabina, A., 1999. Volcanic-hosted precious opal: In: Selected mineral deposit profiles, volume 3 - industrial minerals and gemstones, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Open File 1999-10, pp. 133–136.

IDENTIFICATION

SYNONYMS: Hydrothermal or "volcanic opal"

COMMODITIES (BYPRODUCTS): Precious opal (common opal, chalcedony, jasper, agate).

EXAMPLES (British Columbia - *Canada/International*): Klinker (082LSW125), Northern Lights claim, Whitesail Range (maps 93E10W and 93E/11E) and a precious opal occurrence near Falkland, Eagle Creek (093K 095); pale green and apple green common opal occurs at Savona Mountain (092INE158); *Queretaro Mines (Mexico), Virgin Valley (Nevada, USA), Tepe Blue Fire Opal Mine (Idaho, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Opal occurs commonly in seams of volcanic ash or lahars sandwiched between successive lava flows. It occurs mainly as open space fillings and impregnations. Common opal, opalized wood and to some extent "fire opal" are widespread within Triassic or younger volcanic sequences, but precious opal is rare. Where opal occurs in massive volcanic rocks, it occurs also as open space fillings, however the opal-bearing areas are much smaller. Regardless of volcanic hostrock, the precious opal occurrences are discrete, whereas common opal occurs over large areas.

TECTONIC SETTINGS: Volcanic arcs, rifts, collapsed calderas, hot spot related volcanism and others.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Volcanic sequences formed in subaerial or shallow marine environments where porous, pyroclastic or lacustrine rocks are interbedded with lava flows.

AGE OF MINERALIZATION: Tertiary or younger, commonly Miocene.

HOST/ASSOCIATED ROCKS: Common host rocks are rhyolite, basalt, andesite and trachyte lavas, lahars and other volcaniclastic rocks. Associated rocks are perlite, bentonite, scoria, volcanic ash and diatomite; volcanic rocks may be intercalated with lacustrine sedimentary rocks.

DEPOSIT FORM: Favourable opal-bearing horizons are commonly stratabound. Occurrences of precious opal within these horizons are erratic, controlled by permeability at the time of opal deposition. Individual precious opal-bearing fractures or lenses may grade into common opal and agate over distances of centimetres.

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TEXTURE/STRUCTURE: Opal occurs as open space fillings in irregular cavities, narrow discontinuous seams, partially-filled pillow tubes, fractures, vesicles, matrix in volcaniclastic rocks and replacing wood fragments and logs. Common opal may form miniature stalagmites and stalactites within cavities, nodules in clay or diatomite beds and "thunder eggs".

ORE MINERALOGY [Principal and *Subordinate*]: Precious opal; “fire opal”, *chalcedony, agate, common opal.*

GANGUE MINERALOGY [Principal and *Subordinate*]: Common opal, agate, fragments of host rock, clays, zeolites, quartz, *jasper, celadonite, manganese and iron oxides.*

ALTERATION MINERALOGY: Opal-bearing cavities may have zeolite and celadonite coatings, but so do the barren cavities. There is no known alteration which is specific to precious opal.

WEATHERING: In arid environments, opal in surface outcrops may desiccate, become brittle and crack. Such material is not suitable as a gemstone. However, gem-quality opal bodies may be at depth.

ORE CONTROLS: Open spaces and other permeable zones open to the silica-bearing solutions.

GENETIC MODELS: In many large opal districts, it is believed that during the longer periods of volcanic inactivity, shallow lakes developed. Forests grew along the lake-shores and driftwood accumulated in the lakes. Volcanic eruptions covered everything with pyroclastic rocks capped by lava flows resulting in aquifers, perched water tables, and anomalies in the thermal gradient. This in conjunction with subsequent brittle tectonic deformation resulted in ideal conditions for the formation of hydrothermal systems. A variety of silica forms, including silica sinter, opaline silica, chalcedony and common opal are believed to have formed by deposition of silica-bearing fluids. The dissolved SiO_2 content in water is well known to be temperature dependent with the maximum dissolution at around 325°C, however, the conditions needed for the precipitation of precious opal in volcanic environment are not well understood. At least a portion of the opal-CT in volcanic rocks is believed to precipitate directly from supersaturated solutions. The temperatures of formation for precious opal are expected to be relatively low by analogy to sedimentary-hosted precious opal deposits, but temperatures as high as 160°C are reported from fluid inclusion studies. No precious opal is reported from active hydrothermal fields, such as Geyser Valley, Yellowstone or Whakarewarewa (New Zealand). This suggests that the precious opal forms only under very specific physico-chemical conditions. Eh and definitely pH may be important. Chemical composition of hydrothermal fluids in terms of silica concentrations, as well as Na, K, Cl, Ca, SO_4, HCO_3, B, Li and other elements may be important. The composition of the silica-bearing fluid is probably modified during migration through the permeable host rock, specially if the latter contains zeolites and/or clays. Zeolites act as molecular sieves and are well known for their cation exchange properties.

ASSOCIATED DEPOSIT TYPES: Associated deposits can be beds of diatomaceous earth (F06), volcanic ash (E06), zeolite deposits (D01,D02), perlite and a variety of semi-precious or ornamental silica gemstones, such as jasper (Q05), moss agate (Q03), and chalcedony. Other deposit types occurring in the same setting are hot-spring Au-Ag (H03), hot-spring Hg (H02), agate (Q03) and hydrothermal Au-Ag-Cu: high sulphidation (H04). It is possible that these deposit types are the source of primary amorphous silica.

COMMENTS: Precious opal is characterized by a play of color. The term common opal, as used here, covers any opal that does not show this play of colors. Some common opal specimens may be used as gemstones, but in general they have substantially lower value than precious opal. The term “Fire Opal” describes a common opal having a transparent orange to red-orange base color. Such opal is commonly faceted. Precious and common opal coexist within the same deposits.

Common opal and opaline silica are also commonly associated with the spectacular hydrothermal systems characterized by hot springs pools and geysers, mud pots, geyser terraces and fumaroles where it may be deposited as common opal, opaline silica or silica sinter. The well known examples of such systems are: Yellowstone hot springs; Geyser Valley in Kamchatka and now inactive Waimangu Geyser (Taupo volcanic zone, New Zealand). It is possible that some of the precious opal is formed by the dissolution of the previously formed common opal or silica sinter in the same conditions as sedimentary rock-hosted precious opal deposits.

Q11 - Volcanic-Hosted Precious Opal

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mn oxide fracture coating was observed in the proximity of the Klinker deposit. In some cases the indicator elements used in exploration for epithermal metalliferous deposits such as Hg, Sb and As may be indirectly applied to precious opal exploration.

GEOPHYSICAL SIGNATURE: N/A, except for detecting perched water tables and faults (mainly VLF and resistivity). Thermometry may have use where precious opal is associated with recent hydrothermal activity.

OTHER EXPLORATION GUIDES: Boulder tracing is commonly used in opal exploration. Unmetamorphosed or weakly metamorphosed (zeolite facies) terrains (gem opal deteriorates and becomes brittle if subject to moderate temperatures); Tertiary or younger volcanic rocks. Areas containing known occurrences of precious or common opal, opalized wood and possibly chalcedony. Opal occurrences hosted by volcaniclastic rocks are commonly confined to the same lithologic unit over a large area. The presence of warm springs in an appropriate setting may also be considered as an indirect exploration indicator.
At the Klinker deposit, mineralogical zoning within vesicule fillings may be used to delimit the most favourable areas. For example the common opal occurs only within broad areas of agate mineralization and precious opal only in small areas within the common opal mineralization.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grade and tonnage for volcanic-hosted opal deposits are not well documented, largely because the opal extraction is done by individuals or family type businesses. The precious opal distribution within most deposits is erratic, “Bonanza-type”. The deposits at Querétaro were discovered in 1835 and are still in production. Furthermore, the term “grade” as commonly used for metalliferous deposits is much harder to apply to gemstone deposits and especially to opal deposits. For example “fire opal” ranges in value from $CDN 5 to 300 per gram. Average commercial precious opal will sell probably around $CDN40 per gram, the top quality stones may sell for $CDN 1400.00 per gram.

ECONOMIC LIMITATIONS: Some of the common opal specimens may be used as semi-precious or ornamental stones, but in general they have substantially lower value than precious opal. Gem opal contains up to 10% water, which contributes to the translucency of the specimens. Precious opal from some localities is not suitable for gems because they crack too easily; however, the opal from many other volcanic-hosted occurrences is as stable as that from the Australian sedimentary-hosted deposits. Deposits located in intensely weathered terrains are easier to mine than deposits in unaltered rocks. Prices of the best quality opal have risen steadily since 1991. There is a relatively good market for precious opal, nevertheless strong marketing and value-added processing are considered essential parts of successful opal mining operations.

END USES: Precious opal is highly priced gemstone; “fire opal” may be faceted, opalized wood is a speciality ornamental stone commonly used for book ends.

IMPORTANCE: Volcanic rock-hosted opal deposits are numerous, but most of today's high quality opal production comes from Australian sedimentary-hosted deposits.

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R - Industrial Rocks

	Profile Title	Authors
R01	Cement shale	Z.D. Hora, 2008
R02	Expanding shale	Z.D. Hora, 2009
R03	Dimension stone - granite	Z.D. Hora, 2007
R04	Dimension stone - marble	Z.D. Hora, 2007
R05*	Dropped (Dimension stone – andesite)	
R06	Dimension stone - sandstone	Z.D. Hora, 2009
R07	Silica-rich rocks	Z.D. Hora, 2009
R08	Flagstone	Z.D. Hora, 2009
R09	Limestone	Z.D. Hora, 2009
R10	Dolomite	Z.D. Hora, 2009
R11	Volcanic ash/cinder and pumice	Z.D. Hora, 2007
R12	Perlite	Z.D. Hora, 2007
R13	Nepheline syenite	Z.D. Hora, 2009
R14	Alaskite	Z.D. Hora, 2009
R15*	Crushed rock	

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

R01 - Cement “Shale”

by Z.D. Hora[1]

Hora, Z.D., 2008. Cement “shale”: mineral deposit profile R01, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Claystone, mudstone.

COMMODITY: Cement shale.

EXAMPLES: (British Columbia – *Canada/International*): Dunsmuir shale – Nanaimo area (Haslam shale; 092F 345), Sumas Mountain (Huntingdon Formation), Buse Lake; *Wabamum shale and Wapiabi shale in Alberta.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sedimentary rocks with a high clay mineral content such as claystone, mudstone and shale. Rock must provide silica and alumina and contain very small amounts of sodium, potassium and magnesium minerals to be used for cement manufacturing. The presence of sulphur in any form is considered detrimental.

TECTONIC SETTINGS: A variety of sedimentary basins: foreland, forearc or island arc type; also oceanic environments. In a continental setting: rift- and graben-type basins, lacustrine depressions and continental shelves.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Nonmarine and shallow marine basins with low-energy environments. Oxidizing sedimentary environments.

AGE OF MINERALIZATION: Paleozoic to Tertiary. In British Columbia, the best deposits occur in Tertiary lacustrine sedimentary basins.

HOST/ASSOCIATED ROCK TYPES: Cement “shales” have a broad compositional range in clay and silt content, from argillite to siltstone. The host sequence typically includes sandstone, conglomerate and sometimes coal seams or tuffaceous sediments.

DEPOSIT FORM: Stratiform, bedded sediments. May be flat or deformed by folding and faulting. Lacustrine deposits are from several to tens of metres thick with a lateral extent of several hundreds of metres to a few kilometres. Marine deposits are much more extensive.

TEXTURE/STRUCTURE: Laminated, frequently with thin silty or sandy interbeds in lacustrine deposits. Marine shale is more uniform in composition.

ORE MINERALOGY [Principal and *Subordinate*]: Clay minerals: kaolinite and illite, silica; *calcite, mica, calcite, limonite and amorphous carbon.*

GANGUE MINERALOGY [Principal and *Subordinate*]: pyrite; gypsum, chlorides, sulphates and Mn minerals.

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R01 - Cement “Shale”

METAMORPHIC MINERALOGY: Metamorphism can lead to increased sodium and potassium content and recrystallization into harder rocks with a higher melting point.

WEATHERING: Alteration of pyrite improves the acceptability of the weathered shale for the cement industry. A similar effect has a possible decrease in alkali content due to converting illite into kaolinite and the chemical weathering of feldspar in original sediment. Also soluble salts – chlorides and sulphates – can be removed during the weathering process.

ORE CONTROLS: No specific ore controls for shale used to make cement. A wide variety of shale can be used.

GENETIC MODELS: Clay-rich sediments are generally a product of the chemical weathering of aluminosilicate minerals. These can be accumulated in lacustrine as well as in marine environments. Kaolin is the preferred weathering product.

ASSOCIATED DEPOSIT TYPES: Ceramic clays (E07), expanding clays (R02) and coal seams (A02, A03, A05, A05).

COMMENTS: In some instances, where a clay resource is not available locally, industry is using anorthosite instead.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High alumina and silica, very low sodium, potassium and magnesium. Some iron is acceptable.

GEOPHYSICAL SIGNATURE: Geophysical methods are not used.

OTHER EXPLORATION GUIDES: The most readily ascertainable regional attribute is lacustrine sediments associated with coal seams. Marine shale with a thick weathered profile, or deposited in a nonreducing environment.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The main components in cement clinker are 62.5–63.5% CaO, 21–22% SiO_2, 4–6% Al_2O_3 and 2–3% Fe_2O_3. Presence of deleterious minerals containing Na, K and S must be carefully monitored. Depending on the purity of limestone, some of the latter three elements may be part of the carbonate rock. Cement “shale” can add the necessary silica and alumina to obtain roughly the required chemistry for the clinker. Any deficiencies in silica or iron contents can be corrected by adding quartz or iron oxide; in some instances even bauxite may be added to increase the alumina content. Therefore, the industry often uses the nearest acceptable “shale” and adjusts by adding other feedstock. The noncarbonate component in cement mixture is only 22%. Typical cements contain between 0.5% and 1.5% of combined Na_2O and K_2O. Sometimes only a weathered zone of shale deposit can be used.

ECONOMIC LIMITATIONS: The current standard for making Canadian cement is between 0.6% and 1.0% combined $Na_2O + K_2O$ in the final clinker, which usually comes from the shale. As well, the shale should be homogeneous and not very difficult to grind. As a low-value commodity, cement shale is generally restricted to local markets. Cement and clinker, on the contrary, are higher-value commodities; therefore, they can travel longer distances.

END USES: As a source of silica and alumina (and sometimes iron) in cement manufacturing.

IMPORTANCE: A typical North American cement plant has a capacity of 1 million tonnes of cement annually. Consumption of cement “shale” is tied closely to the capacity of local Portland cement plants and the demand for cement and cement products in general. Deposits are relatively common throughout the continent and the world; however, they may be scarce locally. Shale makes up approximately 30% of Portland cement.

R01 - Cement "Shale"

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R02 - Expanding “Shale”

by Z.D. Hora[1]

Hora, Z.D., 2009. Expanding “shale”: mineral deposit profile R02, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Bloating shale, coated lightweight aggregate, pyroplastic clay/shale/slate and a number of commercial product names.

COMMODITIES (BYPRODUCTS): Lightweight aggregate (pozzolan). Expanding slate may be a by-product of roofing slate.

EXAMPLES (British Columbia - *Canada/International*): Saturna Island (092B 043), Regal (092B 085), Niagara Creek (092B 046); *Upper Cretaceous Wabamum shales in Alberta, glaciolacustrine clays in Alberta and Saskatchewan.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Beds of claystone and mudstone or "shale" and slate, deposited usually in low energy marine or lacustrine environments. The rock expands to produce a porous, volcanic cinder or slag-like material when rapidly heated to 1000 to 1300°C.

TECTONIC SETTINGS: Wide variety of sedimentary basins, including oceanic foreland, forearc or island arc type, and also rift and graben type basins, lacustrine depressions and shelf accumulations in the continental environment.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: In British Columbia form in primarily low energy environments in Upper Cretaceous and Tertiary non-marine and shallow marine sedimentary basins. Elsewhere also form in deep sea shales, lacustrine basins, glaciolacustrine lakes and turbidites. Low energy, subaqueous anaerobic depositional environments collecting primarily mud over long periods of time. Deposits can be distal from erosional source or associated with source producing only fine clastic material.

AGE OF MINERALIZATION: Precambrian to Holocene.

HOST/ASSOCIATED ROCK TYPES: Host rocks are argillite, mudstone, siltstone, shale and slate occurring within sequences of sandstones and conglomerates, with or without coal, and a very minor carbonate component.

DEPOSIT FORM: Stratiform, bedded deposits, may be flat or deformed by folding and faulting. The deposit thickness may be from several tens to hundreds of metres, lateral extent of kilometers or more within beds that can be much more extensive.

TEXTURE/STRUCTURE; Expanding shale, slate and clay are usually thinly to thickly laminated, fairly uniform in appearance along strike. Some lacustrine deposits may be thickly bedded to almost massive. Depending on level of lithification, some may exhibit a conchoidal to semi-conchoidal fracture.

ORE MINERALOGY [Principal and *subordinate*]: Clay minerals (illite, smectite, kaolinite), silica, feldspar, *mica, calcite.*

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R02 - Expanding “Shale”

GANGUE MINERALOGY [Principal and *subordinate*]: Interbeds of siliceous siltstone and sandstone; *pyrite, gypsum and amorphous carbon.*

WEATHERING: Alteration of illite and smectite clays into kaolinite, oxidation of pyrite and/or leaching away of carbon may result in loss of expanding properties.

ORE CONTROLS: The introduction of volatile component (molecular water like in finely dispersed gypsum, some clay minerals or some organic substances) and a fluxing component (alkalies such as feldspar) that melts the rock at the same temperature at which the volatile component escapes.

GENETIC MODELS: Clays and silts are deposited in a reducing environment with very small amounts of other materials. Gas is trapped in the sediment and incorporated into a "shale' during lithification. Marine, littoral, lacustrine and fluviatile clays, shales and slates are all possible expanding products. Low grade metamorphism (for example shale to slate) may not hinder the expanding properties.

ASSOCIATED DEPOSIT TYPES: Common clays and shales (E07), cement shales (R01), coal seams (A02, A03, A04, A05), black roofing slate.

COMMENTS: A variety of admixtures (for example, carbonate, sulphate and organic) added in minor quantities to common, non-bloating clays can produce expanding properties. This process has been used commercially on a minor scale where natural expanding materials are not available. In recent years, the US EPA has been developing a process to use the municipal wastes as admixture in clays to produce the lightweight aggregate.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Favourable shales usually have between 52 – 80 % SiO_2, 11 – 25 % Al_2O_3 and 10-25% combined fluxes (Fe_2O_3, FeO, S, CaO, MgO, P_2O_5, Na_2O, K_2O, NO_3).

GEOPHYSICAL SIGNATURE: Geophysical methods are not utilized.

OTHER EXPLORATION GUIDES: Most readily ascertainable regional attribute is the depositional environment with a thick shale or argillite sequence. Economic deposits occur within homogeneous, argillitic sediment sequences, deposited usually in a reducing environment.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Certain clays, shales and slates have the property of expanding into a porous product when heated rapidly to 1,000 to 1,300 degrees C. The fusion into a viscous form and evolution of the gas must take place simultaneously. This gas may be oxygen, sulphur dioxide, or carbon dioxide. Illitic and montmorillonitic sediments are more favorable for expansion, as are darker colored and unweathered shales. Thinly fissile slates tend to expand unidimensionally, which is undesirable. Depending on its end use, expanded shale product must meet a variety of quality specifications. Unit weight of expanded product may vary from 881 to 1121 kg/m^3. Depending on the final concrete product, there are requirements for compressive strength, ignition loss, adsorption and sizing. Material should be homogeneous and free of hard interbeds, such as quartzite. Distribution of the volatile component may have impact on product density and its homogeneity.can influence quality. Homogeneity is an important quality parameter. The reported average annual production capacity for operating plants in the United States in 1970 was 150,000 tons per year. The present U.S. total annual production is 3.8 million tones from plants operating in 16 states. In Canada, three producers report annual sales of between 200,000 and 400,000 m^3.

R02 - Expanding “Shale”

ECONOMIC LIMITATIONS: Expanded shales are often developed primarily as a lightweight aggregate in regions lacking sources of quality hard rock aggregate and sand and gravel and distant from sources of pumice and volcanic cinder. Therefore, the relationship between production expenses and transportation cost is very important in competition with alternative materials. The consumption of lightweight aggregates declined during the late 1970's and 1980's due to rising energy costs and the use of high performance concrete. During the last decade, the production levels in North America kept steady.

END USES: Specialty aggregate for insulation, particularly for water and sewer systems on the prairies (about 50%), and low-density concrete products. Small quantities are also used in horticulture.

IMPORTANCE: Relatively common deposits throughout North America and the world. Particularly important for durable, inorganic insulation around water lines and other thermally sensitive infrastructure in cold regions with deep freezing of surface in winter time, also in areas lacking standard construction aggregate sources. There is research into recycling fly ash and other waste products as an alternative for expanding shale.

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R03 - Dimension Stone - "Granite"

by Z.D. Hora[1]

Hora, Z.D., 2007. Dimension stone - "granite": mineral deposit profile R03, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Commercial term "granite" for dimension stone includes all fine, medium and coarse-grained, igneous rocks and some metamorphic rocks.

COMMODITIES (BYPRODUCTS): Dimension stone blocks and a variety of shaped, split products (aggregate, rip-rap).

EXAMPLES (British Columbia - *Canada/International*): Kelly Island (092F 196), Fox Island (092F 378) Nelson Island (092F 189), Squamish (092GNW067), Ashlu River (092GNW070), Elaho River (092JW041), Skagit Valley (092HSW159), East Anderson River (092HNW075), Beaverdell (082ESW169), Okanagan Sunset (082LSW068), Pacific Pearl (082ENW083), Nelson (082FSW343); *Sudbury, Vermilion Bay (Ontario), Lac Saint-Jean, Saint Didace, Riviere a Pierre (Quebec), Black Hills (South Dakota), Massachusets, Georgia, Vermont, North Carolina; Sardinia (Italy), Norway, Finland, India, Brazil.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Dimension stone deposits in plutonic intrusions of granite, syenite, gabbro, anorthosite and other igneous rocks. Fresh, unaltered rock masses with jointing at least 2 metres apart and an absence of microfractures may be suitable for quarrying. Quarriable bodies may be up to several hundred metres large, but are not very common since the majority of intrusives have high frequency of joints.

TECTONIC SETTINGS: Granitic plutons in subduction setting, zones of extension, back-arc spreading, island-arc environment. In continental setting, alkaline intrusions associated with extensional tectonic and rift zones.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Synorogenic and post-orogenic intrusions emplaced at different levels within the earth crust. Post-orogenic intrusions are considered more apt to be free of internal strain and to make a better quality dimension stone.

AGE OF MINERALIZATION: Precambrian to Tertiary.

HOST/ASSOCIATED ROCK TYPES: The host intrusive rocks are a variety of compositions, including granite, syenite, diorite, gabbro and anorthosite. Higher grade metamorphic equivalents are also produced under the "granite" name. Associated rocks can be related dikes and pegmatites.

DEPOSIT FORM: Massive unfractured parts of large intrusive bodies without exfoliation features and particularly lacking systems of microfractures. Usually a sound core or large mass, several hundred metres to more than one thousand metres in diameter, irregular in shape, that is surrounded by more fractured and microfractured rock. The size of some bodies may increase with depth; however, even deeply eroded intrusives can exhibit microfractured areas. A single intrusive body may contain several such bodies separated from each other by fractured rock. In more deeply eroded areas, large groups of exfoliated huge boulders may provide a source of commercial blocks.

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R03 - Dimension Stone - “Granite”

TEXTURE/STRUCTURE: Texture is typically granular, but may be gneissic, either homogeneous or banded, with parallel alignment of mineral grains. Commercial stones are coarse to fine-grained, sometimes porphyritic with feldspar phenocrysts in intrusive rocks, or augen aggregates in metamorphic ones. Augen gneiss can be an attractive commercial stone. Good quality dimension stone has a well developed interlocking texture.

ORE MINERALOGY [Principal and *subordinate*]: Most commonly an interlocking texture composed of feldspar, quartz, hornblende, pyroxene and mica. Some commercial stone is composed of a single mineral, such as pyroxenite or anorthosite. Coarser grained mica may be detrimental for the stone to take a good polish.

GANGUE MINERALOGY [Principal and *subordinate*]: Waste consists of altered, fractured and unsound rock; stone containing inhomogenities, like blacks knots and aggregates of mafic minerals; and any minerals that that upon weathering could produce stains, e.g. pyrite, chalcopyrite.

ALTERATION MINERALOGY: Typically rock must be fresh to be useable. But some alteration products, epidote for example, can produce attractive colour or veining without affecting the physical properties of the stone.

WEATHERING: Chemical weathering may affect the stone by producing unsightly stains as a result of leaching soluble components, particularly iron, and occasionally also copper. Undesireable minor components, like pyrite or other sulphides, and some other iron and manganese minerals, in dimension stone may oxidize and stain in contact with moisture. This may differ in distinct climatic zones; stone with excellent performance record in continental climate may be very sensitive to a coastal climate (salt), or smog-filled air in large cities. Also, not all biotite, or even pyrite, may be sensitive to weathering. Some feldspars and altered feldspars, olivine, hornblende and pyroxene are more sensitive to the loss of polish then other minerals. Physical weathering produces structural deterioration and decreases strength and durability. This is particularly important for stones affected by development of microfractures, especially in climatic areas with frequent freeze/thaw cycles which can cause flaking.

ORE CONTROLS: Frequency of joints and any change in composition, colour, or texture which affects significantly the look and performance of the stone.

GENETIC MODELS: Due to the cooling of magma and tectonic processes, intrusive rocks develop joints and fractures of variable frequency. Also, the presence of volatile components and hydrothermal processes may affect the soundness of the rocks

ASSOCIATED DEPOSIT TYPES: Marble (R04), andesite (R05), and sandstone (R06) dimension stone, Alaskite (R14) and anorthosite (as a cement raw material).

COMMENTS: Requirements for soundness, homogeneous character and absence of components producing staining generally excludes granitic rocks in areas of metallic mineralization.

R03 - Dimension Stone - "Granite"

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: NIL

GEOPHYSICAL SIGNATURE: Resistivity surveys have been used to identify low fracture densities and deeply weathered zones in areas with Pleistocene cover. Also, well developed microfracturing in contrast with the sound stone can be outlined by a resistivity survey. Some intrusions will have strong, positive or negative, magnetic or gravity signatures that could be used to identify their location or extent.

OTHER EXPLORATION GUIDES: Intrusive rocks showing consistent and uniform colour with few fractures or forming large boulders. Prospect for large boulder fields as a result of exfoliation and unfractured and smooth rock faces exposed along mountain slopes. Use air photo studies to locate probable areas of intrusions with few large fractures. The type of physical weathering can distinguish an unsound stone, particularly a sharp, angular and raspy surface and angular, detrital feldspar are indicators of low strength and high absorption of water.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Opening face should be at least 50 metres long; some quarries can reach a thousand metres width. Physical properties of stone are an important aspect and have to meet American Society for Testing and Materials Standards (ASTM). These may significantly differ depending on the end use. Outside wall cladding is much more demanding on the strength than for example a floor tile. As BC producers have proven, even a small operation of few thousand tonnes per year from a quarry site can be a successful business venture.

ECONOMIC LIMITATIONS: Waste to commercial size block is an important economic factor. This changes within the deposit as well as from deposit to deposit. If the quarry can sell the waste for aggregate or other commercial products, like split facing stone, landscaping chips and roofing chips, then a more fractured common granite can afford larger waste to block ratio. As a rule of thumb, common types of granite can afford some 20% of waste, while the high end value stone (Blue Pearl larvikite) can have waste up to 80% of quarried rock. For exterior applications, the stone should take good, uniform and lasting polish with good frost resistance. Transportation is a major cost of the finished product. Common types of granite can compete in local markets only, while special varieties (black, red, blue) can travel worldwide.

END USES: Granite tile, facing sheets, monumental stone, and masonry blocks. Waste rock can be used for ashlar, curbing stone, flagstone and facing chips, paving stone and aggregate.

IMPORTANCE: This deposit type is a main source of granite for dimension stone applications.

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R04 - Dimension Stone - “Marble”

by Z.D. Hora[1]

Hora, Z.D., 2007. Dimension stone - “marble”: mineral deposit profile R04, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Commercial term “marble” includes all carbonate-rich sedimentary and metamorphic rocks that are suitable for dimension stone, such as limestone, crystalline limestone, dolomite or marble.

COMMODITIES (BYPRODUCTS): Marble blocks (lime or cement rock, aggregate, rip-rap and white fillers).

EXAMPLES (British Columbia - *Canada/International*): Marblehead (082KSE076), Lardeau (082KSE077), Anderson Bay (092F 088), Hisnit Inlet (092F 020); *Tyndall stone (Manitoba), Bruce Peninsula (Ontario), Saint-Marc-des-Carrieres (Quebec), Pittsford District* (*Vermont, USA), Sylacauga (Alabama, USA), Tate District (Georgia, USA), Yule Creek (Colorado, USA), Takaka Hill (New Zealand), Carrara (Italy), Thassos, Attica, Argolis (Greece), Spain, Portugal*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Marble dimension stone deposits occur in recrystallized/metamorphosed limestone or dolomite, where a general lack of joints makes the recovery of large blocks feasible. The marble should take a good polish and have an aesthetically pleasing colour and texture. Some metamorphosed limestones are suitable for dimension stone and are referred to as “marble” by the stone industry.

TECTONIC SETTINGS: Continental shelf and subsiding marginal marine basins and island arc environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Subtropical and tropical shallow sea environments. Slightly magnesian limestone, is the typical carbonate sediment; dolomite is rather uncommon. Original limestone is frequently aragonite, later recrystallized into calcite. Most of dolomite is secondary, magnesium being introduced during lithification, diagenesis and regional hydrothermal dolomitization. Both rocks become parts of folded, faulted and thrusted, sometimes metamorphosed and recrystallized geological units as parts of orogenic belts and uplifted, exposed platform sediments.

AGE OF MINERALIZATION: Late Proterozoic to Mesozoic, some limestones may be Tertiary.

HOST/ASSOCIATED ROCKS: Depends on tectonic setting. In an island arc environment, the associated rocks are frequently a variety of volcanic, usually more mafic rocks and tuffaceous sediments, and sedimentary rocks, often greywacke, sandstone and argillite, with or without chert. Where metamorphosed, these rocks become schists, slates, gneisses and quartzites. Limestone may be contaminated by a tuffaceous component and form very colourful varieties. Higher metamorphic grades may result in skarn mineralogy. In a continental shelf setting, the volcanic component is usually missing and the associated rocks are argillites, sandstones, greywackes and the occasional conglomerate.

DEPOSIT FORM: The metamorphosed carbonate deposits are stratiform, may be folded, and may have gradational contacts. The thicknesses of mineable marble deposits range from 10 metres to several hundred metres. Marble deposits commonly extend more than a hundred metres along strike; often individual deposits are parts of continuous carbonate belts (like in the Appalachian belt from Vermont to Alabama).

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R04 - Dimension Stone - “Marble”

TEXTURE/STRUCTURE: Bedded with compositional and colour layers. Some marbles display complexly folded bedding or breccias that can enhance their appearance. In metamorphic marbles, the carbonate is so thoroughly recrystallized that much, or even all of the sedimentary features, are obliterated and replaced with an interlocking, mosaic texture. Highly metamorphosed varieties may exhibit features indicating a plastic flow, where original layering may be stretched or pulled apart and highly deformed. The limestones and weakly metamorphosed varieties may contain fossils and retain biological textures. In some deposits, fractured carbonate has been re-cemented to form a healed breccia texture.

ORE MINERALOGY [Principal and *subordinate*]: Calcite and dolomite.

GANGUE MINERALOGY [Principal and *subordinate*]: A large group of minerals that affect the processing and final appearance – some are harder than calcite or dolomite and result in elevations on a polished surface (chert, other forms of silica, silicate minerals like garnet and spinel, pyrite). Others are softer, or with well-developed cleavage, that results in hollows (graphite, phlogopite, chlorite, talc, tremolite, wollastonite, brucite). Some prevent the stone from taking a good polish (clay, finely disseminated graphite and hematite). Some are easy to oxidize and stain (pyrite).

ALTERATION MINERALOGY: Recrystallization due to metamorphism improves the stone’s ability to take a high polish and results in more massive beds, sometimes with enhanced colours and texture features. Soft minerals like clays may recrystallize into harder silicates that take a good polish. Secondary veining may cement the broken and fractured carbonate rock into attractive textured stone breccia. The metamorphic process may also totally remove the dark-coloured organic matter disseminated in original limestone or recrystallize it in the form of graphite.

WEATHERING: Solution weathering results in a variety of karst features, but may also produce semiprecious varieties like Mexican onyx, a banded form of aragonite precipitated from hydrothermal waters or from calcium-rich groundwater in karst areas. Mexican onyx and other semiprecious varieties are sometimes included commercially under the term marble. Marbles with a silicate component (tremolite, flogopite and garnet) might significantly deteriorate in durability and strength. The weathering of pyrite results in unsightly stains and further deterioration by sulphuric acid attacking the surrounding carbonate. Exposure to salty air in coastal areas and smog in the cities frequently results in a rapid loss of luster on exposed polished marbles. Frequently, a weathered surface of the outcrop can indicate presence of impurities and their impact on stone quality.

ORE CONTROLS: The basic ore control is rock of suitable composition, attractive colour and consistent appearance. The frequency of bedding planes and transversal jointing determines the waste to ore ratio and the economics of production. In some regions, quarries are developed only in thickened beds near fold hinges.

GENETIC MODELS: Most limestones of economic importance were partly or wholly biologically derived from seawater and accumulated in a relatively shallow, subtropical and tropical marine environment. Calcium carbonate producing organisms, such as corals, algae and mollusks can build reef structures hundreds of kilometres long and kilometres wide. Limestones that form in a high-energy environment have more probability to be high-purity carbonate rocks. Very fine carbonate muds, sometimes contaminated with clay-sized particles of silica and silicate minerals, accumulate in a low-energy environment of lagoons and deep water. Under some specific conditions, original calcium carbonates may be enriched in magnesium, thus transforming original limestone into dolomite. Under both regional and contact metamorphism, carbonate rocks recrystallize, sometimes reacting with internal contaminants to form a new suite of minerals. Such recrystallization may result in a significant improvement of aesthetic appeal to the end user in resulting colour, structure and texture. Both contact and regional metamorphism may remove black or dark grey organic substances resulting in highly prized pure white carbonate.

R04 - Dimension Stone - “Marble”

ASSOCIATED DEPOSIT TYPES: Limestone (R09), sandstone (R06), skarns (K01 to K09), travertine (H01).

COMMENTS: So called “green marble”, or “Verde Antico”, of Italy and Greece in particular, is a variety of serpentine, classed commercially as a marble. Under low metamorphic conditions, peridotites and related rocks may produce bright green serpentinite, which has been used as a building and ornamental stone since ancient times.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High-purity marbles will consist almost exclusively of calcite or dolomite and contain only very minor amounts of other elements.

GEOPHYSICAL SIGNATURE: Resistivity methods can outline karst features in covered terrain.

OTHER EXPLORATION GUIDES: Favourable marble beds are commonly found in belts of regionally metamorphosed sedimentary rocks or adjacent to a specific suite of intrusions, which have thermally metamorphosed carbonate beds. Massive beds exposed along valley slopes and in natural cuts and outcrops. Green “marble” in serpentinite belts, usually parts of accreted ophiolitic oceanic crust.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Canada and United States produce annually close to 500,000 tonnes of ornamental limestone and marble. Approximately 40 production centres are scattered over the continent, in at least ten states and three provinces. Commercial stone must meet ASTM specifications for its intended use.

ECONOMIC LIMITATIONS: “Marble” may be not attractive economically when dolomite forms thin layers in calcite because of different hardness and usually difference in grain size when dolomite is significantly finer grained than calcite. Waste to commercial size block ratio – depending on the type of quarry, waste should normally not surpass 25 to 30% of mined material. This may be higher if there is a market for the rejected material, for example, white limestone, which can be processed into calcium carbonate fillers, landscaping chips, etc. Limestone and marble in particular, are very sensitive to blast shock; therefore, in marble deposits the use of blasting must be avoided entirely. Also the mineral composition – presence of some deleterious minerals may be a limiting factor on the end use and restrictive to potential end uses. Minor components, like pyrite and other easily oxidized minerals, can stain marble when installed in some environments. Hard inclusions like chert nodules, silica veinlets, intrusive sills and dikes can make the marble difficult to process into a quality product and/or lead to differential weathering. Common types of marble can be produced and processed for a local market only; special varieties (coloured, snow-white) can travel globally. Marble deposits have been successfully quarried underground throughout history. Marble deposit production in British Columbia has partly been quarried both from open pit quarries and underground. Modern methods using chainsaws and wiresaws have simplified removing blocks from underground quarries.

END USES: Marble tile, facing sheets, monumental stone, statues, fillers for paper and plastics, soil conditioner.

IMPORTANCE: Marble has provided structural, building and ornamental stone for millennia. Many historical landmarks, artwork, buildings and structures used marble or limestone.

R04 - Dimension Stone - “Marble”

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R06 - Dimension Stone - Sandstone

by Z. D. Hora[1]

Hora, Z.D., 2009. Dimension stone - sandstone: mineral deposit profile R06, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Bluestone, brownstone, freestone, arkose, greywacke, quartzite.

COMMODITIES (BYPRODUCTS): building stone.

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Newcastle Island (092GSW022), Gabriola Island (092GSW021), Saturna Island (092B 068), Denman Island (092F 426), Jack Point (092GSW049), Koksilah (092B 122); *Paskapoo sandstone, Alberta; Nepean sandstone, Ontario; Wallace sandstone, Nova Scotia; Potsdam sandstone, New York; Ohio sandstone, Ohio; UK, France, Germany.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Uniform massive beds of sandstone with very few and well spaced (over 1 metre) fractures and bedding planes. Sandstone must be suitable to be removed from a quarry face in square shaped blocks that are 10 tonnes or larger with minimum waste. Some sandstones may be feldspathic (arkose) or with prominent dark component (greywacke).

TECTONIC SETTING(S): Shallow marine or lacustrine basins, tectonically rather quiet with wide spread uplift or downthrust events.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Shallow continental shelf, inland sea or large continental lacustrine basins with low energy environment and a steady supply of well sorted, detrital, sand size particles. The mineral composition is influenced by the regional climate over the source area; speed, type and intensity of weathering and speed of transportation into the sedimentary basin.

AGE OF MINERALIZATION: Any age. Dimension stone sandstones are known to be of Cambrian, Carboniferous, Permian, Triassic, Cretaceous and Tertiary ages.

HOST/ASSOCIATED ROCK TYPES: Sandstone beds are part of sedimentary sequences, which may include shale, siltstone, greywacke, limestone and conglomerate. Coal may be associated with sandstone beds. Limestone beds in sandstone sequences are rather uncommon.

DEPOSIT FORM: Massive beds of thickness more than 1 metre, may be layered or cross bedded, uniform in appearance. Deposits commonly extend over areas of at least several square kilometers. Usually the deposits are horizontal or tilted, rarely folded.

TEXTURE/STRUCTURE: Sandstones possessing uniform grain size and a massive, inconspicuous cementing matrix; they can exhibit bedding and cross bedding features. In outcrop the stone has a smooth surface with very few irregularities which would result from preferential weathering, either due to inhomogeneous composition or the presence of microfractures.

ORE MINERALOGY (Principal and *Subordinate*): Quartz, feldspar, volcanic rock fragments; clay, ferrous and ferric oxides, chlorite, mica, calcium carbonate, detrital coal.

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R06 - Dimension Stone - Sandstone

GANGUE MINERALOGY (Principal and *Subordinate*): Clay, silt and mica layers, wispy coal layers, conglomerate; *pyrite, phosphatic nodules, fossil shells.*

ALTERATION MINERALOGY: Weathering of the sandstone can change ferrous ions into ferric iron staining or overall colour change. Feldspathic component may alter into a variety of clay minerals.

WEATHERING: Sandstone weathering may result both in physical and chemical deterioration. High porosity sandstones are sensitive to freeze – thaw activity resulting in exfoliation and surface erosion. Chemical deterioration may affect cementing matrix (carbonate leaching), oxidation of some components (pyrite) with resulting rusty stains and soluble salts leaching out of the stone and precipitated as white stains on the surface or enhancing exfoliation activity. Most common weathering effect, even in the best quality sandstones is changing the bluish colour of fresh stone into beige or brown as a result of oxidation of ferrous component into ferric. This change does not have to affect the physical durability of the stone.

PRODUCT CONTROLS: The primary control is the presence of thicker sandstone beds. Secondary controls are absence of significant deformation and limited amounts of other rock types.

GENETIC MODEL: Shallow continental shelf or inland sea or large lacustrine basin with low energy environment and a steady supply of well sorted clastic material. After the deposition, the accumulated sediment has to be cemented either by a chemical process (usually carbonate or silica) or by a physical compaction.

ASSOCIATED DEPOSIT TYPES: Cement shale (R01), expanding shale (R02), coal (AO3, A04, A05), silica sandstone/quartzite (R07).

COMMENTS: In British Columbia, sandstone as a building stone was replaced in part by so called “Haddington Island andesite”, which has very similar look, but much better physical properties and durability. Sandstones are in general not suitable for polishing and are used with rough or just plain cut surface. Only some quartzites may have potential for polished ornamental stone products (Babette Lake quartzite). Use of sandstone in Canada and North America in particular is very limited, quarried mostly for maintenance and repairs of heritage structures.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High silica contents and low aluminosilicate and carbonate contents.

GEOPHYSICAL SIGNATURE: Resistivity can identify fracture density and bedding features in areas of insufficient outcrops, also the presence of clay layers and their frequency can be established. Shallow seismic can identify inhomogeneities in the deposit – like shale layers, weakly cemented beds and different lithologies.

OTHER EXPLORATION GUIDES: Large smooth bedrock exposures in cuts, on valley slopes and along shorelines lacking fragmented rock are good indicators. An air photo study can identify large outcrop areas and boulder fields.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Required properties, standard specifications for stone used in construction and industrial applications, are listed in ASTM (American Society for Testing Materials) designations, particularly C616. Production volumes in North America are relatively small, in 1998 dimension sandstone production in USA was reported to total 185,000 tonnes, coming from 30 production centers, with value of approximately US$ 80 per metric tonne. In Canada, six provinces in 1999 produced 47,000 tonnes, with value of CDN$ 125 per metric tonne.

R06 - Dimension Stone - Sandstone

ECONOMIC LIMITATIONS: The frequency of joints, structural and textural inhomogeneities, presence of shale interbeds and abundance of irregular and oblique shape fractures are all features that increase waste and affect the volume of sandstone needed to be removed in recovering square 10 to 20 tonnes blocks. Economic deposits can afford a maximum of 25 to 30 % of waste. The price per metric tonne does allow for only a minimum waste to saleable block ratio. The presence of some undesirable minor components like pyrite can produce unsightly stains if in contact with moisture that diminish the desirability and value of a particular stone. Susceptibility to an increased rate of deterioration due to smog in the cities or salty air in coastal areas tends to reduce sandstone demand in such areas. Transportation is a major cost factor in reaching more distant markets.

END USES: Sandstone is a traditional building stone in many parts of Europe and elsewhere. Originally it was used as ashlar and construction blocks, lintels, sills, door and window frames and grinding wheels. Presently sandstone is utilized mostly for maintenance and repair of heritage buildings, paving and wall facing sheets and ashlar. Flagstone is a common substitute.

IMPORTANCE: In the past a very important structural material, replaced in the 20th century by more durable materials. Important stone used for restoration, repairs and maintenance of heritage structures.

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R07 - Silica-Rich Rocks

by Z.D. Hora[1]

Hora, Z.D., 2009. Silica-rich rocks: mineral deposit profile R07, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: High silica quartzite, quartz sandstone, silica rock, silicastone.

COMMODITIES: Silica sand, lump silica.

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Golden (082N 001), (082N 043), Longworth (093H 038), Bridesville (082ESW144); *Selkirk (Manitoba, Canada), Badgley Island (Ontario, Canada), St. Canut (Quebec;Canada), Oriskany sandstone (Pennsylvania and West Virginia,USA), St.Peter sandstone (Illinois and Missouri, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Uniform, massive beds of siliceous sediments, such as sandstone and chert, or their metamorphic equivalents, like quartzite. These beds are commonly formed in sedimentary sequences, although some cherts can be found with volcanic rocks. They have high silica contents with very limited impurities, usually under 1%.

TECTONIC SETTINGS: **Siliceous sediments** formed on a shallow continental shelf or deposited in inland seas, large lacustrine basins or rift zones on the continent. **Cherts** form in oceanic environments associated with island arcs and spreading centers. Quartzites found in orogenic belts of all ages.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: **Siliceous sediments** deposited into a low energy environment slowly sinking or stagnant sedimentary basin. Source area has to be rich in siliceous sedimentary, igneous or metamorphic rocks to provide a steady supply of well sorted and weathered clastic material to estuaries along the shoreline. Weathering conditions before and during transportation should be able to separate resistant quartz from less stable feldspars, hornblende and pyroxenes, transportation will separate the clay minerals and mica with heavy minerals from the silica particles. **Cherts** form in oceanic environments near and distal to spreading centers and rift zones and along volcanic belts as exhalative deposits. They can also form as biogenic and/or chemical precipitates of silica gel in an oceanic environment.

AGE OF MINERALIZATION: Precambrian to Tertiary. modern protolithic facies on the seafloor.

HOST/ASSOCIATED ROCK TYPES: **Siliceous sediments** are found with a wide spectrum of clastic and carbonate rocks, including coal and associated with clay deposits. **Cherts** are found with felsic to mafic and ultramafic volcanics and associated greywacke and shale. Quartzites and metamorphic cherts are found with the metamorphic equivalents of the rocks listed previously.

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R07 - Silica-Rich Rocks

DEPOSIT FORM: The siliceous sediments occur as metres thick beds that can extend more than tens of kilometers., while the chert beds may be up to several tens of metres thick and laterally extend for hundreds of metres but are frequently discontinuous.

TEXTURE/STRUCTURE: **Silica-rich sediments** typically have uniform grain size, may be well lithified or friable, and can be layered, cross bedded or massive beds. Massive or rhythmically bedded chert is found sometimes with argillaceous interbeds and soft sediment deformation features. Quartzites as metamorphosed equivalents of sandstones or cherts usually display the structure of the original rock.

ORE MINERALOGY (Principal and *Subordinate*): Quartz; chert can also have other forms of amorphous and microcrystalline silica.

GANGUE MINERALOGY (Principal and *Subordinate*): Siliceous sediments can contain clay minerals, pyrite, mica and minor *heavy minerals (rutile, sphene, ilmenite, zircon, etc.). Cherts can contain* clay minerals, hematite, manganese oxides, pyrite; *rhodonite, rhodochrosite, calcite, barite.*

ALTERATION MINERALOGY: Fractures can have secondary Fe – Mn hydroxides and/or calcium carbonate.

WEATHERING: Usually weathering resistant, resulting in morphological highs. Only some friable sandstones result in depressions.

ORE CONTROLS: Source terrains that minimize impurities and depositional environments that includes long or repeated transportation with intensive wear of particles which includes separation from other silicates like feldspars for example. This may occur both by physical as well as chemical weathering.

GENETIC MODEL: **Siliceous sediments** form on the shallow continental shelf and in inland seas or large lacustrine basins with a relatively low energy environment and a steady supply of well sorted silica sand. After the deposition, the accumulated sediment will be cemented by compaction, a minor clay component, or introduced secondary silica. **Cherts** form in deep water oceanic environment with hydrothermal activity and abundance of radiolarians suggest oceanic upwelling that enriches water in nutrients, or recrystallized under metamorphic conditions.

ASSOCIATED DEPOSIT TYPES: **Siliceous sediments** - building stone; **cherts** - Sedex and VMS deposits, marine diatomite.

COMMENTS: Crystalline silica in dust form is considered a carcinogenic health hazard. Mineral processing of alaskite feldspar rocks can produce a very high purity (10 to 200 ppm impurities) silica co-product.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: In general more than 98% silica with traces of other elements.

GEOPHYSICAL SIGNATURE: Only where contrast with host rocks is significant.

OTHER EXPLORATION GUIDES: Look for resistant ridges and outcrops and absence of impurities in hand sample visible to the naked eye.

R07 - Silica-Rich Rocks

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Each use has its very specific requirement for the particle size and shape, physical strength and permissible amounts of different impurities. For lump silica the concerns are purity, sizing of crushed rock (fracture and bedding density) and contamination by Ca, Fe, Mn, Ti, Al, Na and K minerals or graphite and silica sand they are friability and size of silica particles and contamination by Fe, Mn and Al minerals and refractory minerals of Al, Zr, Cr. Generally silica contents have to be 98% with significant impurities removable by processing. Which depend on the end use. Even high purity orthoquartzite usually contains minute titanium minerals which are detrimental for silicon metal (even at 0.2% TiO_2). Also, even trace of Ca can make silica unacceptable for specific end uses. Lasca grade silica may contain impurities in ppm only. Such contaminants may be absent in oceanic cherts. Individual deposits range from 1 million to 100 million tonnes.

ECONOMIC LIMITATIONS: While some very specific silica raw materials may be relatively expensive, the basic types of silica sand or lump silica are low priced, bulk commodities sensitive to transportation costs. For its main uses, silica sand from sandstones has a number of substitutes and their use depends on local or regional availability. Silica is available as a co-product or by-product of feldspar and residual kaolin mining and is produced locally from dune and beach sands. Foundry sand can be substituted by some other minerals, like olivine, for example.

END USES: Most silica is used in the form of sand to manufacture glass products and as foundry sand. In North America, about one third is used in glass and one-fifth as foundry sand. The remaining silica is divided among a multitude of metallurgical and chemical uses, including cement, ceramics, fillers and blasting sand. Very high quality silica is being used for a long list of synthetic silicas and silicon chemicals, silicon metal, ferrosilicon and silicon carbide, cultured silica crystals and silica glass. Silica sand for hydraulic fracturing has to be well rounded and to withstand very high pressures when pumped into oil and gas wells to enhance the recovery. The past widespread use of fine grained silica rocks was to make acid refractory bricks (dinas) used in iron metallurgy. These silica rocks were termed “dinas rock”.

IMPORTANCE: In the year 2000 Canadian production was 2.0 million tonnes and the United States produced 28.5 million tones annually. Cement, glass and ceramics are unthinkable without silica, so is the use as a foundry sand. Most of other applications are less visible, but equally important for industrial societies.

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R07 - Silica-Rich Rocks

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R08 - Flagstone

by Z.D. Hora[1]

Hora, Z.D., 2009. Flagstone: mineral deposit profile R08, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3pp.

IDENTIFICATION

SYNONYMS: Paving stone, facing stone, split stone.

COMMODITIES (BYPRODUCTS): Paving and wall cladding stone, ashlar, roofing slate as a co-product, (aggregate, landscaping stone)

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Nipple Mountain (082ENW109), Porcupine Creek (082FSW279), Sheep Creek (082FSW288), Revelstoke (082LNE025), McNaab Creek (092GNW009), Jervis Inlet (092JW029), Dome Creek (093H028), Beaverdell (082ESW169); *Exshaw, Alberta; Coconino sandstone, Arizona; Pennsylvania Bluestone, Pennsylvania and New York.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Flagstone is a rock, often sedimentary or metasedimentary, that splits into sheets and slabs with parallel sides due to bedding, schistosity, cleavage, planar weakness or natural jointing. Flagstone can be of any type of rock as long as it meets the basic requirements of soundness and resistance to abrasion and weathering.

TECTONIC SETTING(S): Practically any setting; type of lithified sediments , sand dunes, volcanosedimentary deposits, schistose metamorphic rocks, magmatic and volcanic rocks.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Clastic and chemical sediments and their metamorphic equivalents; intrusive and volcanic rocks and their tuffaceous equivalents.

AGE OF MINERALIZATION: Any age – Precambrian to Tertiary.

HOST/ASSOCIATED ROCK TYPES: Sandstone, siltstone, shale, carbonate rocks; quartzite, gneiss, schist, slate, marble; granitic rocks, rhyolite, phonolite and related tuffs (particularly zeolitized).

DEPOSIT FORM: Bedded or schistose unit which may be flat or steeply dipping. Plutonic bodies of intrusive rocks, lava flows. Deposits of flagstone are usually tens of metres thick by thousands of metres square.

TEXTURE/STRUCTURE: **Sedimentary and metasedimentary**: Bedded structure with absence of folding or other irregularities affecting flat surface. Clastic sediments cemented by silica, calcium carbonate or by compaction. Foliated metamorphosed equivalents with graphite or mica separating individual sheets. **Igneous:** Magmatic rocks may be equigranular or porphyritic. More commonly the igneous rocks have a blocky or platy structure with large scale open folds, banded intrusives and flows with preferential parallel splitting.

ORE MINERALOGY (Principal and *Subordinate*): Rocks types that are resistant to weathering due ot the presence of silicate and carbonate minerals and with a lack of clays, sulphides and minerals susceptible to chemical or physical weathering, like cordierite and chlorite.

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R08 - Flagstone

GANGUE MINERALOGY (Principal and *Subordinate*): Clay and coaly wisps and layers, carbonate and siliceous nodules and veinlets, massive thick beds not splitting in a saleable product, different colour unhomogenities like black nodules and knots, beds or zones with minerals producing unsightly stains.

ALTERATION MINERALOGY: Clay minerals after feldspars, sericite, chlorite, zeolites.

WEATHERING: Microfractures and presence of clay minerals may result in exfoliation. High porosity can be frost sensitive. Bi-valent iron component turns into tri-valent form, resulting in colour change from bluish-green into beige to brown. Common sulphides like pyrite and pyrrhotite, some biotite and other iron containing minerals oxydize, producing rusty stains and spots. Also the presence of soluble salts (chloride, sulphate or carbonate) in some rocks (mostly sandstones, but also limestones and siltstones) can result in unsightly staining and exfoliation.

PRODUCT CONTROLS: Frequency of bedding planes to produce a standard thickness of the product, frequency of jointing to allow production of commercial size of sheets and shapes with minimum waste. Distribution and presence of deleterious minerals affecting the end use and durability of product in construction trades. Presence of unusable beds, like conglomerate in sandstone, etc.

GENETIC MODEL: Sandstone – beach and near shore clastic sediment in low energy environment, deltaic fans in shallow sea, aeolian deposits, diagenetically cemented by silica, limestone or by compaction. Quartzite may be the metamorphic equivalent. Laterally may grade into siltstone or silty limestone. Slate – a clayey, monotonous and uniform deep water sediment with well developed cleavage as a result of low grade metamorphism. Schist – fine grained clastic or clayey sediment highly metamorphosed into the muscovite or biotite schist, where mica layers separate quartz-feldspathic sheets. Limestone – organic or inorganic sediment in a variety of marine environments, of bedded texture. .As flagstone frequently with many impurities, sometimes fossiliferous. Beds may be separated by clayey partings. Tuff – air-fall or waterlain, fine grained volcanic ash cemented by recrystalization, devitrification (zeolitization for example) or compaction. Igneous rocks – medium to fine grained magmatic rocks, sometimes porphyritic, of massive or banded texture, with preferential splitting in sheets.

ASSOCIATED DEPOSIT TYPES: Sandstone - coal (A02, A03) , expanding shale, cement shale, dimension sandstone; slate - schist - slate, quartzite,s andstone, limestone; marble, industrial limestone (cement and lime, filler); zeolite, diatomite, bentonite, sedimentary kaolin; igneous rocks - dimension granite, crushed aggregate.

COMMENTS: Some flagstones are produced by cutting or splitting large square blocks of sandstone, slate and granite. Roofing slate is a type of flagstone that splits into thin sheets.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High silica, feldspar, mica, sometimes carbonates.

GEOPHYSICAL SIGNATURE: Not normally used. This is very often a cottage type industry where economics do not allow expensive exploration methods.

OTHER EXPLORATION GUIDES: Good flagstone is indicated by large sheets of stone naturally exposed by physical weathering.

R08 - Flagstone

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: For many end uses the most important criteria is previous performance. While there are ASTM specifications for a number of physical properties required in specific applications, many popular stones have never been thoroughly tested. Annual production in the USA is between 130,000 and 140,000 tonnes from some 50 main quarrying site. Established producers in British Columbia and Alberta were processing in the year 2000 approximately 17,500 tonnes a year from 13 sites.

ECONOMIC LIMITATIONS: Most of the flagstone types are used in local or regional markets, and the use of some particular stone depends on the personal taste, or sometimes fashion. Also, local availability is an important factor for choosing one stone over another. Transportation cost has important role in distributing flagstone to more distant markets. Only few flagstones, of particularly attractive or a rather unusual colour or texture can reach far away destinations. Such products are for example so called “Pennsylvania Bluestone” from New York, red or green slate from Vermont, and “Tyndall Stone” dolomitic limestone from Manitoba.

END USES: Floor and wall cladding, retaining walls, steps, window sills, fireplaces and landscaping.

IMPORTANCE: As a product that is labour intensive both to make and use, flagstone is mostly used in niche markets like higher end residences and recreational developments. Examples of the latter are Whistler – Blackcomb or Banff.

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R09 - Limestone

by Z.D. Hora[1]

Hora, Z.D., 2009. Limestone: mineral deposit profile R09, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Limerock, cement rock, calcium carbonate.

COMMODITIES (BYPRODUCTS): Limestone (aggregate, rip-rap, white fillers).

EXAMPLES: (British Columbia – *Canada/International*): Blubber Bay (092F 397, 479), Lafarge Limestone (092F 396), Gillies Bay (092F 395), Imperial (092F 394), Bamberton (092B 005), Benson Lake (092L 295), Pavilion Lake (092INW081), Harper Ranch(092INE001), Lost Creek (082FSW307), Dahl Lake (093G 032), Ptarmigan Creek (093H 017); *Palliser Formation Cadomin and Exshaw limestones (Alberta), Detroit River Group – Woodstock, Beachville (Ontario), Trenton Group – Joliette, Beauport, Saint-Constant (Quebec), Mississippian Monte Cristo limestone, Lucerne Valley, (California, USA), Ordovician Kimmswick limestone, Clarksville (Missouri, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Calcium carbonate sedimentary rock that occurs in beds, usually tens of metres thick, with or without minor dolomite. High-grade limestone can be almost pure (less than 1.4% impurities for chemical lime). Lowest grades of limestone (marlstone) can be used for cement with as little as 65% calcium carbonate, with contamination by finely disseminated clay and silica. The limestone may be recrystallized by various degrees of metamorphic grade. Marl and chalk are poorly lithified forms of limestone.

TECTONIC SETTINGS: Recent and Ancient continental shelf and subsiding marginal marine basins are the most common settings; island arc environments also important.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Subtropical and tropical shallow sea environment. Calcium carbonate, usually slightly magnesian, is the typical primary component; dolomite is rather uncommon. The original mineral is frequently aragonite, later recrystallized into calcite. During lithification and diagenesis, under a variety of geological processes, it may be partially or completely dolomitized (see R10).

AGE OF MINERALIZATION: Late Proterozoic to Holocene, main producers globally are Paleozoic, Mesozoic and Tertiary.

HOST/ASSOCIATED ROCK TYPES: Shelf-deposited limestone beds are often found within thicker sedimentary sequences with associated dolomite, argillite, sandstone and intermediate sedimentary rocks. Island arc limestone often has a volcanic component, such as tuffaceous rocks, sills, submarine lava and palagonite breccia. Sometimes found in cherty layers and interbeds.

DEPOSIT FORM: Lenses, massive beds; folded and unfolded. Thickness of mineable limestone deposits range from ten to several hundreds of metres. The areal extent of some deposits covers hundreds of square kilometres.

TEXTURE/STRUCTURE: Massive, bedded, fine- to coarse-grained, sometimes with crossbedding features, sometimes porous, fossiliferous, with stylolites. Interbeds with chert nodules.

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R09 - Limestone

ORE MINERALOGY [Principal and *Subordinate*]: Calcium carbonate with minor *dolomite, clay,* shale and silica. Some limestones may contain finely dispersed bitumen.

GANGUE MINERALOGY: All types of silicate rocks, chert, pyrite, intrusive dikes on Texada Island.

ALTERATION MINERALOGY: Groundwater dissolution results in karst cavities, which are frequently filled with clay. Metamorphism recrystallizes the limestone and mobilizes the dispersed bitumen, which can remain as graphite. With high metamorphic grades, clay and silica will recrystallize into skarn-like groups of silicate minerals and crystalline silica.

WEATHERING: Solution weathering results in a variety of karst landforms in most climatic areas, but intensifies with a warmer climate. Most intensive karstification may produce deposits of bauxite.

ORE CONTROLS: Favourable limestone units often occur in belts that reflect original depositional environments. Limestone very often forms well-defined stratigraphic and lithological units. Horizontally, limestone will grade gradually into impure limestone and other sedimentary facies, which will reduce the value depending on the end use due to changes in chemical composition and quantity and type of contaminants. Highly sought white limestone for mineral fillers is usually a product of the contact or regional metamorphic processes.

GENETIC MODELS: Most limestone deposits of economic importance were biologically derived from seawater as detrital calcium carbonate and accumulated in a relatively shallow marine environment. The other form is by organic frame builders like coral and algae as local and regional reef structures. The environment of deposition determines the size, shape and purity of the carbonate rock.

ASSOCIATED DEPOSIT TYPES: Deposits of dolomitic limestone and dolomite (R10), marble building stone (R04).

COMMENTS: A relatively small percentage of limestone contains alumina and other oxides in the right proportions to make cement and are termed “cement rock”. Recrystallization of limestone may have a significant effect on the limestone use. Particularly coarse crystalline rock may decrepit during calcinations and make the rock unusable in rotary and vertical kilns. In some African countries, carbonatites are used in the absence of sedimentary limestone to manufacture both cement and lime.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High $CaCO_3$ content.

GEOPHYSICAL SIGNATURE: Resistivity has been used to identify karst features in covered terrain.

OTHER EXPLORATION GUIDES: Regional belts of sedimentary rocks with limestone potential are the primary exploration tool. Karst topography and underground streams indicate carbonate units.

R09 - Limestone

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Limestone is an extremely versatile industrial rock processed into many end products. Diverse uses have diverse quality requirements, controlled by numerous ASTM standards and industry specifications on chemical composition, physical properties, local availability and consistency. Some specifications deal with the final product and may be controlled during processing (for example, cement). Other end uses require exact limits in composition or physical properties.

The main global limestone uses are cement and lime manufacturing. In 2000, the U.S. produced 15 million tonnes of lime and 83 million tonnes of cement. In the same year, the U.S. imported 25 million tonnes of cement and 113 thousand tonnes of lime.

A typical cement plant in developed countries has a capacity of approximately 1 million tonnes annually, while a typical lime plant will produce between 100 and 200 thousand tonnes of lime per year. Because high-grade limestone contains 44% carbon dioxide, a plant requires almost 2 tonnes of limestone for every tonne of product.

In many regions, where rocks of magmatic origin are absent, fine-grained, unmetamorphosed limestone and dolomite are the most common source of crushed, quarried aggregate. Some of these types of stone products can be a source of extremely undesirable alkali-aggregate reactivity. Such reactivity may result in early deterioration of concrete structures.

In filler application, a calcium carbonate and dolomite mix is extremely undesirable due to the difference in hardness. For many applications, paper in particular, the presence of dolomite contamination ruins the product.

ECONOMIC LIMITATIONS: In some regions, limestone is mined by underground methods even for uses such as cement production. Limestone used for paper and fillers requires a high brightness (over 90GE), chemical purity, absence of hard minerals like quartz and absence of graphite or other colour components. For high-end uses, flotation to remove deleterious components is routine. Lime is produced from limestone with high calcium carbonate (>9597%) and low MgO (<5%) contents. The rock must not decrepitate in the kiln during calcination. Cement normally contains <6% MgO and <0.6% $Na_2O + K_2O$ in the final product. Transportation is frequently a major cost of the finished product. Limestone quarries operate near many cities; limestone products often travel longer distances to markets. For example, white filler-grade limestone in Washington State is shipped by rail some 600 kilometres from the quarry to the processing plant. Lime-grade limestone from Texada Island is barged to coastal users from Alaska to northern California. Cement is imported to many coastal points in the United States from overseas.

END USES: Cement, lime, soil conditioner, glass, fillers, fluxing agent, acid neutralization. Some limestone is used for dimension stone and is discussed in profile R04.

IMPORTANCE: This deposit type accounts for virtually all production of cement and lime in North America.

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R10 - Dolomite

by Z.D. Hora[1]

Hora, Z.D., 2009. Dolomite: mineral deposit profile R10, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Dolostone, dolomitite, dolospar.

COMMODITIES (BYPRODUCTS): Dolomite (aggregate, filler). Sometimes dolomite may be a byproduct of quarrying limestone.

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Crawford Creek (82FNE113), Pilot Point (82FNE075), Oro Viejo (82M 254), Rock Creek (82ESE200); *Gunton, Stonewall, Stony Mountain (Manitoba, Canada), Guelph, Bruce Peninsula (Ontario, Canada), Portage-du-Fort, Havre-Saint-Pierre (Quebec, Canada), Kelly Cove (Nova Scotia, Canada), Addy, Keystone (Washington, USA), St.Paul, Minneapolis (Minnesota, USA), Thornton, Joliet, Kankakee (Illinois, USA),York (Pennsylvania, USA),Sussex and Somerset Co. (New Jersey, USA); United Kingdom; Italy; France.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: A bedded or massive carbonate sedimentary rock that occurs as tabular bodies concordant with stratigraphy and beds up to tens of metres thick and zones controlled by faults and permeable zones. Dolomite contains more than 90% of the mineral dolomite and is usually a finely crystalline and slightly porous rock. Calcite is the most common other mineral.

TECTONIC SETTING(S): Dolomite is more common in Recent and Ancient continental shelf and subsiding marginal marine environment, however, economically attractive deposits also occur in island arc environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Dolomite is most common as a secondary replacement of marine sediments that were a slightly magnesian calcium carbonate that was frequently aragonite originally and later recrystallized into calcite. Circulating ground water (sea water, hypersaline brine, pore water) containing magnesium reacted with the calcium carbonate to produce dolomitic limestones and dolomites. Dolomite may also form as a primary sediment, but this is not very common.

AGE OF MINERALIZATION: Dolomite can be any age, but the ages of dolomitization for secondary deposits often are not well defined. Large scale regional dolomitization in western Canada has been linked to fluid circulation taking place during Devono-Mississipian and late Cretaceous-Tertiary periods. Generally these deposits are believed to be concurrent with large scale tectonic activity.

HOST/ASSOCIATED ROCK TYPES: Dolomites are often found within thicker sedimentary sequences with associated limestones, dolomitic limestones, argillites, sandstones and evaporates. In island arcs, dolomites often have a volcanic component, such as tuffaceous rocks, sills, submarine lavas, palagonite breccias and sometimes cherty layers and interbeds.

DEPOSIT FORM: Large tabular bodies concordant with stratification that may be up to several tens of metres thick and extend for hundreds to thousands of metres. There are also regional nonconformable dolomitized zones, sometimes controlled by faults and by permeability of both the host and adjacent sedimentary units.

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R10 - Dolomite

TEXTURE/STRUCTURE: Finely to medium grained, crystalline, sucrosic texture, sometimes retaining textures like fossils and laminations of original limestone. Solution-collapse breccias and replacement zones are usually a medium grained, white, granular texture.

ORE MINERALOGY (Principal and *Subordinate*): Dolomite / *quartz, brucite, calcite, chert, kaolinite, illite, sometimes bitumen*.

GANGUE MINERALOGY (Principal and *Subordinate*): Limestone and dolomitic limestone.

ALTERATION MINERALOGY: Dolomite is typically an alteration product. It may be accompanied by a variety of sulphides (pyrite, sphalerite, galena), Fe-Mn-Mg-Ca carbonates, chlorite, barite, gypsum or anhydrite and fluorspar. High temperature/low pressure metamorphism may result in converting dolomite into a mixture of periclase (Mg0) and calcite. Periclase in nature easily alters into brucite $Mg(OH)_2$.

WEATHERING: In outcrop dolomitic layers in limestone may have a positive relief because of their lower solubility. Common to see concentrations of iron in the rims of individual dolomite crystals which result in the brown-yellow colour of dolomite outcrops. Because of higher porosity, some secondary dolomites are more susceptible to physical weathering and outcrops have frequently sandy talus developments (because of the sugary texture).

ORE CONTROLS: Ore control reflects the mode and intensity of dolomitization. In some deposits a primary control is the chemical composition of the carbonate rock, in some others it is the upper and lower limits of the original limestone bed. For some deposits, the locations where fluid pathways along faults and permeable zones intersect reactive carbonate rocks are the control on the location of the replacement zones.

GENETIC MODEL: A number of models for dolomitization have been suggested by the scientific community.

- Hypersaline water from a shelf lagoon percolated through the underlying sediment, transforming calcium carbonate into dolomite.
- Burial compaction resulting in expulsion of pore water containing Mg^{2+} from shales may react with adjacent limestones to form dolomite.
- Elevated topography of a mountain thrust belt provides the hydrodynamic potential for gravity-driven meteoric fluids which became enriched in soluble components, including Mg^{2+}, that react with calcium carbonate beds in the subsurface to form stratiform dolomite zones.
- Tectonic loading and compression during the buildup of orogenic thrust belts may cause the rapid expulsion of formation fluids into the foreland basins and bring the necessary Mg^{2+} to react with limestone deposits in the basin.

The two models listed below are currently the most popular explanation for most of global dolomites.

- Dolomitization can occur within the mixing zone of phreatic sea water with fresh groundwater. The Mg^{2+} ions for dolomitization are derived primarily from seawater. The delivery mechanism is the continual circulation of seawater induced by the flow of fresh groundwater.
- Deep convection circulation of basinal brines has been invoked for forming some regional subsurface dolomites. Deep crustal scale convection of meteoric ground waters to 10 kilometres depth appears to have been the dominant subsurface flow during Early Tertiary time in southeastern B.C. Thermal convection can support long-lived flow systems that are capable of cycling subsurface solutions many times through the rock mass. Alternately thermal convection can occur in strata beneath the sea bed, the sea water-derived solutions would be continuously added to the system to provide an ongoing source of magnesium.

ASSOCIATED DEPOSIT TYPES: Mississippi Valley Type Pb, Zn (E12), barite (E17) and fluorspar (E11) deposits, limestone (R09), accumulations of oil and natural gas, hydrogen sulphide.

COMMENTS: Most dolomite production is as quarried rock for use as aggregate which relies mainly on its physical properties.

R10 - Dolomite

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High magnesium in carbonate rock.

GEOPHYSICAL SIGNATURE: While karst features in dolomite are rather uncommon, resistivity and gravity could be used to outline karst affected areas.

OTHER EXPLORATION GUIDES: Sometimes yellow or brown colour of outcrops, sandy talus. Because of lower solubility, dolomite does not fizz with diluted hydrochloric acid.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Commercial dolomite must be very high purity carbonate rock, and almost stochiometric in composition (30.4% CaO and 21.9% MgO). Industry specifications are set for the calcined product – i.e. a dolomitic lime. Depending on the end use, the limits for impurities are usually between 0.1 and 4.5% Fe_2O_3, SiO_2 between 0.5 and 1.0%, and Al_2O_3 between 0.3 and 0.8%.

ECONOMIC LIMITATIONS: Information on dolomite production is difficult to obtain. In mineral statistic data, dolomite is covered together with limestone, and individual uses are frequently confidential. It is estimated, that USA and Canada together produce 500,000 tonnes of calcined dolomite annually. The quantity of dolomite used as a granular or ground industrial product is not relatively small. Dolomite used for magnesium metal may be as much as one million tonnes annually, but is gradually being replaced by other sources, such as seawater. Some limestone operators produce dolomite and limestone from different beds as coproducts.

END USES: Refractory products, magnesium metal ore, dolomitic lime, glass, desulphurization of coal, iron and steel, smelter flux, variety of fillers, mineral wool, agriculture soil conditioner.

IMPORTANCE: As a source of magnesium to improve a fluidity of molten product, like in mineral wool. float glass, slag in metallurgical process very important. As agriculture soil conditioner the magnesium content improves the neutralizing power, and helps to retain the soil nutrients better than pure limestone. In many other end uses dolomite can be substituted by some other industrial minerals.

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R11 - Volcanic Ash/Cinder and Pumice

By Z.D. Hora [1]

Hora, Z.D., 2007. Volcanic ash/cinder and pumice: mineral deposit profile R11, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Volcanic scoria, volcanic ejecta, agglomerate, pyroclastics, lapilli, tuff.

COMMODITIES: Lightweight aggregate, landscaping aggregate, anti-skid sand, stonewashing pumice, “lava (barbecue) rock”, pozzolan, abrasive powders, absorbents, insulation fill, filler, filtration media.

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): PUMICE - Mt. Meager (092JW040), Salal Creek (092JW039), Mt. Meager, Bridge River ash, Nazco cone, Wells Grey Park; *Bend (Oregon), Mono Crater, San Bernardino (California), Flagstaff (Arizona), Grant, Albuquerque (New Mexico), Lipari (Italy), Thyra (Greece), Haparangi, Waitahanaui, Mihi (New Zealand)*. CINDER – Nazco (093G/4), Wells Grey Park, *Flagstaff (Arizona), Grant, Albuquerque (New Mexico), San Bernardino (California)*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Unconsolidated pumice, cinder and other pyroclastic deposits are usually found near a volcanic vent or edifice. It is typically the vesicular pyroclastic material that is exploited because of its appearance or attractive strength to weight ratio. Pumice occurs in felsic pyroclastic flows, air-fall blankets and flow domes; cinder usually forms basaltic pyroclastic tephra cones and blankets.

TECTONIC SETTINGS: Volcanic arcs and rift zone belts.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Pumice in calderas, lava flow dome complexes and Plinian-type central eruptions. Blanket deposits are found in the vicinity of stratovolcanoes.

AGE OF ROCK FORMATION: Any age, although preserved deposits are commonly Tertiary to recent. In Canada, older deposits are commonly eroded by glaciation.

HOST/ASSOCIATED ROCK TYPES: Ash, lapilli and agglomerate pyroclastic deposits. Associated with lava flows, high-level dikes, ash flows and flow domes. All these rock types can vary in composition from rhyolite to basalt.

DEPOSIT FORM: Cinder cones can be elliptical or circular in plan view, or elongated in the case of a fissure vent. Individual cones can be up to hundreds of metres high and more than a kilometre in diameter. The largest cinder cone in USA and Canada, located near Flagstaff, Arizona, is 1 kilometre in diameter and 200 metres in height. Larger cinder cones may be seen in active volcanic regions. Airfall ejecta form blankets composed of multiple units that can be 5 to 13 metres thick (Bend, Oregon). The Mazama ash covers area of 5,200 square kilometres with thicknesses of 1 to 3 metres.

TEXTURE/STRUCTURE: Clinker-like, rough, irregular fragments of lava thrown out by explosive eruption. Pumice and cinder are composed of vesicular, volcanic glass that may contain minor phenocrysts of feldspar, various forms of quartz, mica and/or a number of ferromagnesian minerals. Pyroclastic flows, flow domes and sometimes cinder cones consist of unsorted particle sizes. Air-fall blankets are usually sorted with particle size decreasing with distance from the eruption centre and intensity of the eruption.

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R11 - Volcanic Ash/Cinder and Pumice

ORE: Pumice, cinder, volcanic ash, bombs, blocks.

GANGUE (Principal and *Subordinate*): Fragments and blocks of solid rock (cognate and accidental) in pumice deposits; lava flows and dikes in cinder cones. *Native sulphur and highly altered pumice and cinder in near-vent area.*

ALTERATION MINERALOGY: Clay minerals, alunite, zeolites, hematite, limonite.

WEATHERING: Weathered pyroclastics may deteriorate physically into smaller, dust-sized particles and chemically into palagonite, clay minerals, limonite, jarosite and alunite. In both cases, this can reduce the value of the material significantly.

ORE CONTROLS: Pumice, a product of highly viscous rhyolite magma, commonly forms an ash-fall blanket surrounding the source vent. Its thickness depends on intensity and longevity of eruption. Large volumes of pumice and pumiceous rhyolite also accumulate in the upper parts of rhyolite and obsidian flow domes, as well in ash-flow tuffs in calderas. Volcanic cinder, because of low viscosity and higher density of the mafic magma, is more concentrated in proximity to the vent as cone-shaped deposits.

GENETIC MODEL: The formation of highly vesicular rocks involves the interplay of temperature, viscosity, gas pressure and gas diffusion rates within the erupting magma, and external conditions, such as wallrock permeability, water influx and vent blockage. Conditions that reduce gas escape may lead to violent eruptions, during which the suddenly released pressure results in the expansion of volatiles in frothy masses of expelled lava. These cool quickly in the atmosphere to form glass fragments with innumerable bubble cavities. Basaltic magmas tend to be relatively fluid, allowing more gases to escape and producing less vesicular ejecta (cinder). Silicic magmas are more viscous and offer less opportunity for gas to escape. Therefore, pumice can be extremely vesicular and can float in water. In rhyolite flow domes, pumiceous rhyolite flow breccias are associated with perlite or obsidian flows and felsic dikes.

ASSOCIATED DEPOSIT TYPES: Perlite (R12), open and closed system zeolites (D01, D02), andesite dimension stone (R05). Secondary deposits are produced by erosion of primary deposits and subsequent deposition in stream and river beds, for example, in Kansas and Oklahoma, USA, or along the Waikato and Wanganui.Rivers in New Zealand.

COMMENTS: Free silica is a potential health hazard in rhyolite pumice, and dusty material must be handled accordingly. Natural clinker, rocks heated by burning underground coal seams, can be used as an alternative to volcanic cinder.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: For pumice, look for rhyolite compositions.

GEOPHYSICAL SIGNATURE: Ground penetrating radar can delineate structure and thickness of a pyroclastic deposit. Shallow seismic surveys can help to outline the presence of lave flows or dikes in cinder cones, as well as the boundary between pumiceous rhyolite and non-porous rock facies.

OTHER EXPLORATION GUIDES: Proximity to volcanic vents, particularly on the downwind side; areas with remnant volcanic edifices. Remote sensing and air photo interpretation are useful to map the limits of cinder and pumice blanket areas.

R11 - Volcanic Ash/Cinder and Pumice

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits range in size from 10,000 to 10 million tonnes, although occasionally, deposits may reach 400 million tonnes in size. The average production from a single deposit in western USA is approximately 35,000 tonnes per year for cinder and 10,000 tonnes per year for pumice. Use of a lightweight aggregate has several ASTM specifications for particle sizing and unit weight. So do some specific end uses, like stone washing, for example.

ECONOMIC LIMITATIONS: Lightweight aggregate transportation costs ultimately determine the geographic extent of the market as it can be substituted by expanded shales and similar products. Only specialty products, like 'barbecue lava rock', stone washing pumice, absorbents, landscaping cinder and filter media can reach more distant markets. The demand for these specialty products is only a fraction of total production.

END USES: The main use for pumice is as lightweight aggregate in concrete and masonry, with smaller quantities consumed for in horticulture, stone washing, abrasives and filter media, and pozzolan. Volcanic cinder is also used as lightweight aggregate, in landscaping, as road and highway aggregate and for skid control on icy highways.

IMPORTANCE: Regionally important as a specialty aggregate, but represents only a small portion of the overall aggregate market in North America (0.1% in the year 2000).

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R12 - Perlite

by Z.D. Hora[1]

Hora, Z.D., 2007. Perlite: mineral deposit profile R12, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Onion skin rhyolitic glass, pitchstone, obsidian.

COMMODITIES (BYPRODUCTS): Expanding perlite (pumice, foundry flux, synthetic zeolite feedstock)

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Frenier (092O072), Francois Lake (093K 001), Uncha Lake (093F 026); *Mount Tuzo (Quebec), No Agua, Grants, Socorro (New Mexico, USA), Caliente (Nevada, USA), Malad City (Idaho, USA), Greece, Italy, Turkey*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Hydrated volcanic glass, usually of rhyolite composition, formed through secondary alteration by the incorporation of water into the glass/silica structure. It is often distinguished by vitreous, pearly luster and concentric (onion skin) fractures. When heated, it will expand up to ten to forty times its original volume.

TECTONIC SETTINGS: Orogenic rift belts and volcanic arcs.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Rapidly cooled volcanic rocks of rhyolite composition occurring as the glassy parts of domes and flows, vitric tephra, chill margins of dikes and sills, and welded ash-flow tuffs.

AGE OF MINERALIZATION: Normally Tertiary through middle Quaternary, occasionally older.

HOST/ASSOCIATED ROCK TYPES: Perlite is hosted by flow domes and lava flows of rhyolite composition. Most obsidian contains less than 1% of total water (water left after heating to 105°C), the hydration of perlite increases the water content level to 2 to 5%, but may reach as much as 10%. It is associated with vitric tephra, ash-flow tuffs, pumiceous rhyolite and pumicite.

DEPOSIT FORM: Perlite deposits are very irregular in shape, reflecting the original extent of the glassy volcanic rock and the zones that have experienced significant hydration. The boundaries are usually gradational from perlite to obsidian to devitrified volcanic glass to a crystalline felsite core. Perlite deposits are usually measured in hundreds of metres in horizontal dimensions and metres to tens of metres in the vertical dimension. Big Pine deposit in California has a perlite thickness of 27 metres; Picketpost Mountain in Arizona is 2 to 17 metres thick. The No Agua Peaks deposit in New Mexico is considered the largest in North America and is 50 metres thick, covering 10 square kilometers. The Socorro perlite deposit in New Mexico is 200 metres thick and covers an area of 0.7 square kilometers.

TEXTURE/STRUCTURE: Many flows and domes are texturally zoned, reflecting the rapid cooling of exterior surfaces and slower crystallization within the interior. The glass mantle can occur at the base, margin, and/or near the top of the flow. Hydration and resulting perlitic cracks due to expansion by the incorporation of water are superimposed on primary textures of flow. Perlite can have classical, concentric, and arcuate onion skin-like fractures with remnant obsidian kernels; a granular texture with obsidian remnants absent; or a pumiceous and vesicular character.

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R12 - Perlite

ORE: Expandable hydrated siliceous volcanic glass. Most commercial perlites are 'high silica rhyolites' with 75 to 77.5% of SiO_2. In a few countries, obsidian and pitchstone are also expanded.

GANGUE MINERALOGY (Principal and *subordinate*): Non-hydrated obsidian, devitrified glass, microlites or small phenocrysts of feldspar, mica and quartz; sometimes with *chalcedony and clay fracture filling.*

ALTERATION MINERALOGY: Since volcanic glass is unstable, devitrification changes Tertiary age or older volcanic glass into a microcrystalline equivalent (there may be some rare exceptions of older volcanic glass being preserved). Hydrothermal alteration can introduce clay minerals and/or chalcedony and can produce deposits of halloysite.

WEATHERING: Because of high fracture density, exposed perlite is highly susceptible to both physical and chemical weathering. Chemical weathering can be very fast in humid and temperate climate conditions. Weathering products such as palagonite, clay minerals and calcium carbonate are commonly present as infilling of cracks and fissures. Excessive fines and clay presence may render the perlite deposit uneconomic.

ORE CONTROLS: Perlite forms carapaces that partially or fully comprise extrusive domes and flows, tephra and tuff beds, where percolating meteoric water had access to hydrate the glassy volcanic material. Since felsic flows are viscous, most perlite deposits from proximal to the volcanic vent.

GENETIC MODEL: Glassy component of rhyolite volcanic rocks wherever accessible to percolating meteoric water, mostly on top, but sometimes also at the bottom of the dome flow. Hydration of obsidian and the formation of perlite is a gradual process, coincident with the inward migration of meteoric water into glass selvages and its incorporation into glass structure as molecular water. Hydration rate slows with decreasing temperature and with increasing calcium and magnesium content in the glass. The rate increases with increasing silica content.

ASSOCIATED DEPOSIT TYPES: Pumice, pumiceous rhyolite (R11).

COMMENTS: Petrological definition of perlite covers all glass with perlitic texture, including the non-expanding varieties. The presence of crystalline silica is considered as a potential health hazard, and the product has to be controlled and handled accordingly. Some perlites are sensitive to decrepitation. This can be controlled by preheating and by adjusting the temperature regime during the expansion process.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Felsic volcanics with more than 65% silica, preferably greater, up to 75%; water contents of 2 to 10%.

GEOPHYSICAL SIGNATURE: Hydrated glass can be distinguished from non-hydrated obsidian by electrical properties.

OTHER EXPLORATION GUIDES: A small portable blow torch is the most effective field test. A potential perlite either expands or decrepitates; non-expanding rock just glows red. Detailed mapping must delineate rock types, perlite textures and the abundance of contaminants, such as clay, felsite, phenocrysts and obsidian. A great variability of textures and zonation require careful deposit modeling. For drilling the potential deposit, the core diameter must be large enough to ensure high and representative core recovery.

R12 - Perlite

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Average perlite has an expanded density between 20 and 40 kg per cubic metre. Some deposits can contain up to 15% non-perlite material. The quality of perlite products is controlled by performance standards developed by the Perlite Institute, as well as ASTM specifications. Deposits range in size from less than 5 Mt to more than 100 Mt. The Frenier deposit produced 6000 tonnes over 3 years from an inferred reserve of 3.8 Mt. In New Zealand, the Maungaiti dome, and at Awana, on Great Barrier Island, there are 20 Mt and 100 Mt of inferred resources respectively. Annual production in North America is reported between 500,000 and 600,000 tonnes annually. It comes from 10 production centres in western USA.

ECONOMIC LIMITATIONS: Perlite is usually mined from open pits (the Caliente deposit in Nevada is underground) and processed in expanding plants located in market areas. Raw perlite is shipped by truck, or by rail and boat to more distant processing plants. The average capacity of an expanding plant is about 10,000 tonnes per year. As a relatively large volume product, perlite products are sensitive to transportation costs.

END USES: Crushed perlite is heated to between 900 and 1200°C to create steam in the molten rock that produces gas bubbles. The product is cooled to form globules of artificial pumice. The light, fluffy globules are known commercially as ‘perlite’ and marketed with different brand names. They have a porous texture with low density and thermal conductivity and high sound absorption and chemical stability. Construction uses, such as insulation products and acoustic tile, accounted for 66% of North American consumption in the late 1990s. Horticulture and a variety of fillers accounted for 19%, and filter aid products make up the remaining 15%.

IMPORTANCE: Important for horticulture and for construction products. Expanded perlite has a very limited number of substitutes; therefore, it can be shipped considerable distances. For example, Greece has exported perlite to the eastern seaboard of North America, while New Mexico supplies Canada and numerous eastern US locations.

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R13 - Nepheline Syenite

by Z.D. Hora[1]

Hora, Z.D., 2009. Nepheline syenite: mineral deposit profile R13, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYM: Undersaturated granitoids

COMMODITIES (BYPRODUCTS): Nepheline syenite (magnetite, apatite)

EXAMPLES (British Columbia (MINFILE) - *Canada/International*):

- **Sodium Feldspar-rich:** Trident Mountain (082M 173), Mount Copeland (082M 002); *Blue Mountain, (Ontario), Fourche Mountain, Arkansas, Wind Mountain, New Mexico, Stjernoy Island, Norway, Khibina Massif, Russia*.
- **Potassium Feldspar-rich:** No producers yet. Kruger Mountain (082ESW106), Barriere (092P 159).

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sodium Feldspar Rich: Small alkalic intrusive bodies of white, granular feldspathic rocks composed essentially of soda and potash feldspars and nepheline, with accessory biotite, hornblende, magnetite, apatite, sodalite and cancrinite.

TECTONIC SETTINGS: Nepheline syenites are found in continental settings and at convergent plate boundaries.

- **Sodium Feldspar-rich:** Continental environment generally associated with extensional faulting and major rift zones and grabens that can control extensive alkaline igneous provinces. Economic deposits of nepheline and apatite are associated with this setting.
- **Potassium Feldspar-rich:** In orogenic belts, commonly oceanic volcanic island arcs overlying oceanic crust. Magmatism with alkalic composition varies from gabbro to nepheline syenite. The magmas are introduced inboard parallel to the axis of the arc that coincides with deep-seated faults.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING:

- **Sodium Feldspar-rich:** Intrusive bodies and plugs, differentiated ring complexes frequently associated with carbonatites; sills, dikes and layered intrusives that intrude Precambrian to Mesozoic continental clastic and carbonate rocks. Many known ages predate major regional unconformities and may be manifestations of crustal upwelling and extension.
- **Potassium Feldspar-rich:** High level stock emplacement levels in magmatic arcs. The high level stocks and related dikes intrude their coeval and cogenetic volcanic equivalents.

AGE OF MINERALIZATION:

- **Sodium Feldspar-rich:** Mid-Proterozoic to Eocene. Recent volcanoes along the Kenya Rift.
- **Potassium Feldspar-rich:** Archean to Cretaceous, in Canadian Cordillera mostly Late Triassic to Early Jurassic.

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R13 - Nepheline Syenite

HOST/ASSOCIATED ROCK TYPES:

- **Sodium Feldspar-rich:** A broad spectrum of sedimentary rocks and their metamorphic equivalents / carbonatite complexes with a variety of nepheline containing intrusive rocks, fenites.
- **Potassium Feldspar-rich**: Multiple emplacement of successive intrusive phases with composition from alkalic gabbro to syenite. The most undersaturated nepheline normative rocks commonly contain pseudoleucite. Volcanic equivalents are mostly basic in composition and only rarely phonolite.

DEPOSIT FORM: **Sodium Feldspar-rich:** Intrusive bodies in a variety of shapes, including dikes, sills, stocks and small plutons and layered complexes. Two production centres in Ontario are mining 200 to 300 metre wide zones of biotite/magnetite/muscovite facies of a nepheline syenite intrusion. The intrusion is 1 by 4 kilometres at surface; with a 400 metre wide apophysis extending 6 kilometres to the southwest. In Norway, an underground mine is exploiting a hornblende/pyroxene facies of nepheline syenite, which forms about 80% of lenticular body 1800 metres long and up to 300 metres wide.

TEXTURE/STRUCTURE: A typical nepheline syenite ore deposit is a relatively uniform rock consisting of albite, microcline, nepheline and a few percent of mafic minerals, namely magnetite, biotite and hornblende. The rock is typically white, medium grained, with an open granitic texture. The rock mined in Norway is well foliated. For commercial use in glass and ceramics the mafic minerals must be coarse grained enough to allow for separation at about 20 mesh. Under the microscope, the texture may suggest a metasomatic process had a role in the rock`s composition.

ORE MINERALOGY (Principal and *subordinate*):

- **Sodium Feldspar-rich:** Albite, microcline and nepheline, often apatite, *magnetite; cancrinite, sodalite, calcite.* In some nepheline syenites, apatite with zirconium and titanium minerals can attain rock-forming proportions.
- **Potassium Feldspar-rich:** Magnetite and apatite may form high grade accumulations of economic interest.

GANGUE MINERALOGY (Principal and *subordinate)*

- **Sodium Feldspar–rich:** Magnetite, biotite, hornblende; zircon, corundum, pyroxene, sphene, apatite.
- **Potassium Feldspar-rich:** Pyrite in apatite/magnetite deposits.

ALTERATION MINERALOGY: Zeolite, prehnite, kaolin, also cancrinite and sodalite are considered alteration products. Nepheline also alters readily to a variety of poorly known secondary products, usually more or less micaceous and variously referred to as hydronephelite and giesekite.

WEATHERING: The weathered surface varies from a dove-grey to distinctly bluish colour. This and the pitted surface are the most distinctive characteristics for recognition in field. Intense lateritic weathering of nepheline syenite may produce economic deposits of bauxite (for example, Pocos de Caldas, Brazil).

ORE CONTROLS: Nepheline syenite occurs as alkalic intrusions with strong structural control. Specific phases in albite-rich nepheline syenites can be ore if they are easy to process into a low iron commercial product free of detrimental minerals like corundum.

GENETIC MODEL: Nepheline syenite occurs as undersaturated, alkali – rich leucocratic magma intrusive bodies with a metasomatic alkali overprint. They are generally small, discordant intrusions, with few signs of forceful emplacement. Simple stoping and emplacement along ring fractures and as a consequence of cauldron subsidence have all been proposed as intrusion mechanisms. Common mafic minerals are mica, amphibole and pyroxene. The contacts between intrusive phases is transitional in both Blue Mountain and Stjernoy Island deposits. In the Khibina massif complex intrusion, the sequence of rock units from oldest to youngest developed from peridotite to pyroxenite to potassium-rich nepheline syenite to nephelinite to carbonatite. An apatite-rich unit is part of the potassium-rich nepheline syenite phase. Syenite gneiss complexes are likely the metamorphosed and deformed equivalents of original nepheline syenites intrusions. Some have been interpreted as possible products of fenitization and metasomatism.

R13 - Nepheline Syenite

ASSOCIATED DEPOSIT TYPES: Apatite-rich phase in ultramafic complexes, carbonatite hosted deposits (N01).

COMMENTS: The former USSR developed an aluminum industry based on processing originally wasted nepheline produced in large volumes from apatite mining that has operated since 1941. This industry was developed for strategic reasons because of the lack of domestic bauxite deposits. Phonolite is a fine grained volcanic equivalent of nepheline syenite. Leucocratic varieties of phonolite are used in some countries in place of nepheline syenite for making coloured types of container glass.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sodium Feldspar-Rich type is more sodium rich, while the Potassium Feldspar-Rich type is more potassic.

GEOPHYSICAL SIGNATURE: Magnetic and IP surveys can distinguish between nepheline syenite intrusions and many types of surrounding rocks.

OTHER EXPLORATION GUIDES: Explore for nepeheline syenite intrusions that are generally small and elongate in shape. In complex intrusions the later phases seem to be more likely to have lower iron contents and be more nepheline-rich. Detailed geological mapping and petrographical study can assist with identifying attractive intrusive phases. Uniformity, grain size which will allow to separate mafic minerals from a commercial product, absence of refractory minerals. White colour is desirable for filler applications.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits can be volumetrically very large, although often only a portion can be mined at a profit. Typical nepheline syenite produced from the Blue Mountain deposit in Ontario has 60.2% SiO_2, 23.5% Al_2O_3, 0.08% Fe_2O_3, 10.6% Na_2O and 5.1% K_2O. The higher the nepheline content the better. The annual output in Canada is between 500,000 and 600,000 tonnes from two production centers in Ontario. Only sodium feldspar-rich are of economic interest.

ECONOMIC LIMITATIONS: As a typical bulk and low cost product, nepheline syenite is not usually shipped very far. Canadian deposits are mined as open pits, while the deposit in Norway is mined by underground methods because it has suitable morphology and it minimizes the impact of severe winters. For nepheline syenite to be an economic resource it must be reasonably uniform, light coloured, medium to coarse grained with minimal mafic mineral intergrowths. The rock should be, rather massive or only moderately gneissic. The absence of refractory minerals, like corundum or zircon, is a must for glass grade product.

END USES: Traditional uses are glass (70 to 80%) and ceramics (15%). The other major use is in filler applications which is steadily increasing. Nepheline syenite is also favoured as blasting sand, since it contains no free silica which is considered a health hazard.

IMPORTANCE: Nepheline syenite is the preferred source of alumina and alkalies for glass manufacturing. In some countries with phonolite resources, the nepheline syenite volcanic equivalent is used for coloured glass in spite of a much higher iron content. In markets more distant from nepheline syenite sources, a feldspar resource (alaskite, aplite, leucocratic granitoids, feldspathic sands) is used instead. Glass recycling is increasingly important secondary source of a raw material for new glass products. Blast furnace slag and “calumite” (artificial slag prepared as glass raw material) are also used in some types of glass products.

R13 - Nepheline Syenite

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R14 - Feldspar-Rich Rocks (Alaskite)

by Z. D. Hora[1]

Hora, Z.D., 2009. Feldspar-rich rocks (Alaskite): mineral deposit profile R14, Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, published on website, 3 pp.

IDENTIFICATION

SYNONYMS: Feldspar, sodaspar, feldspar ore, feldspar rock, leucogranite, aplite, leucosyenite.

COMMODITIES (BYPRODUCTS / COPRODUCTS): Feldspar (silica, mica)

EXAMPLES (British Columbia (MINFILE) - *Canada/International*): Boundary Creek (082ESE224), Sumas Mountain (092GSE037), *Spruce Pine, North Carolina, Monticello, Georgia, Montpelier, Virginia, Middletown, Connecticut*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Feldspathic igneous rocks are the source, like alaskite, porphyritic leucogranites, aplite and rhyolite. Leucocratic facies of medium to coarse grained granitic intrusive bodies with only very minor or absent coarser grained mafic minerals (generally less than 5%). The mafic minerals must be in larger grains or aggregates for easy separation by a simple, preferably dry method. Such granitic rocks should have feldspar as the main constituent and silica subordinate or absent.

TECTONIC SETTING(S): In orogenic belts, probably related to subduction related magmatism. High level, well differentiated bodies that crystallized slowly.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High level magma emplacement in volcano-plutonic arcs, frequently in association with fields of pegmatite dikes.

AGE OF MINERALIZATION: Early Paleozoic for the classical deposit, but can be part of any orogenic granitic complex.

HOST/ASSOCIATED ROCK TYPES: Pegmatite and granodiorite-granite-syenite intrusive rocks, commonly porphyritic / sedimentary and metamorphic rocks.

DEPOSIT FORM: Intrusive bodies of irregular shape, in the classical area of North Carolina up to 1600 meters wide and 3200 metres long.

TEXTURE/STRUCTURE: Massive, may have foliated appearance close to contacts, with inclusions of country rock. The grain size may vary, in the average about 1.25 centimetres in diameter, locally coarser near the intrusive`s center, but less than 0.5 centimetre near the contact. In the Spruce Pine district the post-magmatic recrystallization produced a “mortar-like” structure where relatively large grains of feldspar, quartz and muscovite 5 to 10 mm in diameter are enclosed in a fine-grained recrystallized matrix of feldspar, quartz and muscovite with epidote. (resulting from removal of Fe from muscovite).

ORE MINERALOGY (Principal and *Subordinate*): The classical deposit has 40% oligoclase, 20% quartz, 20% microcline and 15% muscovite.

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R14 - Feldspar-Rich Rocks (Alaskite)

GANGUE MINERALOGY (Principal and *Subordinate*): Biotite, garnet; apatite, allanite, epidote, thulite, pyrite and pyrrhotite. In general do not exceed in total some 5%. Reported Fe_2O_3 content of rock is 0.33%.

ALTERATION MINERALOGY: Secondary albitization, sericite. epidote.

WEATHERING: Kaolinization of feldspar.

ORE CONTROLS: Uniformity of rock composition, particularly in feldspar/quartz relationship and quantity of iron containing minerals. Grain size and form of distribution of mafics and other accessories. Grain sizes are important to separate feldspar and quartz from mafic minerals within commercial sized particles (glass 20 – 100 mesh).

GENETIC MODEL: Late stage intrusion of alkali rich leucocratic magma into slowly cooling environment, sometimes in more than one stage. In case of Spruce Pine district the oligoclas/microcline composition of feldspars may suggest either very slow cooling or recrystallization. The rock structure of larger isometric grains in fine-grained matrix support the recrystallization idea. Also, the silica in Spruce Pine alaskite is almost free of fluid inclusions. The age of associated pegmatite field of 380 Ma is coincident with waning regional metamorphism. Postmagmatic recrystallization is also suspected for removal of many impurities (including fluid inclusions) from quartz grains.

ASSOCIATED DEPOSIT TYPES: Pegmatite deposits of feldspar, mica, beryl, lithium, REE.

COMMENTS: Feldspathic sands and gravels are an alternative source of Na, K, and Al in many regions worldwide. In British Columbia Scuzzy Creek (092HNW052) is an example of a feldspathic sand occurrence. Partially kaolinitized granites can successfully replace feldspar in some ceramic products.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Feldspar and silica, no mafic minerals – High K, Na, Al, Si; low Fe, Mg, Ca.

GEOPHYSICAL SIGNATURE: Depends on local geology. In some circumstances the feldspar-rich rock may have contrasting properties from the host rock – electric, magnetic, density, gamma – which could be used in geophysics to prospect for or explore an feldspathic target. Presence of Fe minerals may be contrasting in using the magnetic or IP methods.

OTHER EXPLORATION GUIDES: Resistance to weathering can be good prospecting tool in areas of weak host rocks.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Uniformity of the rock is more important than relative content of Na, K, Al and Si. Important is the Fe_2O_3, which should be below 0.1%, and absence of refractory minerals like zircon, corundum or spinel. Also, the end use can make a difference – some industries prefer more potassic than sodium feldspar. In 2001, North America produced some 800,000 tonnes of feldspar, of which about half came from three alaskite production centers in North Carolina. Another 12%, of a potassic feldspar used for more special end uses came from the producer of leucogranite in Georgia. The bulk of the rest came from feldspathic sands and a small fraction as a co-product from pegmatites.

ECONOMIC LIMITATIONS: Feldspar Corporation of Middletown, Connecticut shut down in 1991 its aplite processing plant, when its production capacity of 90,000 tonnes per year suffered the market reduction to 37% as a result of competition with nepheline syenite from Ontario sources. Feldspar, as all low priced bulk commodities is transportation sensitive, and feldspar resource in a variety of deposit types is distributed through many parts of North America.

R14 - Feldspar-rich Rocks (Alaskite)

END USES: Main uses for feldspar is in glass (~60%) and ceramics (~35%) manufacturing. The remaining 5% is used as a specialty fillers, abrasives and some other minor uses. Very high purity silica (in the order of 10 to 100 ppm impurities) is very important co-product from Spruce Pine district, North Carolina, and is exported for high-tech product manufacturing globally (QUINTAs and IOTA grades).

IMPORTANCE: Production of glass and ceramics requires feldspar (or nepheline syenite). Alaskite and other feldspar-rich rocks is a very important resource, since the bodies are suitable for large scale, inexpensive mining and processing techniques. The deposits location is convenient for economic transportation to glass and ceramic plants in southeast USA. The high purity silica from Spruce Pine is the only major producer worldwide.

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S - Other

	Profile Title	Author
S01	Broken Hill type Pb-Zn-Ag±Cu	T. Höy, 1996

‘* An asterisk after alphanumeric code indicates that there is no published mineral deposit profile description.

S01 - Broken Hill-Type Pb-Zn-Ag+/-Cu

By Trygve Höy[1]

Höy, T., 1996. Broken Hill-Type Pb-Zn-Ag+/-Cu: In: Selected mineral deposit profiles, volume 2 - metallic deposits, Ministry of Employment and Investment, British Columbia Geological Survey Open File 1996-13, pp. 117–120.

IDENTIFICATION

SYNONYMS: Shuswap-type, Ammeburg-type Zn-Pb, Jervois-type.

COMMODITIES (*BY-PRODUCTS)*: Pb, Zn, Ag, *(Cu, Au, barite*).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Cottonbelt (082M 086), River Jordan (082M 001), Ruddock Creek (082M 082-084), Big Ledge? (082LSE012), Colby? (082ESW062); *Broken Hill and Pinnacles (New South Wales, Australia); Broken Hill and Black Mountain, Aggeneys district and Gammsberg area (South Africa), Knalla and Nygruvan, Bergslaggen district (Sweden).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits comprise massive to semi-massive galena, sphalerite, pyrrhotite and pyrite and/or magnetite layers or stacked lenses hosted by thin-bedded, commonly calcareous paragneiss successions. A complex gangue mineralogy includes a variety of calcsilicate minerals. These stratabound deposits are typically thin, but laterally extensive and were deformed and metamorphosed together with their hostrocks.

TECTONIC SETTING: In strongly deformed and metamorphosed supracrustal rocks commonly referred to as ‘mobile belts’ which probably originated in an intracratonic rift or possibly continental margin setting.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Marine sediments and associated minor bimodal (?) volcanics (often felsic, possibly alkalic) reflect active extensional tectonics. Host successions include inferred evaporites and are generally interpreted as shallow marine. Underlying gneissic successions suggest some deposits formed on or along margins of tectonic highs. However, intense deformation and metamorphism have commonly masked relationships.

AGE OF MINERALIZATION: Commonly Lower and Middle Proterozoic; some British Columbia deposits may be hosted by Late Proterozoic to Cambrian rocks.

HOST/ASSOCIATED ROCK TYPES: Hosted by thin-bedded calcareous schists, impure marble, quartzites and, less commonly, graphitic schists. A common and important host rock is garnet quartzite which occurs as envelopes to the sulphide bodies; associated with well layered and heterogenous successions of quartzite, crystalline marble, quartzo-feldspathic gneiss, hornblende gneiss, and abundant pelitic and calcareous schist and gneiss; locally associated carbonatite and amphibolite. Banded iron formations, chert, gahnite quartzites and tourmalinites are common in the host stratigraphic succession as distal facies or in the footwall successions. Scapolite-rich units and sulphur isotopes suggest associated evaporites. Metamorphic grades vary from amphibolite to granulite.

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[1] British Columbia Geological Survey, Victoria, British Columbia, Canada

S01 - Broken Hill-Type Pb-Zn-Ag+/-Cu

DEPOSIT FORM: Stacked sulphide or sulphide/magnetite lenses are common; they are thin, irregular, discontinuous, strongly deformed massive sulphide bodies. Thickening in fold hinges is often critical to make economic thicknesses. Individual lenses vary from less than a metre to tens of metres and may extend hundreds of metres often grading laterally into quartzite, quartz gahnite, garnet quartzite or pyrite/pyrrhotite disseminated units that may persist for tens of kilometres.

TEXTURE/STRUCTURE: Mineralization occurs as discontinuous massive to semimassive sulphide lenses or as disseminated stratabound sulphides. Sulphides are massive to irregular banded, with locally coarse “skarn” textures; locally well layered or laminated sulphides and silicates occur. They are commonly medium to coarse grained and intimately intergrown with gangue calcsilicate minerals, quartz or magnetite; as well, there are occasional thin monominerallic sulphide layers. Disseminated sulphides are common in granular marble. Pegmatitic zones are present in some ore zones.

ORE MINERALOGY (Principal and *subordinate*): Galena, sphalerite, magnetite, pyrrhotite, pyrite; *chalcopyrite, tetrahedrite, molybdenite, arsenopyrite, löllingite*. In some deposits magnetite makes up more than 40% of the ore. Some deposits display zoning from siliceous Zn-rich to distal carbonate-silicate Pb-Ag rich ore.

GANGUE MINERALOGY (Principal and *subordinate*): Quartz, garnet, calcite, rhodonite, magnetite, siderite, pyroxenes and amphiboles, commonly manganiferous, fluorite; *Mn olivine, apatite, gahnite, plagioclase, biotite, chlorite, ankerite, epidote, graphite, barite, hematite, wollastonite, sillimanite, staurolite, vesuvianite*. The complex gangue mineralogy is a characteristic of Broken Hill-type deposits.

ALTERATION MINERALOGY: Original alteration assemblages are replaced by a complex variety of metamorphic minerals. Alteration envelopes and deposit zoning are common in larger deposits, but are generally not recognized in smaller ones. Footwall alteration pipes are generally not recognized, except for some of the Cu-rich deposits, which complicates their interpretation**.** Typically the alteration reflects enrichment of Fe, Si, Mn, Ca, P, F, K and CO_3 and includes metamorphic silicates including amphiboles, olivine, biotite, phlogopite, sillimanite, orthoclase and clinozoisite as well as carbonates, fluorite and a variety of other minerals. Spessartine-quartz halos surround many deposits, with more regional silicification (quartz) and K (sillimanite) enrichment. In the Broken Hill area, Australia, with increasing intensity of mineralization, Fe-Si-Mn systems (typical of metamorphosed iron formations) are overprinted by extreme Ca-Mn-F enrichment with calcsilicate assemblages.

WEATHERING: Large gossans are not common; however, pyrrhotite and pyrite in some deposits locally produce rusted outcrops. Some Australian deposits have deep weathered zones: gossanous quartz-garnet-gahnite rocks, with abundant Mn and Fe oxides at surface, and secondary Ag enrichment at depths associated with oxides (goethite and coronadite) and carbonates (dolomite, cerussite and smithsonite). Leached sulphides mark the transition into underlying sulphide ore.

ORE CONTROLS: Not well understood; deposits appear to be restricted to Proterozoic “mobile belts”, generally interpreted to be intracratonic rifts. Oxidized shallow-marine basins, possibly developed due to extensional faulting above basement highs, and associated bimodal (?) volcanism are local controls.

GENETIC MODEL: Difficult to interpret due to high metamorphic grades. A sedimentary exhalite origin, with sulphide deposition in rapidly deepening rifts, is preferred because the deposits are associated with iron formations, chert and Mn-rich iron oxide facies. This environment, dominated by oxidized facies, contrasts with reduced, anoxic basins that commonly host sedex deposits. However, associated bimodal volcanics, ore and gangue chemistry and sulphide textures suggest similarities with volcanogenic massive sulphide deposition. Some workers have supported replacement models for the mineralization.

ASSOCIATED DEPOSIT TYPES: Sedimentary exhalative Pb-Zn deposits (E14), carbonatites (N01), nepheline syenites, polymetallic veins (I05) and W-Mo veins.

COMMENTS: Broken Hill-type deposits are a difficult exploration target due to their setting in strongly metamorphosed and deformed rocks.

S01 - Broken Hill-Type Pb-Zn-Ag+/-Cu

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalous enrichments of Mn, Cu, Au, Bi, Sb, W, Co and As in the ore and some proximal exhalative units; high Ag:Pb ratios, Mn and K enrichment (with muscovite, K-feldspars and sillimanite) in alteration halos; elevated base metal values (particularly Zn) and Mn in more regional iron formations. In silt samples expect anomalous Pb, Zn, Ag, Mn and Ba.

GEOPHYSICAL SIGNATURE: Deposits with associated magnetite produce strong magnetic anomalies. Electromagnetic and induced polarization surveys may detect those deposits with pyrrhotite and pyrite massive sulphides lenses. Associated graphite in some (*e.g.*, Big Ledge) may provide local targets.

OTHER EXPLORATION GUIDES: Main exploration guide is appropriate sedimentary/tectonic environment - thin-bedded succession of paragneisses with abundant carbonate. The mineralization may occur at, or near, the transition from quartzo-feldspathic basement rocks to fine-grained clastic metasediments. Rapid lithologic facies changes in the vicinity of deposits may indicate local hydrothermal systems. Associated volcanism is indicative of extension or rifting. In closer proximity to deposits, unusual mineral assemblages include garnet quartzites, gahnite quartzites and Mn-rich calcsilicates with skarn textures.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits frequently occur in clusters with numerous small, uneconomic deposits. Broken Hill-type targets average less than 5 to 20 Mt, but may be in excess of 100 Mt (Broken Hill, Australia: 280 Mt containing 10.0% Pb, 8.5% Zn and 148 g/t Ag, including approximately 150 Mt of more that 20% Pb+Zn). Grades are variable, commonly with 2 to 10 % Pb, 2 to 8% Zn and 10 to 150 g/t Ag. Some deposits contain no byproduct copper, others have 0.1 to 1% Cu. In British Columbia, known deposits range in size from less than one million to 6.5 Mt; geological reserves may be considerably larger. Grades range from approximately 2 to 5 % Zn and 2.5 to 6.5 % Pb with up to 50 g/t Ag. Ruddock Creek contains 5 Mt with 7.5% Zn, 2.5% Pb and Jordan River, 2.6 Mt with 5.6% Zn, 5.1% Pb and 35 g/t Ag.

ECONOMIC LIMITATIONS: Structural thickening is often critical to the genesis of economic deposits. Broken Hill-type deposits have not been mined in British Columbia, due mainly to their form - thin, though laterally persistent layers - and their location in remote, mountainous terrains.

IMPORTANCE: These deposits are an important source for lead, zinc and silver, and remain an attractive exploration target in British Columbia.

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ACKNOWLEDGEMENTS: This description has drawn from information written up by Stephen Walters of BHP Exploration, Australia, and presented by Garry Davidson of CODES Key Centre, University of Tasmania at the 1995 MDRU short course, Metallogeny of Proterozoic Basins, in Vancouver.

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Appendix 1. Commodity listing of mineral deposit profiles (version 2.1 - 2020)

* - indicates the commodity can be a byproduct for that particular mineral deposit profile and also that a particular profile is not published.

Commodity	Deposit Type	Profile #
Ag	Gossan Au-Ag	B10*
Ag	Carbonate-hosted disseminated Au-Ag	E03
Ag	Sediment-hosted Cu	E04
Ag	Mississippi Valley-type Pb-Zn	E12
Ag	Irish-type carbonate-hosted Zn-Pb	E13
Ag	Sedimentary Exhalative Zn-Pb-Ag	E14
Ag	Carbonate-hosted, Nonsulphide Zn (hypogene)	E18
Ag	Besshi massive sulphide Cu-Zn	G04
Ag	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
Ag	Subaqueous hot spring Au-Ag	G07
Ag	Epithermal Au-Ag-Cu; high sulphidation	H04
Ag	Epithermal Au-Ag; low sulphidation	H05
Ag	Sn-Ag veins	H07
Ag	Alkalic intrusion-associated Au-Ag	H08
Ag	Intrusion-related Au pyrrhotite veins	I02
Ag	Polymetallic veins Ag-Pb-Zn±Au	I05
Ag	Five-element veins Ni-Co-As-Ag±(Bi,U)	I14
Ag	Polymetallic mantos Ag-Pb-Zn	J01
Ag	Sulphide manto Au	J04*
Ag	Pb-Zn skarns	K02
Ag	Subvolcanic Cu-Au-Ag (As-Sb)	L01
Ag	Broken Hill-type Pb-Zn-Ag±Cu	S01
Ag*	Laterite-Saprolite Au	B03*
Ag*	Buried-channel placers	C02
Ag*	Marine placers	C03
Ag*	Volcanic redbed Cu	D03
Ag*	Iron oxide breccias and veins ±P±Cu±Au±Ag±U	D07
Ag*	Kipushi Cu-Pb-Zn	E02
Ag*	Sandstone Pb	E05
Ag*	Carbonate-hosted barite	E10*
Ag*	Carbonate-hosted fluorspar	E11*
Ag*	Blackbird sediment-hosted Cu-Co	E15
Ag*	Cyprus massive sulphide Cu (Zn)	G05
Ag*	Hot spring Au-Ag	H03
Ag*	Au-quartz veins	I01
Ag*	Turbidite-hosted Au veins	I03
Ag*	Iron formation-hosted Au	I04
Ag*	Cu±Ag quartz veins	I06
Ag*	Silica-carbonate Hg	I08
Ag*	Vein barite	I10
Ag*	"Classical" U veins	I15
Ag*	Manto and stockwork Sn	J02
Ag*	Cu skarns	K01

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
Ag*	Fe skarns	K03
Ag*	Au skarns	K04
Ag*	Porphyry Cu-Au: alkalic	L03
Ag*	Porphyry Cu G486 Mo ± Au	L04
Ag*	Porphyry Sn	L06
Ag*	Porphyry W	L07
agate	Agate	Q03*
agate*	Opal deposits in volcanic sequences	Q11
aggregate	Sand and Gravel	B12
aggregate	Expanding shale	R02
aggregate*	Dimension stone - granite	R03
aggregate*	Dimension stone - marble	R04
aggregate*	Dimension stone - sandstone	R06
aggregate*	Limestone	R09
Al	Bauxite Al	B04*
Al*	Playa and Alkaline Lake Evaporites	F09*
alunite	Hydrothermal alteration clays	H09
amethyst	Amethyst	Q04*
analcime	Closed-basin zeolites	D02
andalusite	Andalusite schist and hornfels	P01
andalusite	Kyanite family minerals	P02
andesite	Dimension stone – “granite”	R03
anhydrite	Volcanogenic anhydrite / gypsum	G03*
anhydrite*	Bedded gypsum	F02
apatite	Iron oxide Cu±Au±P±REE	D07
apatite*	Magmatic Fe-Ti±V oxide deposits	M04
apatite*	Vermiculite deposits	M08
aquamarine*	Schist-hosted emerald deposits	Q07
As*	Volcanic-hosted U	D06
As*	Subaqueous hot spring Au-Ag	G07
As*	Epithermal Au-Ag-Cu; high sulphidation	H04
As*	"Classical" U veins	I15
As*	Subvolcanic Cu-Au-Ag (As-Sb)	L01
asbestos	Ultramafic-hosted asbestos	M06
Au	Laterite-Saprolite Au	B03*
Au	Gossan Au-Ag	B10*
Au	Surficial placers	C01
Au	Buried-channel placers	C02
Au	Marine placers	C03
Au	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
Au	Iron oxide Cu±Au±P±REE	D07
Au	Carbonate-hosted disseminated Au-Ag	E03
Au	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
Au	Subaqueous hot spring Au-Ag	G07
Au	Hot spring Au-Ag	H03

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodities	Deposit Type	Profile #
Au	Epithermal Au-Ag-Cu; high sulphidation	H04
Au	Epithermal Au-Ag; low sulphidation	H05
Au	Au-quartz veins	I01
Au	Intrusion-related Au pyrrhotite veins	I02
Au	Turbidite-hosted Au veins	I03
Au	Iron formation-hosted Au	I04
Au	Sulphide manto Au	J04
Au	Au skarns	K04
Au	Subvolcanic Cu-Au-Ag (As-Sb)	L01
Au	Porphyry-related Au	L02*
Au	Porphyry Cu-Au: alkalic	L03
Au	Porphyry Cu ± Mo ± Au	L04
Au	Plutonic-related Au quartz veins & veinlets	L09
Au*	Bog Fe, Mn, U, Cu, Au	B07*
Au*	Volcanic-hosted U	D06
Au*	Sediment-hosted Cu	E04
Au*	Blackbird sediment-hosted Cu-Co	E15
Au*	Shale-hosted Ni-Zn-Mo-PGE	E16
Au*	Besshi massive sulphide Cu-Zn	G04
Au*	Cyprus massive sulphide Cu (Zn)	G05
Au*	Hot-spring Hg	H02
Au*	Sn-Ag veins	H07
Au*	Polymetallic veins Ag-Pb-Zn±Au	I05
Au*	Cu±Ag quartz veins	I06
Au*	Silica veins	I07*
Au*	Silica-carbonate Hg	I08
Au*	Stibnite veins and disseminations	I09
Au*	Unconformity-associated U	I16
Au*	Polymetallic mantos Ag-Pb-Zn	J01
Au*	Cu skarns	K01
Au*	Pb-Zn skarns	K02
Au*	Fe skarns	K03
Au*	Mo skarns	K07
Au*	Gabbroid Ni-Cu-PGE	M02*
Au*	Broken Hill-type Pb-Zn-Ag±Cu	S01
barite	Mississippi Valley-type fluorite±barite	E11*
barite	Mississippi Valley-type Pb-Zn	E12
barite	Sedimentary-hosted stratiform barite	E17
barite	Vein fluorite-barite	I11
barite*	Surficial placers	C01
barite*	Buried-channel placers	C02
barite*	Volcanic-hosted U	D06
barite*	Iron oxide Cu±Au±P±REE	D07
barite*	Irish-type carbonate-hosted Zn-Pb	E13
barite*	Sedimentary Exhalative Zn-Pb-Ag	E14
barite*	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodities	Deposit Type	Profile #
barite*	Five-element veins Ni-Co-As-Ag±(Bi,U)	I14
barite*	Carbonatite-hosted deposits	N01
barite*	Broken Hill-type Pb-Zn-Ag±Cu	S01
Be	Rare element pegmatite - LCT family	O01
Be*	Rare element pegmatite - NYF family	O02
Bentonite	Bentonite	E06
bertrandite*	Vein fluorite-barite	I11
beryl	Columbia-type emerald deposits	Q06
beryl*	Surficial placers	C01
beryl*	Buried-channel placers	C02
beryl*	Schist-hosted emerald deposits	Q07
Bi	Five-element veins Ni-Co-As-Ag±(Bi,U)	I14
Bi*	Blackbird sediment-hosted Cu-Co	E15
Bi*	Sn-Ag veins	H07
Bi*	"Classical" U veins	I15
Bi*	Polymetallic mantos Ag-Pb-Zn	J01
Bi*	Manto and stockwork Sn	J02
Bi*	Mo skarns	K07
borate minerals*	Fe skarns	K03
calcite*	Carbonatite-hosted deposits	N01
carbon	Anthracite	A05
carbon dioxide*	Playa and Alkaline Lake Evaporites	F09*
Cd*	Mississippi Valley-type Pb-Zn	E12
Cd*	Irish-type carbonate-hosted Zn-Pb	E13
Cd*	Carbonate-hosted, nonsulphide Zn (hypogene)	E18
Cd*	Besshi massive sulphide Cu-Zn	G04
Cd*	Cyprus massive sulphide Cu (Zn)	G05
Cd*	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
Cd*	Sn-Ag veins	H07
Cd*	Manto and stockwork Sn	J02
Cd*	Pb-Zn skarns	K02
celestite	Bedded celestite	F04*
cement feedstock	Cement shale	R01
cement feedstock*	Sedimentary kaolin	E07
ceramic clay*	Sedimentary kaolin	E07
chabazite	Open-system Zeolites	D01
chabazite	Closed-basin zeolites	D02
chalcedony*	Opal deposits in volcanic sequences	Q11
chromite	Podiform chromite	M03
chromite*	Surficial placers	C01
chromite*	Buried-channel placers	C02
chrysoberyl*	Schist-hosted emerald deposits	Q07
cinnabar*	Surficial placers	C01
cinnabar*	Buried-channel placers	C02
clay (fireclay)	Sedimentary kaolin	E07
clinoptilolite	Open-system Zeolites	D01

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
clinoptilolite	Closed-basin zeolites	D02
Co	Blackbird sediment-hosted Cu-Co	E15
Co	Five-element veins Ni-Co-As-Ag±(Bi,U)	I14
Co*	Carbonate-hosted Cu-Pb-Zn	E02
Co*	Sediment-hosted Cu	E04
Co*	Besshi massive sulphide Cu-Zn	G04
Co*	Cyprus massive sulphide Cu (Zn)	G05
Co*	"Classical" U veins	I15
Co*	Fe skarns	K03
Co*	Gabbroid Ni-Cu-PGE	M02*
Co*	Magmatic Fe-Ti±V oxide deposits	M04
coal	Lignite	A02
coal	Sub-bituminous coal	A03
coal	Bituminous coal	A04
coal	Anthracite	A05
coal liquids	Lignite	A02
coal liquids	Sub-bituminous coal	A03
coal liquids*	Bituminous coal	A04
coke	Bituminous coal	A04
construction aggregate*	Residual kaolin	B05
corundum	Ultramafic-related corundum	Q09
corundum	Alkali basalt and lamprophyre-hosted sapphire	Q10
corundum*	Surficial placers	C01
corundum*	Buried-channel placers	C02
corundum*	Kyanite family minerals	P02
corundum*	Corundum in aluminous metasedimentary rocks	P06
Cu	Volcanic redbed Cu	D03
Cu	Iron oxide Cu±Au±P±REE	D07
Cu	Carbonate-hosted Cu-Pb-Zn	E02*
Cu	Sediment-hosted Cu	E04
Cu	Blackbird sediment-hosted Cu-Co	E15
Cu	Carbonate-hosted, nonsulphide Zn (hypogene)	E18
Cu	Besshi massive sulphide Cu-Zn	G04
Cu	Cyprus massive sulphide Cu (Zn)	G05
Cu	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
Cu	Epithermal Au-Ag-Cu; high sulphidation	H04
Cu	Cu-Ag quartz veins	I06
Cu	Cu skarns	K01
Cu	Subvolcanic Cu-Au-Ag (As-Sb)	L01
Cu	Porphyry Cu-Au: alkalic	L03
Cu	Porphyry Cu ± Mo ± Au	L04
Cu	Basaltic subvolcanic Cu-Ni-PGE	M01*
Cu	Gabbroid Ni-Cu-PGE	M02*
Cu*	Bog Fe, Mn, U, Cu, Au	B07*
Cu*	Surficial placers	C01
Cu*	Buried-channel placers	C02

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
Cu*	Sandstone U	D05
Cu*	Irish-type carbonate-hosted Zn-Pb	E13
Cu*	Sedimentary Exhalative Zn-Pb-Ag	E14
Cu*	Subaqueous hot spring Au-Ag	G07
Cu*	Epithermal Au-Ag; low sulphidation	H05
Cu*	Sn-Ag veins	H07
Cu*	Au-quartz veins	I01
Cu*	Intrusion-related Au pyrrhotite veins	I02
Cu*	Iron formation-hosted Au	I04
Cu*	Polymetallic veins Ag-Pb-Zn±Au	I05
Cu*	Vein barite	I10
Cu*	Vein fluorite-barite	I11
Cu*	“Classical” U veins	I15
Cu*	Polymetallic mantos Ag-Pb-Zn	J01
Cu*	Manto and stockwork Sn	J02
Cu*	Pb-Zn skarns	K02
Cu*	Fe skarns	K03
Cu*	Au skarns	K04
Cu*	W skarns	K05
Cu*	Mo skarns	K07
Cu*	Porphyry-related Au	L02*
Cu*	Porphyry Mo (Low F- type)	L05
Cu*	Magmatic Fe-Ti±V oxide deposits	M04
Cu*	Carbonatite-hosted deposits	N01
Cu*	Broken Hill-type Pb-Zn-Ag±Cu	S01
dawsonite*	Playa and Alkaline Lake Evaporites	F09*
diamond	Kimberlite-hosted diamonds	N02
diamond	Lamproite-hosted diamonds	N03
diamond*	Surficial placers	C01
diamond*	Buried-channel placers	C02
diamond*	Marine placers	C03
diamond*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
diatomite	Lacustrine diatomite	F06*
dolomite	Dolomite	R10*
emerald	Columbia-type emerald deposits	Q06
emerald	Schist-hosted emerald deposits	Q07
emerald*	Surficial placers	C01
emerald*	Buried-channel placers	C02
emery*	Corundum in aluminous metasedimentary rocks	P06
erionite	Closed-basin zeolites	D02
Fe	Laterite Fe	B01*
Fe	Bog Fe, Mn, U, Cu, Au	B07*
Fe	Iron oxide breccias and veins ±P±Cu±Au±Ag±U	D07
Fe	Lake Superior & Rapitan types iron-formation	F10
Fe	Ironstones	F11
Fe	Algoma-type iron-formation	G01

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
Fe	Fe skarns	K03
Fe*	Carbonate-hosted, nonsulphide Zn (hypogene)	E18
feldspar	Nepheline syenite	R13
feldspar*	Rare element pegmatite – NYF family	O02*
feldspar*	Muscovite pegmatite class	O03*
filler (white)*	Dimension stone – “marble”	R04
filler (white)*	Limestone	R09
fluorite	Vein fluorite-barite	I11
fluorite	Carbonatite-hosted deposits	N01
fluorite	Mississippi Valley-type fluorite±barite	E11
flourite*	Volcanic-hosted U	D06*
flourite	Mississippi Valley-type Pb-Zn	E12
garnet	Garnet skarns	K08
garnet*	Surficial placers	C01
garnet*	Buried-channel placers	C02
garnet*	Marine placers	C03
garnet*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
garnet*	Andalusite schist and hornfels	P01
garnet*	Kyanite family minerals	P02
gas*	Lignite	A02
gas*	Sub-bituminous coal	A03
gas*	Bituminous coal	A04
gemstones*	Rare element pegmatite - NYF family	O02
granite	Dimension stone - granite	R03
graphite	Microcrystalline graphite	P03
graphite	Crystalline flake graphite	P04
graphite	Vein graphite	P05
gravel	Sand and Gravel	B12
gypsum	Bedded gypsum	F02
gypsum	Volcanogenic anhydrite / gypsum	G03*
gypsum*	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
hematite*	Carbonatite-hosted deposits	N01
Hg	Almaden Hg	E01*
Hg	Hot-spring Hg	H02
Hg	Silica-carbonate Hg	I08
Hg*	Subaqueous hot spring Au-Ag	G07
Hg*	Hot spring Au-Ag	H03
hydromagnesite	Playa and Alkaline Lake Evaporites	F09*
ilmenite*	Surficial placers	C01
ilmenite*	Buried-channel placers	C02
ilmenite	Marine placers	C03
In*	Sn-Ag veins	H07
In*	Manto and stockwork Sn	J02
Ir*	Podiform chromite	M03
Ir*	Alaskan-type PGE	M05
jade	Jade (nephrite)	Q01

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
jade*	Ultramafic-hosted asbestos	M06
jasper	Jasper	Q05*
jasper*	Opal deposits in volcanic sequences	Q11
kaolin	Residual kaolin	B05
kaolin	Hydrothermal alteration clays	H09
kaolin*	Muscovite pegmatite class	O03*
kyanite	Kyanite family minerals	P02
lime*	Dimension stone – “marble”	R04
magnesite	Sparry magnesite	E09
magnesite	Cryptocrystalline ultramafic-hosted magnesite veins	I17
magnesite	Ultramafic-hosted talc-magnesite	M07
magnesite*	Marine placers	C03
magnetite	Cu skarns	K01
magnetite	Fe skarns	K03
magnetite	Garnet skarns	K08
magnetite	Ultramafic-hosted asbestos	M06
magnetite*	Surficial placers	C01
magnetite*	Buried-channel placers	C02
magnetite*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
magnetite*	Sn skarns	K06
magnetite*	Alaskan-type Pt±Os±Rh±Ir	M05
magnetite*	Carbonatite-hosted deposits	N01
mica	Muscovite pegmatite class	O03*
mica*	Andalusite schist and hornfels	P01
Mn	Sedimentary Manganese	F01
Mn	Volcanogenic Mn	G02
Mn	Epithermal Mn	H06*
Mn*	Bog Fe, Mn, U, Cu, Au	B07*
Mn*	Carbonate-hosted, nonsulphide Zn (hypogene)	E18
Mn*	Algoma-type iron-formation	G01
Mn*	Polymetallic veins Ag-Pb-Zn±Au	I05
Mo	Shale-hosted Ni-Zn-Mo-PGE	E16
Mo	Mo skarns	K07
Mo	Porphyry Cu ± Mo ± Au	L04
Mo	Porphyry Mo (Low F- type)	L05
Mo	Porphyry Mo (Climax-type)	L08
Mo*	Volcanic-hosted U	D06
Mo*	Besshi massive sulphide Cu-Zn	G04
Mo*	W veins	I12*
Mo*	"Classical" U veins	I15
Mo*	Cu skarns	K01
Mo*	W skarns	K05
Mo*	Porphyry W	L07
monazite*	Marine placers	C03
mordenite	Open-system Zeolites	D01
mordenite	Closed-basin zeolites	D02

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
muscovite*	Kyanite family minerals	P02
Nb	Carbonatite-hosted deposits	N01
Nb	Rare element pegmatite - LCT family	O01
Nb*	Rare element pegmatite - NYF family	O02
nepheline	Nepheline syenite	R13
Ni	Laterite Ni	B02*
Ni	Shale-hosted Ni-Zn-Mo-PGE	E16
Ni	Five-element veins Ni-Co-As-Ag±(Bi,U)	I14
Ni	Basaltic subvolcanic Cu-Ni-PGE	M01*
Ni	Gabbroid Ni-Cu-PGE	M02*
Ni*	Blackbird sediment-hosted Cu-Co	E15
Ni*	"Classical" U veins	I15
Ni*	Magmatic Fe-Ti±V oxide deposits	M04
onyx*	Travertine	H01
opal	Sedimentary-hosted opal deposits	Q08
opal	Opal deposits in volcanic sequences	Q11
Os*	Podiform chromite	M03
Os*	Alaskan-type Pt±Os±Rh±Ir	M05
palygorskite	Palygorskite	F05*
Pb	Carbonate-hosted, Nonsulphide Zn–Pb (supergene)	B09
Pb	Carbonate-hosted Cu-Pb-Zn	E02
Pb	Sandstone Pb	E05
Pb	Mississippi Valley-type Pb-Zn	E12
Pb	Irish-type carbonate-hosted Zn-Pb	E13
Pb	Sedimentary Exhalative Zn-Pb-Ag	E14
Pb	Carbonate-hosted, nonsulphide Zn (hypogene)	E18
Pb	Besshi massive sulphide Cu-Zn	G04
Pb	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
Pb	Polymetallic veins Ag-Pb-Zn±Au	I05
Pb	Polymetallic mantos Ag-Pb-Zn	J01
Pb	Pb-Zn skarns	K02
Pb	Broken Hill-type Pb-Zn-Ag±Cu	S01
Pb*	Sediment-hosted Cu	E04
Pb*	Mississippi Valley-type fluorite±barite	E11
Pb*	Blackbird sediment-hosted Cu-Co	E15
Pb*	Sedimentary-hosted stratiform barite	E17
Pb*	Subaqueous hot spring Au-Ag	G07
Pb*	Epithermal Au-Ag; low sulphidation	H05
Pb*	Sn-Ag veins	H07
Pb*	Alkalic intrusion-associated Au-Ag	H08
Pb*	Vein barite	I10
Pb*	Vein fluorite-barite	I11
Pb*	Manto and stockwork Sn	J02
Pb*	Mo skarns	K07
Pd*	Shale-hosted Ni-Zn-Mo-PGE	E16
peat	Peat	A01

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
perlite	Perlite	R12
PGE	Surficial placers	C01
PGE	Buried-channel placers	C02
PGE*	Sediment-hosted Cu	E04
PGE*	Gabbroid Ni-Cu-PGE	M02*
phenacite*	Vein fluorite-barite	I11
phillipsite	Open-system Zeolites	D01
phillipsite	Closed-basin zeolites	D02
phlogopite*	Fe skarns	K03
phosphate	Upwelling-type phosphate	F07
phosphate	Warm current-type phosphate	F08*
phosphate	Carbonatite-hosted deposits	N01
phosphate*	Sedimentary Manganese	F01
pozzolan*	Expanding “shale”	R02
Pt	Alaskan-type Pt±Os±Rh±Ir	M05
Pt*	Shale-hosted Ni-Zn-Mo-PGE	E16
pumice	Volcanic ash/cinder and pumice	R11
pyrophyllite	Hydrothermal alteration clays	H09
quartz	Silica-rich rocks	R07
quartz	Feldspar-rich rocks (alaskite)	R14
Ra	Rare element pegmatite - LCT family	O01*
Rb	Rare element pegmatite - LCT family	O01*
red ochre*	Gossan Au-Ag	B10*
REE	Volcanic-hosted U	D06
REE	Carbonatite-hosted deposits	N01
REE	Rare element pegmatite - NYF family	O02*
REE*	Marine placers	C03
REE*	Iron oxide Cu±Au±P±REE	D07
refractory claystone	Sedimentary kaolin	E07
Rh*	Alaskan-type PGE	M05
rhodonite	Rhodonite	Q02
rhodonite*	Volcanogenic Mn	G02*
rip-rap	Crushed rock	R15
rip-rap*	Dimension stone – “granite”	R03
rip-rap*	Dimension stone – “marble”	R04
rip-rap*	Dimension stone - sandstone	R06*
Ru*	Podiform chromite	M03
ruby	Corundum in aluminous metasedimentary rocks	P06
ruby	Ultramafic-related corundum	Q09
ruby	Alkali basalt and lamprophyre-hosted sapphire	Q10
ruby*	Surficial placers	C01
ruby*	Buried-channel placers	C02
rutile	Marine placers	C03
rutile*	Surficial placers	C01
rutile*	Buried-channel placers	C02
S	Gypsum-hosted sulphur	F03

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
S*	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
sand	Sand and Gravel	B12
sapphire	Corundum in aluminous metasedimentary rocks	P06
sapphire	Alkali basalt and lamprophyre-hosted sapphire	Q10
sapphire*	Buried-channel placers	C02
Sb	Stibnite veins and disseminations	I09
Sb*	Volcanic-hosted U	D06
Sb*	Subaqueous hot spring Au-Ag	G07
Sb*	Epithermal Au-Ag-Cu; high sulphidation	H04
Sb*	Au-quartz veins	I01
Sb*	Turbidite-hosted Au veins	I03
Sb*	Silica-carbonate Hg	I08
Sb*	Manto and stockwork Sn	J02
Sb*	Subvolcanic Cu-Au-Ag (As-Sb)	L01
Se*	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
silica	Silica veins	I07*
silica	Hydrothermal alteration clay	H09
silica	Quartz pegmatite	O04*
silica	Silica-rich rocks	R07
silica sand*	Residual kaolin	B05
silica*	Muscovite pegmatite class	O03*
sillimanite	Kyanite family minerals	P02
Sn	Surficial placers	C01
Sn	Marine placers	C03
Sn	Sn-Ag veins	H07
Sn	Sn veins and greisens	I13*
Sn	Manto and stockwork Sn	J02
Sn	Sn skarns	K06
Sn	Porphyry Sn	L06
Sn*	Surficial placers	C01
Sn*	Buried-channel placers	C02
Sn*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
Sn*	Besshi massive sulphide Cu-Zn	G04
Sn*	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
Sn*	Polymetallic mantos Ag-Pb-Zn	J01
Sn*	W skarns	K05
Sn*	Mo skarns	K07
Sn*	Porphyry W	L07
Sn*	Porphyry Mo (Climax-type)	L08
Sn*	Rare element pegmatite - LCT family	O01*
soda ash	Playa and Alkaline Lake Evaporites	F09*
soil conditioner	Travertine	H01
sphene*	Surficial placers	C01
spinel*	Buried-channel placers	C02
spodumene	Rare element pegmatite - LCT family	O01
Sr*	Carbonatite-hosted deposits	N01

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
staurolite*	Surficial placers	C01
staurolite*	Buried-channel placers	C02
staurolite*	Andalusite schist and hornfels	P01
staurolite	Kyanite family minerals	P02
stone (building)	Travertine	H01
stone (building)	Dimension stone - marble	R04
stone (building)	Dimension stone - sandstone	R06
stone (flagstone)	Flagstone	R08
stone (limestone)	Limestone	R09
Ta*	Carbonatite-hosted deposits	N01
Ta*	Rare element pegmatite - NYF family	O02*
talc	Carbonate-hosted talc	E08
talc	Ultramafic-hosted talc-carbonate	M07
tar*	Lignite	A02
tar*	Sub-bituminous coal	A03
tar*	Bituminous coal	A04
Th*	Marine placers	C03
Th*	Carbonatite-hosted deposits	N01
Th*	Volcanic-hosted U	D06
Ti	Marine placers	C03
Ti	Magmatic Fe-Ti±V oxide deposits	M04
Ti*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
Ti*	Carbonatite-hosted deposits	N01
topaz*	Surficial placers	C01
topaz*	Buried-channel placers	C02
topaz*	Schist-hosted emerald deposits	Q07
tourmaline*	Surficial placers	C01
tourmaline*	Buried-channel placers	C02
tourmaline*	Schist-hosted emerald deposits	Q07
U	Surficial U	B08
U	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
U	Sandstone U±V	D05
U	Volcanic-hosted U	D06*
U	Five-element veins Ni-Co-As-Ag±(Bi,U)	I14
U	"Classical" U veins	I15
U	Unconformity-associated U	I16
U	Rare element pegmatite - NYF family	O02*
U*	Bog Fe, Mn, U, Cu, Au	B07*
U*	Iron oxide Cu±Au±P±REE	D07
U*	Sediment-hosted Cu	E04
U*	Mo skarns	K07
U*	Carbonatite-hosted deposits	N01
V	Sandstone U±V	D05
V*	Sediment-hosted Cu	E04
V*	Carbonate-hosted, nonsulphide Zn (hypogene)	E18
V*	Magmatic Fe-Ti±V oxide deposits	M04

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
V*	Carbonatite-hosted deposits	N01
vermiculite	Vermiculite	M08
vermiculite	Carbonatite-associated deposits	N01
W	W veins	I12*
W	W skarns	K05
W	Porphyry W	L07
W*	Sn-Ag veins	H07
W*	Turbidite-hosted Au veins	I03
W*	Sn veins and greisens	I13*
W*	Cu skarns	K01
W*	Pb-Zn skarns	K02
W*	Sn skarns	K06
W*	Mo skarns	K07
W*	Porphyry Mo (Low F- type)	L05
W*	Porphyry Sn	L06
W*	Porphyry Mo (Climax-type)	L08
wolframite*	Surficial placers	C01
wollastonite	Wollastonite skarns	K09
wollastonite*	Garnet skarns	K08
Y	Rare element pegmatite - NYF family	O02*
Y*	Marine placers	C03
zircon	Marine placers	C03
zircon*	Surficial placers	C01
zircon*	Buried-channel placers	C02
zircon*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	C04*
Zn	Carbonate-hosted, nonsulphide Zn-Pb (supergene)	B09
Zn	Carbonate-hosted Cu-Pb-Zn	E02*
Zn	Mississippi Valley-type Pb-Zn	E12
Zn	Irish-type carbonate-hosted Zn-Pb	E13
Zn	Sedimentary Exhalative Zn-Pb-Ag	E14
Zn	Carbonate-hosted, nonsulphde Zn (hypogene)	E18
Zn	Besshi massive sulphide Cu-Zn	G04
Zn	Noranda / Kuroko massive sulphide Cu-Pb-Zn	G06
Zn	Polymetallic veins Ag-Pb-Zn±Au	I05
Zn	Polymetallic mantos Ag-Pb-Zn	J01
Zn	Pb-Zn skarns	K02
Zn	Broken Hill-type Pb-Zn-Ag±Cu	S01
Zn*	Sediment-hosted Cu	E04
Zn*	Sandstone Pb	E05
Zn*	Mississippi Valley-type fluorite±barite	E11
Zn*	Blackbird sediment-hosted Cu-Co	E15
Zn*	Shale-hosted Ni-Zn-Mo-PGE	E16
Zn*	Sedimentary-hosted stratiform barite	E17
Zn*	Cyprus massive sulphide Cu (Zn)	G05
Zn*	Subaqueous hot spring Au-Ag	G07
Zn*	Epithermal Au-Ag; low sulphidation	H05

Appendix 1. Commodity listing of mineral deposit profiles (cont.)

Commodity	Deposit Type	Profile #
Zn*	Sn-Ag veins	H07
Zn*	Alkalic intrusion-associated Au-Ag	H08
Zn*	Vein barite	I10
Zn*	Vein fluorite-barite	I11
Zn*	Manto and stockwork Sn	J02
Zn*	W skarns	K05
Zn*	Sn skarns	K06
Zn*	Mo skarns	K07
Zr*	Carbonatite-hosted deposits	N01

Appendix 2. Earth material affinities of the mineral deposit profiles (version 2.1 - 2020)

The one or two most common earth materials associated with the different mineral deposit profiles are listed below. The secondary association is indicated by brackets. Profiles that have no published model have an asterisk following their deposit group code alphanumeric number in the right-hand column.

Appendix 2 – Earth material affinities of the mineral deposit profiles

DEPOSIT TYPE	GLOBAL EXAMPLES	BC EXAMPLES	ID
	Deposit (Province, State or Country)		
UNCONSOLIDATED DEPOSITS			
Peat	Ireland, Ontario, New Brunswick	Fraser Delta, North Coast	A01
Bog Fe, Mn, U, Cu, Au	Trois Riviéres (Québec)	Whipsaw Ck, Limonite Ck	B07*
Surficial U	Flodelle Creek (Washington)	Prairie Flats	B08*
Residual			
Laterite Fe	Glenravel (Ireland), Araxa (Brazil)		B01*
Laterite Ni	Riddle (Oregon)		B02*
Laterite-saprolite Au	Boddington (Australia), Akaiwang (Guyana)		B03*
Bauxite Al	Pocos de Caldas (Brazil), Salem Hills (Oregon)	Florence (Sooke)	B04*
Residual kaolin	Germany, North Carolina, Idaho	Lang Bay, Sumas Mtn	B05
Carbonate-hosted, nonsulphide Zn-Pb	Balmat (USA), Skorpio (Nambia), (Peru)	Reeves MacDonald	B09
"Terra Rossa" Au-Ag	Rio Tinto (Spain)	Villalta	B10*
Alluvium			
Sand and gravel		Colwood Delta, Coquitlam	B12
Surficial placers	North Saskatchewan River, Nome (Alaska)	Fraser and Quesnel rivers	C01
Buried-channel placers	Livingstone Creek (Yukon), Valdez Ck (Alaska)	Williams Creek, Otter Ck	C02
Marine			
Marine placers	Australia (New South Wales, Queensland)	Middlebank	C03
SEDIMENTARY ROCKS			
CHEMICAL SEDIMENTARY ROCKS			
Shale-hosted Ni-Zn-Mo-PGE	Nick (Yukon), Tianeshan & Zunyi (China)		E16
Sedimentary Mn	Molongo (Mexico), Atasu (Kazakhstan)		F01
Palygorskite	Metalline Falls (Washington)		F05*
Phosphate, upwelling type	Phosphoria Formation (Idaho)	Fernie synclinorium	F07
Phosphate, warm-current type	Athabaska Basin (Saskatchewan), Florida		F08
Iron formation - Lake Superior & Rapitan	Mesabi Ranges (Minnesota), Crest (Yukon)	Falcon	F10

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
SEDIMENTARY ROCKS cont			
CHEMICAL SEDIMENTARY ROCKS cont			
Playa Evaporites			
Playas		Milk River	F09*
Lacustrine			
Marl		Cheam Lake (Chiliwack)	B11*
Marine Evaporites			
Bedded gypsum	Paris Basin (France), Appalachian Basins (USA)	Lussier River, Windermere	F02
Gypsum-hosted sulphur	Texas, Louisiana, Poland, Coronation (Alberta)	Trutch area	F03
Bedded celestite	Lake Enon (Nova Scotia), Mexico, Germany	Kitsault Lake	F04*
CARBONATE ROCKS			
No Associated Igneous Rocks			
Carbonate-hosted Cu±Pb±Zn	Kipushi (Zaire), Tsumeb (Namibia)		E02
Carbonate-hosted talc		Red Mountain, Silver Dollar	E08
Sparry magnesite	Eugui (Spain), Veitsch (Austria)	Mt. Brussilof, Driftwood Creek	E09
Mississippi Valley type fluorite±barite	Illinois - Kentucky, Italian Alps	Liard Fluorite	E11
Mississippi Valley type Pb-Zn	Viburnum Trend (Missouri), Pine Point (NWT)	Robb Lake, Monarch	E12
Kootenay Arc type Pb-Zn	Navin & Tynagh (Ireland)	Reeves MacDonald, H.B	E13
Travertine		Clinton, Slocan	H01
(Vein barite)		Muncho Lake	I10
(Polymetallic mantos Ag-Pb-Zn)		Bluebell	J01
(Sn mantos and stockworks)			J02
Sulphide manto Au	Ketza River (Yukon)	Mosquito Creek, Island Mtn	J04
Limestone		Texada Island, Quatsino Belt	R09
Dolomite		Crawford Bay, Rock Creek	R10

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
SEDIMENTARY ROCKS cont			
CARBONATE ROCKS cont.			
Associated Igneous Rocks			
Carbonate-associated disseminated Au-Ag	Carlin (Nevada, USA)	Golden Bear	E03
Polymetallic mantos Ag-Pb-Zn	East Tintic (Utah), Naico (Mexico)	Midway	J01
Sn mantos and stockworks	Renison Bell (Australia), Dachang district (China)		J02
Mn veins and replacements	Lake Valley (New Mexico),Phillipsburg (Montana)		J03*
(Cu skarn)	Mines Gaspé (Québec), Carr Fork (Yukon)	Craigmont, Phoenix	K01
Zn-Pb skarn	Yeonhwa-Ulchin District (S. Korea)	Piedmont, Contact	K02
(Fe skarn)	Shinyama (Japan)	Tasu, Jessie, Merry Widow	K03
(Au skarn)	Fortitude (Nevada), Buckhorn Mtn (Washington)	Nickel Plate	K04
(W skarn)	Cantung & Mactung (Yukon), Pine Ck (California)	Emerald Tungsten, Dimac	K05
(Sn skarn)	Lost River (Alaska), JC (Yukon)	Daybreak	K06
(Garnet skarn)		Crystal Peak	K08
(Wollastonite skarn)	Fox Knoll, Lewis (New York)	Mineral Hill	K09
CLASTIC SEDIMENTARY ROCKS			
Biogenic			
(Phosphate, upwelling type)	Phosphoria Formation (Idaho), Meskala (Morocco)	Fernie synclinorium	F07
(Phosphate, warm-current type)	Athabaska Basin (Saskatchewan), Florida		F08*
Clays			
(Bentonite)	Black Hills (Wyoming), Pembina (Manitoba)	Princeton, Quilchena	E06
Sedimentary kaolin	Cordova District (Alabama), Ozarks (Missouri)	Sumas Mountain, Quinsam	E07

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
SEDIMENTARY ROCKS cont.			
CLASTIC SEDIMENTARY ROCKS cont.			
Shale-Siltstone			
Lignitic coal	Estevan (Saskatchewan)	Skonun Point (Graham Island)	A02
Sub-bituminous coal	Highvale (Alberta), Powder River (Wyoming)	Hat Creek, Princeton	A03
Bituminous coal	Sydney Coalfield (Nova Scotia)	Quintette, Greenhills, Fording	A04
Anthracitic coal	Pennsylvannia Coalfields, Canmore (Alberta)	Mt Klappan	A05
(Carbonate-hosted disseminated Au-Ag)	Carlin (Nevada), Cortez (Nevada)		E03
Sediment-hosted Cu	Kupferschiefer (Germany), White Pine (Michigan)	Roo, Commerce	E04
Sedex Zn-Pb-Ag-S	Mount Isa (Australia), Faro, Grum (Yukon)	Cirque, Driftpile	E14
Blackbird massive sulphide Cu-Co	Blackbird & Sheep Creek (Montana)		E15
Shale-hosted Ni-Zn-Mo-PGE	Nick (Yukon), Tianeshan & Zunyi (China)		E16
Sediment-hosted barite	Tea (Yukon), Magcobar (Ireland)	Kwadacha	E17
Besshi massive sulphide Zn-Cu-Pb	Greens Creek (Alaska)	Goldstream, Windy Craggy	G04
Polymetallic veins Ag-Pb-Zn	Keno Hill (Yukon)	Highland Bell, Lucky Jim	I05
Cu-Ag quartz veins	Nikolai mine & Kathleen-Margaret (Alaska)	Davis-Keays, Churchill Cu	I06
Vein barite	Nevada	Parson, Brisco	I10
(Barite-fluorite veins)	Pforzheim-Naaburg (Germany)	Stone Mountain Park	I11
Columbia-type emerald deposits	Chivor and Muzo districts (Columbia)		Q06
Cement shale		Dunsmuir shale, Sumas Mtn	R01
Expanding shale	Wabamum shales (Alberta)	Nanaimo, Saturna Island	R02
Flagstone		Nipple Mountain	R08

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
SEDIMENTARY ROCKS			
CLASTIC SEDIMENTARY ROCKS cont.			
Sandstone			
(Sub-bituminous coal)			A03
(Bituminous coal)	Gregg River (Alberta)	Quintette, Bullmoose	A04
(Anthracitic coal)		Mt Klappan	A05
(Volcanic redbed copper)	Keewenaw (Michigan), Coppermine (NWT)	Sustut	D03
Sandstone U±V	Colorado Plateau, Grants (New Mexico)	Blizzard, Tyee	D05
(Iron oxide Cu±Au±P±U±REE)		Iron Range	D07
(Sediment-hosted Cu)	Dorchester (New Brunswick), Nacimento (New Mexico)	Sage Creek	E04
Sandstone Pb	Laisvall (Sweden), Largentiere (France)		E05
(Sedex Zn-Pb-Ag-S)			E14
(Blackbird massive sulphide Cu-Co)	Blackbird (Montana)		E15
Agate			Q03*
Australian-type opal	Coober Pedy (Australia)		Q08
Dimension stone - sandstone		Saturna Island, Newcastle Island	R06
Silica-rich rocks	Selkirk Silica (Manitoba)	Moberley	R07
Flagstone	Southowram (England)	Salmo	R08
Conglomerate and Sedimentary Breccia			
Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	Elliot Lake (Ontario), Witwatersrand (South Africa)		C04*
(Sandstone U±V)			D05

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
VOLCANIC ROCKS			
SUBAERIAL VOLCANIC ROCKS - Felsic-Mafic			
Mainly Volcanic Host			
(Open-system zeolites)	John Day Formation (Oregon)		D01
Volcanic redbed copper	Keewenaw (Michigan), Coppermine (Northwest Territories)	Sustut	D03
Volcanic-hosted U	Marysvale (Utah), Aurora (Oregon)	Rexspar, Bullion (Birch Island)	D06
Iron oxide Cu-Au-U breccias and veins	El Romeral (Chile), Sue-Dianne (NWT)		D07
Hot spring Au-Ag	McLaughlin (California), Round Mtn (Nevada)	Cinola	H03
Epithermal Au-Ag; high sulphidation	El Indio (Chile), Nansatsu (Japan)	Taseko property, Expo	H04
Epithermal Au-Ag; low sulphidation	Comstock (Nevada), Sado (Japan)	Lawyers, Blackdome	H05
Epithermal Mn	Talamantes (Mexico), Gloryana (New Mexico)		H06*
Polymetallic Sn veins	Black Range (New Mexico), Potosi (Bolivia)		H07
Hydrothermal clays	Tintic (Utah), Terrraced Hills (Nevada)	Monteith Bay, Pemberton Hills	H09
(Intrusion-related Au pyrrhotite veins)		Scottie	I02
(Cu-Ag quartz veins)	Nikolai mine & Kathleen-Margaret (Alaska)		I06
Silica veins		Granby Point	I07*
Vein barite-fluorite	Spor Mountain & Indian Peak District (Utah)	Rock Candy	I11
Volcanic-hosted opal	Querétaro State (Mexico)		Q11
Volcanic ash/cinder and pumice	Bend (Oregon), Flagstaff (Arizona)	Meagher Mountain	R11
Perlite	No Agua (New Mexico), Caliente (Nevada)	Frenier, Francois Lake	R12
Interbedded or Underlying Sedimentary Rocks			
Almaden Hg	Almaden (Spain), Santa Barbara (Peru)		E01*
Hot spring Hg	Sulphur Bank (California), Steamboat Springs (Nevada)	Ucluelet?	H02
(Subvolcanic shear-hosted gold)		Snip	I02
Silica-Hg carbonate	Red Devil? (Alaska)	Pinchi, Bralorne Takla	I08
Stibnite veins and disseminations	Jerritt Canyon (Nevada), Bolivia	Minto, Congress, Snowbird	I09
(Barite-fluorite veins)		Rock Canyon Creek	I11

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
VOLCANIC ROCKS cont.			
SUBAQUEOUS VOLCANIC ROCKS - Felsic-Mafic			
Mainly Volcanic Host			
Open-system zeolites	Death Valley (California), John Day Formation (Oregon)	Princeton Basin, Cache Creek area	D01
Closed basin zeolites	Bowie (Arizona), Lake Magadi (Kenya)		D02
(Volcanic-hosted U)	Marysvale (Utah), Aurora (Oregon)	Rexspar, Bullion (Birch Island)	D06*
Bentonite	Wyoming, Alberta, Rodalquilar (Spain)	, Hat Creek	E06
Lacustrine diatomite	Juntura Formation (Oregon), Lake Myvatn (Iceland)	Crownite Formation (Quesnel)	F06
Algoma-type iron formation	Vermillion iron formation (Minn.), Helen mine (Ontario)	Falcon, Lady A	G01
(Volcanogenic Mn)	North Island (New Zealand), Rio Tinto (Spain)		G02*
Volcanogenic anhydrite / gypsum		Britannia, Falkland	G03*
Noranda / Kuroko massive sulphide Cu-Pb-Zn	Horne & Millenbach (Québec), Kuroko District (Japan)	Britannia, Kutcho Creek, Myra Falls	G06
Subaqueous hot spring Ag-Au	Osorezan (Japan)	Eskay Creek	G07
Intrusion-related Au pyrrhotite veins		Johnny Mountain	I02
Rhodonite		Hill 60, Arthur Point, Cassiar	Q02
Jasper		Cowichan Lake district	Q05*
MARINE - Mafic (including ophiolites)			
(Blackbird massive sulphide Cu-Co)	Boleo (Mexico)		E15
Volcanogenic Mn	Olympic Mountains (Washington), Nicoya (Costa Rica)		G02*
(Besshi massive sulphide Zn-Cu-Pb)	Besshi (Japan)	Windy Craggy	G04
Cyprus massive sulphide Cu	Cyprus, Oman	Anyox, Chu Chua	G05
VOLCANIC ROCKS - Alkalic			
(Carbonatite-hosted deposits)		Mount Grace tuff	N01
Gem corundum hosted by alkalic rocks			Q10

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
INTRUSIVE ROCKS			
GRANITOID INTRUSIONS			
(Iron oxide Cu±Au±P±U±REE)	Olympic Dam (Australia)		D07
(Polymetallic Sn veins)		D Zone (Cassiar)	H07
(Hydrothermal clays)	Cornwall (England)		H09
"Classical" U veins	Roy Creek (Alaska), Massif Central (France)	Coryell intrusions, Surprise L.	I15
(Alkalic porphyry Cu-Au)	Tai Parit (Philippines)	Copper Mountain, Galore Ck	L03
Porphyry Cu ± Mo ± Au	Chuquicamata & La Escondida (Chile)	Highland Valley, Gibraltar	L04
Porphyry Mo	Quartz Hill (Alaska)	Endako, Kitsault	L05
Porphyry Sn	Llallagua (Bolivia), Potato Hills (Yukon)		L06
Porphyry W	Logtung (Yukon), Xingluokeng (China)	Boya	L07
Climax-type Porphyry Mo	Climax & Henderson (Colorado)		L08
(Rare element pegmatite - LCT family)			O01*
(Rare element pegmatite - NYF family)			O02*
(Muscovite pegmatite)			O03*
(Feldspar-quartz pegmatite)			O04*
Amethyst	Thunder Bay (Ontario)		Q04*
Dimension stone - granite	Riviére á Pierre (Québec), Black Hills (S. Dakota)	Nelson Island	R03
Alaskite	Spruce Pine alaskite (North Carolina)		R14
Coeval Volcanic Wallrocks			
(Epithermal Mn)	Talamantes (Mexico), Gloryana (New Mexico)		H06*
(Polymetallic veins Ag-Pb-Zn)		Silver Queen, Beaverdell	I05
Subvolcanic Cu-Ag-Au (As-Sb)	Lepanto (Philippines), Kori Kollo (Bolivia)	Equity Silver, Thorn	L01
Alkalic porphyry Cu-Au		Copper Mountain, Galore Ck	L03
(Porphyry Cu ± Mo ± Au)	Bajo de la Alumbrera (Argentina)	Island Copper, Fish Lake	L04
(Porphyry Sn)			L06

INTRUSIVE ROCKS cont.

DEPOSIT TYPE	SYNONYMS	GLOBAL EXAMPLES Deposit (Province, State or Country)	B.C. EXAMPLES	ID
GRANITOID INTRUSIONS cont.				
Calcareous Wallrocks				
(Carbonate-hosted talc)	Dolomite-hosted talc			E08
Cu skarn		Mines Gaspé (Québec), Carr Fork (Yukon)	Craigmont, Phoenix	K01
(Zn-Pb skarn)		Yeonhwa-Ulchin District (S. Korea), Darwin (California)	Piedmont, Contact	K02
(Fe skarn)				K03
(Au skarn)				K04
W skarn		Cantung (Yukon), Pine Creek (California), Salau (France)	Emerald Tungsten, Dimac	K05
Sn skarn		Lost River (Alaska)	Daybreak	K06
Mo skarn		Little Boulder Creek (Idaho), Mt. Tennyson (Australia)	Coxey, Novelty	K07
Garnet skarn			Crystal Peak	K08
(Wollastonite skarn)			Mineral Hill	K09
Other Wallrocks				
(Polymetallic Sn veins)				H07
(Gold-quartz veins)	Mesothermal, saddle reefs	Alaska-Juneau (Alaska), Red Lake (Ontario)		I01
(Polymetallic veins Ag-Pb-Zn)		Riverside (Alaska)	Porter-Idaho	I05
W veins	Quartz-wolframite veins	Pasto Bueno (Peru), Carrock Fell (England)		I12*
Sn veins and griesens		Cornwall (England), Lost River (Alaska)	Duncan Lake	I13*
Porphyry-related Au	Granitoid Au, Porphyry Au	Marte & Lobo (Chile)	Snowfields?	L02
(Climax-type Porphyry Mo)		Climax & Henderson (Colorado)		L08
Andalusite hornfels		Bushveld (South Africa), Brittany (France)	Leech River	P01
(Kyanite family)			Coast plutonic complex	P02
(Microcrystalline graphite)	"Amorphous" graphite	South Korea		P03
Gem corundum in contact zones		Umba (Tanzania), Kinyiki Hill (Kenya)		Q09
ANORTHOSITE INTRUSIONS				
Anorthosite Ti-V		Roseland (Virginia), Pluma Hidalgo (Mexico)		M04*
Calcareous Wallrocks				
Wollastonite skarn		Fox Knoll, Lewis (New York)		K09

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
INTRUSIVE ROCKS cont.			
MAFIC AND ULTRAMAFIC INTRUSIONS			
(Laterite Ni)	Riddle (Oregon)		B02*
(Surficial placers)		Atlin, Cassiar	C01
(Buried-channel placers)		Otter Creek	C02
(Gold-quartz veins)	Motherlode (California)	Bralorne, Erickson	I01
(Silica-Hg carbonate)	Red Devil? (Alaska)	Pinchi, Bralorne Takla	I08
Magnesite veins and stockworks	- -		I17
Podiform chromite	Josephine ophiolite (Oregon), Coto (Philippines)	Stuart Lake region	M03
Alaskan-type Pt±Os±Rh±Ir	Duke Island (Alaska)	Tulameen	M05
Asbestos	Thetford (Québec)	Cassiar	M06
Serpentinite-hosted magnesite-talc	Thetford & Magog (Québec), Deloro (Ontario)		M07
Vermiculite	Libby (Montana)	Fraser Lake	M08
Schist-hosted emerald deposits	Habachtal (Austria), Leysdorp (South Africa)		Q07
Jade (Nephrite)	Yukon, Alaska	Cry Lake, Ogden Mountain	Q01
Calcareous Wallrocks			
(Cu skarn)			K01
Fe skarn	Shinyama (Japan)	Tasu, Jessie, Merry Widow	K03
Au skarn	Fortitude (Nevada), Buckhorn Mtn (Washington)	Nickel Plate	K04
Coeval Volcanic Rocks			
Basaltic subvolcanic Cu-Ni-PGE	Noril'sk (Russia), Duluth (Minnesota)		M01*
Gabbroid Ni-Cu-PGE	Lynn Lake (Manitoba), Noril'sk (Russia)	Giant Mascot, Nickel Mtn	M02*
ALKALINE INTRUSIONS			
Alkalic intrusion-associated Au-Ag	Emperor (Fiji), Cripple Ck (Colorado)	Flathead, Howell	H08*
Kimberlite-hosted diamonds	Kimberley & Premier (South Africa)	Cross	N02
Lamproite-hosted diamonds	Argyle (Australia)		N03
Gem corundum in alkalic rocks	Yogo (Montana)		Q10
Nepheline syenite	Blue Mountain (Ontario)	Trident Mountain	R13*
Carbonatites			
(Vermiculite)	Palabora (South Africa)	Perry River	M08
Carbonatite-hosted deposits	Palabora (South Africa), Oka (Québec)	Aley	N01

Appendix 2 – Earth material affinities of the mineral deposit profiles cont.

DEPOSIT TYPE	GLOBAL EXAMPLES Deposit (Province, State or Country)	BC EXAMPLES	ID
REGIONALLY METAMORPHOSED ROCKS			
Carbonate-hosted talc	Treasure Mountain (Montana), Henderson(Ont.)		E08
Gold-quartz veins	Alaska-Juneau (Alaska)		I01
Turbidite-hosted gold veins	Ballarat (Australia), Meguma (Nova Scotia)	Frasergold	I03
Iron formation-hosted gold	Homestake (South Dakota)		I04
"Classical" U veins	Uranium City (Sask.) Schwartzwalder (Colorado)	Little Gem	I15
Unconformity-associated U	Key Lake (Saskatchewan), Jabiluka (Australia)		I16
(Asbestos)	Thetford (Québec)	Cassiar	M06
Rare element pegmatite - LCT family	Bikita Field (Zimbabwe), Blackhills		O01*
Rare element pegmatite - NYF family	South Platte district (Colorado), Bancroft (Ont.)		O02*
Muscovite pegmatite	Rajahstan (India), Appalachian Province (USA)		O03*
Feldspar-quartz pegmatite	Buckingham (Quebec)		O04*
Kyanite family	Willis Mountain (Virginia), NARCO (Québec)		P02
Microcrystalline graphite	Kieserberg (Austria)		P03
Crystalline flake graphite	Lac Knife (Québec)	AA	P04
Vein graphite	Calumet & Clot (Québec), Bogala (Sri Lanka)		P05
Corundum in aluminous metasediments	Gallatin & Madison Counties (Montana)		P06
(Schist-hosted emerald deposits)	Santana Dos Ferros & Itabira (Brazil)		Q07
(Dimension stone - granite)			R03
Dimension stone - marble	Vermont, Alabama, Georgia	Marblehead, Anderson Bay	R04
Silica-rich rocks		Moberley, Nicholson	R07
Flagstone		Revelstoke	R08

Addendum (2021)

New profiles for volcanogenic massive sulphide, porphyry, and mafic-ultramafic deposits

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1. Introduction

The British Columbia Geological Survey (BCGS) has initiated a multi-year mineral potential mapping project. The principal aim of the project is to identify areas of high prospectivity for key mineral systems across the province. The purpose is to assist government with land-use planning and deliver pre-competitive geoscience data to the mineral exploration industry. As a contribution to this project, this Addendum updates mineral deposit profiles for five volcanogenic massive sulphide types, two porphyry types, and one mafic-ultramafic type completed between 1995 and 1999 (Table 1). It also introduces two new mafic-ultramafic profiles. All ten profiles include mineral system descriptions.

Table 1. List of revised and new mineral deposit profiles.

Profile Name	Code	Status		Profile Name	Code	Status
Besshi VMS	G04	update		Alkalic Porphyry Cu-Au	L03	major update
Cyprus VMS	G05	update		Calc-Alkalic Porphyry Cu-Mo	L04	update
Kuroko VMS	G06	major update		Gabbroid-associated Cu-Ni±PGE	M02	new
Hybrid VMS	G07	major update		Ural-Alaskan-type Cu/Ni/Co/PGE	M05	major update
Noranda VMS	G08	major update		Giant Mascot-type Ni-Cu-(PGE)	M09	new

2. VMS mineral deposit profiles

The updated VMS profiles align with five of the six classes presented in Galley et al. (2007) by: 1) splitting the existing Noranda-Kuroko profile (Höy, 1995c) into two separate ones; 2) updating the subaqueous hot spring Au-Ag profile (Alldrick, 1996; Alldrick, 1999) to a hybrid VMS model; and 3) revising the Cyprus and Besshi profiles (Höy, 1995a; Höy, 1995b) to include recent research. One consequence of separating Noranda and Kuroko VMS is that none of the mineral occurrences in the BCGS MINFILE database are clearly Noranda type. This conclusion is consistent with Noranda-type deposits being most common in the Archean and Proterozoic, while Kuroko deposits are largely restricted to the Phanerozoic. In this update, Kuroko VMS deposits retain the G06 profile code and Noranda VMS deposits are assigned a new profile code of G08. The subaqueous hot spring Au-Ag deposit profile (G07) has been changed to reflect the global recognition of this style and, following Galley et al. (2007), renamed as 'hybrid VMS'. Because there is potential for hybrid VMS deposits in regions with Kuroko, Besshi, and Noranda type VMS deposits, the deposit profile is not restricted to specific association with another type of VMS. Hybrid VMS deposits are subdivided into low-and high-sulphidation subtypes, following Sillitoe et al. (1996) and based on long-standing terminology used for epithermal veins.

3. Porphyry Cu-Mo-Au deposit profiles

British Columbia is recognized for its porphyry copper and molybdenum mines, some of which have byproduct gold. Since the original alkalic porphyry Cu-Au (L03) and calc-alkaline porphyry Cu-Mo (L04) profiles by Panteleyev (1995a, 1995b) our understanding of porphyry deposits has improved (e.g., Sharman et al., 2020), particularly for alkalic porphyry deposits first identified in British Columbia (Barr et al., 1976; Sutherland Brown, 1976) and later in New South Wales, Australia (Wilson et al., 2003). Some porphyry deposits in the province exhibit differences from these two well-known deposit models. For example, Seedorff et al. (2005) described a monzonitic Cu-(Mo-Au) class that Riedell et al. (2015) classify as high-K calc alkalic system, with the Red Chris deposit as a type example. A different approach was taken by (Osatenko et al. (2020) who divided all porphyry deposits using the depth-zone classification of plutonic, classic, and volcanic (Sutherland Brown, 1976) and then subdivided based on the composition of the host magmatic rocks as alkalic or calc-alkalic. Acknowledging the possibility of additional porphyry types in the future, we retain the alkalic porphyry Cu-Au (L03) and calc-alkaline porphyry Cu-Mo (L04) profile terminology in the present update.

4. Convergent margin mafic and ultramafic Ni, Cu, and PGE deposit profiles

For more than 150 years much of the world's nickel and platinum group elements (PGE) have come from large ultramafic-mafic intrusions (e.g., Bushvelde, Noril'sk, Stillwater, and Sudbury). Except for the Sudbury mining camp, these deposits have been related to continental rifting (e.g., Naldrett, 1981). Because few nickel and PGE mines were considered to have formed at sites of plate convergence, these settings have generally been regarded as unfavourable for exploration. However, a global compilation of selected magmatic Ni-Cu±PGE deposits and prospects at convergent margins by Nixon and others (2015) demonstrated that such deposits are more common than hitherto appreciated (Fig. 1). They recognized three types of convergent margin nickel deposits: Alaskan; Giant Mascot; and gabbroic hosted. Herein we update the Alaskan-type Pt±Os±Rh±Ir (M05) profile of Nixon (1996), but refer to it as the Ural-Alaskan-type PGE-Cu-Ni±Co (M05) to reflect the two regions with best known examples. We also introduce two new nickel profiles to match convergent margin types identified by Nixon et al. (2015). The Giant Mascot-type Ni-Cu±Co (M09) profile is based on British Columbia's largest nickel mine, which produced from 1958 to 1974, and deposits in China, Eygpt, Spain and Brazil. The gabbroic-associated Ni-Cu±PGE (M02) profile adopts the approach taken by Nixon et al. (2015) to include only those deposits clearly associated with gabbroic rocks rather than ultramafic rocks.

5. Updated mineral deposit profile group index

Three tables based on deposit group, host rock, and commodities are used to catalog the mineral deposit profiles (Lefebure and Jones, 2020). The deposit group index is the primary table used to find individual profiles and see how these relate to other types of mineral deposits. The sections for G (marine volcanic association), L (porphyry), and M (mafic-ultramafic) are updated in Table 2 to correspond to changes to the ten deposit profiles described in this article.

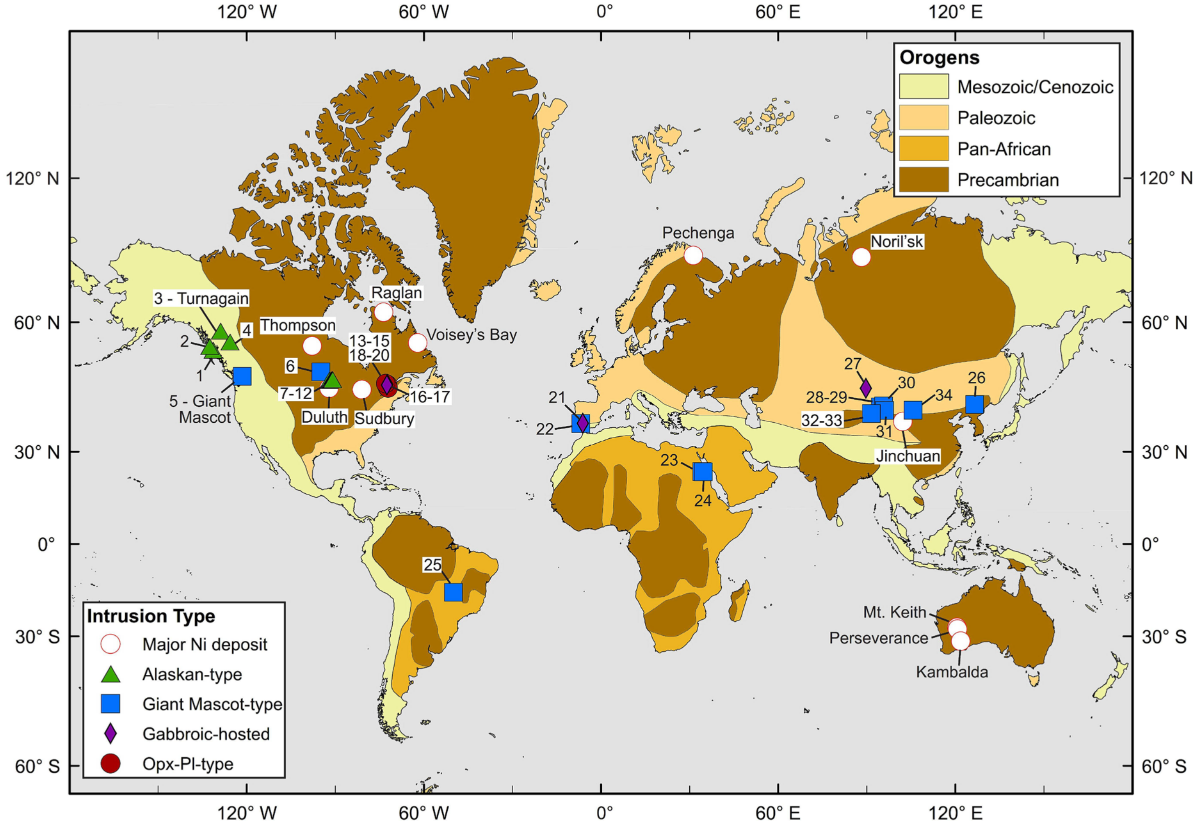

Fig. 1. Global occurrence of selected orthomagmatic Ni-Cu±Co±PGE deposits that form in convergent margin settings, from Nixon et al. (2015). Some major mining camps for other types of nickel deposits, such as Sudbury and Noril'sk, are shown for reference.

6. Conclusions

An expanded model for hybrid VMS deposits including low and high sulphidation subtypes highlights the potential to find more of these precious metal rich deposits in British Columbia. The two new mineral deposit profiles for gabbroic-associated Cu-Ni±PGE and Giant Mascot-type Ni-Cu-(PGE) and the expanded description of Ural-Alaskan-type Cu/Ni/Co/PGE deposits demonstrate the potential to find more nickel deposits that formed at convergent margins in British Columbia and globally. The Noranda/Kuroko VMS profile was split into Noranda and Kuroko deposit types to reflect modern classification systems. Five other existing profiles for VMS and porphyry deposits were updated and revised.

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Table 2. Group mineral deposit profiles index updated for the eight updated and two new deposit profiles. * no published mineral deposit profile,;VMS, volcanogenic massive sulphide.

Profile Code	Deposit Profile Name	Alternate Names	USGS. Model #
	G - Marine Volcanic Association		
G01	Algoma-type iron-formation		28b
G02*	Volcanogenic Mn		24c
G03*	Volcanogenic anhydrite / gypsum		- -
G04	Besshi VMS Cu-Zn	Kieslager, pelitic-mafic VMS	24b
G05	Cyprus VMS Cu±Zn	Back-arc mafic VMS, cuprous pyrite	24a
G06	Kuroko VMS Zn-Cu-Pb	Bimodal-felsic VMS	28a
G07	Hybrid VMS Ag-Au	Hybrid bimodal-felsic	- -
G08	Noranda VMS Cu-Pb-Zn	Bimodal-mafic VMS	28a
G09*	Bathurst VMS Zn-Pb-Cu-Ag-Au	Felsic-siliciclastic VMS	- -
	L - Porphyry		
L01	Subvolcanic Cu-Ag-Au (As-Sb)	Enargite Au, Transitional Au-Ag	22a/25e
L02*	Porphyry-related Au	Granitoid Au, Porphyry Au	20d
L03	Alkalic porphyry Cu-Au	Diorite porphyry copper	- -
L04	Calc-alkaline porphyry Cu ± Mo	Calcalkaline porphyry	17,20,21a
L05	Porphyry Mo (Low F- type)	Calcalkaline Mo stockwork	21b
L06	Porphyry Sn	"Subvolcanic tin"	20a
L07	Porphyry W	Stockwork W-Mo	21c*
L08	Porphyry Mo (Climax-type)	Granite molybdenite	16
L09	Plutonic-related Au quartz veins & veinlets	Reduced intrusion-related gold deposits	- -
	M - Ultramafic / Mafic		
M01*	Flood Basalt-Associated Ni-Cu	Basaltic subvolcanic Cu-Ni-PGE	5a/5b
M02	Gabbroic-associated Ni-Cu±PGE	Tholeiitic intrusion-hosted Ni-Cu	7a
M03	Podiform chromite		8a/8b
M04	Magmatic Fe-Ti±V oxide deposits	Mafic intrusion-hosted Ti-Fe deposits	7b
M05	Ural-Alaskan-type PGE/Cu/Ni±Co	Zoned ultramafic, Uralian-type	9
M06	Ultramafic-hosted chrysotile asbestos	Serpentinite-hosted asbestos	8d
M07	Ultramafic-hosted talc-magnesite		8f*
M08	Vermiculite deposits		- -
M09	Giant Mascot-type Ni-Cu±Co		- -

Table 2. continued.

Profile Code	Global Examples Deposit (Province, State or Country)	British Columbia Examples
	G - Marine Volcanic Association	
G01	Vermillion iron formation (Minnesota), Helen (Ontario)	Falcon, Lady A
G02*	Olympic Mountains (Washington), Nicoya (Costa Rica)	
G03*		Britannia, Falkland
G04	Besshi (Japan), Ducktown (USA), DeGrussa (Australia)	Goldstream, Windy Craggy, Granduc
G05	Konuto (Canada), Mavrovouni (Cyprus), Lasail (Oman)	Chu Chua, Lang Creek
G06	Mattabi (Ontario), Kuroko District (Japan)	Britannia, Myra Falls, Tulsequah Chef
G07	LaRonde (Québec), Nimbus (Australia)	Eskay Creek, Torbritt, Samatosum
G08	Jerome-Unite Verde (USA), Tambo Grande (Peru)	Millenbach (Quebec), Kidd Creek (Ontario)
G09*	Heathe Steel (New Brunswick), Finlayson Lake (Yukon)	
	L - Porphyry	
L01	Lepanto (Philippines), Kori Kollo (Bolivia)	Equity Silver, Thorn
L02*	Marte & Lobo (Chile), Lihir (Papua New Guinea)	Snowfields
L03	Tai Parit (Philippines)	Afton, Copper Mountain, Galore Creek
L04	Chuquicamata and La Escondida (Chile)	Highland Valley, Gibraltar
L05	Quartz Hill (Alaska)	Endako, Kitsault, Glacier Gulch
L06	Llallagua (Bolivia), Potato Hills (Yukon)	
L07	Logtung (Yukon), Xingluokeng (China)	Boya
L08	Climax & Henderson (Colorado)	
L09	Dublin Gulch (Yukon), Fort Knox (Alaska),	
	M - Ultramafic / Mafic	
M01*	Noril'sk (Russia), Duluth (Minnesota)	
M02	Lynn Lake (Manitoba), Kluane (Yukon)	Nickel Mountain
M03	Josephine ophiolite (Oregon), Coto (Philippines),	Castle Mountain, Scottie Creek
M04	Lac Tio & Magpie (Quebec), Tellnes (Norway)	Lodestone Mountain, Tanglewood Hill
M05	Salt Chuck (Alaska), Xiarihamu (China)	Horsetrail, DJ/DB Zone, Champion
M06	Thetford (Québec)	Cassiar, Kutcho
M07	Thetford & Magog (Québec), Deloro (Ontario)	
M08	Enoree (USA)	Fort Fraser area
M09	Gabbbro Akarem (Egypt), Huangshandong (China)	Giant Mascot, Star of Emory

G04: Besshi volcanogenic massive sulphide Cu-Zn±Co

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1. Identification

1.1. Synonyms. Besshi type (Cox, 1986), Kieslager (Cox, 1986); pelitic-mafic VMS (Franklin et al., 2005), siliciclastic-mafic VMS (Galley et al., 2007). The term volcanogenic massive sulphide (VMS) identifies a class of deposits related to volcanism.

1.2. Commodities and by-products. Cu, Zn, Ag, Fe (Au, Co, Mo, Sn).

1.3. Examples. In British Columbia, Goldstream (082M 141), Standard (082M 090), Montgomery (082M 085), True Blue (082FNE002), Granduc (104B 021) and Windy Craggy (114P 002); Fyre Lake (Yukon), Westarm (Manitoba); Beatson and Duchess (Alaska, USA); Ducktown (Tennessee, USA); Matchless and Otjihase (Nanibia); Besshi, Shinga, and Shirataki (Japan); DeGrussa and Red Bore (Western Australia).

2. Geological characteristics

2.1. Capsule description. Besshi VMS Cu-Zn deposits typically comprise thin sheets or lenses of massive to well-banded sulphides consisting of pyrrhotite, pyrite, chalcopyrite, and sphalerite with minor galena and commonly are associated with laterally extensive magnetite iron formation. The massive sulphides are hosted by terrigenous siliciclastic sedimentary rocks and lesser amounts of basaltic sills, flows, and tuffs. The associated rocks are commonly metamorphosed and both the rocks and the deposits may be deformed. Footwall alteration zones or pipes are associated with some massive sulphide lenses and usually do not constitute ore. Supergene enrichment zones formed by subaerial weathering have been mined for gold and silver.

2.2. Depositional environment and geological setting. Submarine rift sub-basins containing terrigenous siliciclastic sedimentary rocks and generally minor basalt flows, tuffs, and sills. Besshi deposits occur associated with volcanic centres in subareas of subsidence within a larger basin.

2.3. Ages of mineralization. Paleoproterozoic, Neoproterozoic, Paleozoic, and Mesozoic. Rarely as young as Paleogene because few deposits <15 Ma have been obducted onto the continents (Franklin et al., 2005). In British Columbia, most deposits are Cambrian, Late Triassic and, less commonly, Mississippian-Permian.

2.4. Associated rocks. Argillite, slate, siltstone, graywacke, and less commonly, sandstone, shale, and limestone are intercalated with marine basaltic flows, tuffs, and sills and their metamorphosed equivalents (quartzite, schist marble, metagraywacke, amphibolite and sometimes gneisses). Deposits are commonly hosted by deformed metamorphic rocks. Subvolcanic sills, dikes, and cryptodomes may be the predominant component of the volcanic facies and form sediment sill-complexes with peperitic margins. Ultramafic and gabbroic, carbonate and conglomeratic rocks are rare; felsic volcanic rocks are absent or rare. The mafic igneous rocks are mid-ocean ridge basalts (MORB) and rarely boninites (Piercey, 2007).

2.5. Host rocks. The massive sulphide horizons can be hosted by either volcanic or sedimentary rocks. The deposits are associated with chert, magnetite iron-formation, coticule (fine-grained, quartz-spessartine rock), tourmalinite, and albitite and their metamorphosed equivalents (Slack, 1993). The chert, coticule, and iron-formation are thin exhalative units and are interbedded with detrital or volcanic material. Commonly in the immediate hanging wall capping a massive sulphide lens (Peter, 2003), the exhalative units can extend 100s to 1000s of m beyond a massive sulphide lens; roughly two to three times the extent of a massive sulphide deposit.

2.6. Deposit form. Typically, the deposit is a concordant, tabular sheet of massive sulphides from a few m to more than 100 m thick and up to 1000s of m in diameter, with aspect ratios between 3:1 and 50:1 (Franklin et al., 2005). The sheets are stratiform and commonly stratabound. Alteration pipes are commonly considerably smaller in diameter than an overlying massive sulphide lens, with a width to depth ratio of 1:3. Massive sulphide lenses occur in clusters and can also be stacked one above another. Massive sulphide lenses can branch or interfinger with adjacent sedimentary rocks (Collins, 1950). Many deposits are deformed along with enclosing rocks.

2.7. Ore controls. Regional extensional; faults and grabens control upward flow of hydrothermal fluids to the seafloor into local sub-basins. Massive sulphide lenses can occur throughout a sedimentary and volcanic sequence during periods of relative quiescence.

2.8. Ore texture and structure. Massive to banded, fine to medium-grained sulphides; gneissic sulphide textures common in metamorphosed and deformed deposits. Pirajno et al. (2016) report breccias containing massive sulphide clasts, remnant chimney fragments and bedded sulphide rich sediments in Australian deposits. Crosscutting pyrite, chalcopyrite and/or sphalerite veins with chlorite, quartz, and carbonate can occur. At the Goldstream deposit in British Columbia, the massive sulfide layer consists primarily of intermixed pyrrhotite, sphalerite, and chalcopyrite, with numerous subrounded inclusions of quartz, carbonate, and phyllite fragments. The sulfides are locally swirled around the gangue inclusions to produce a durchbewegung fabric. Contacts with the hanging wall and the footwall range from sharp to gradational across a few m (Höy et al., 1984).

2.9. Ore mineralogy. Mainly pyrite and/or pyrrhotite, lesser chalcopyrite and sphalerite; minor galena and arsenopyrite; trace amounts in some deposits cubanite, löllingite, molybdenite, bornite, tetrahedrite-tennantite, stibnite, pentlandite, stannite, bismuth, bismuthinite, carrollite, cobaltite, magnetite, mackinawite, electrum, and gold (Slack, 1993). Magnetite is disseminated in some deposits. Minerals uncommon in ordinary massive ores, such as galena and tetrahedrite, are more common in trace amounts in copper-rich ores occurring as offshoots, tongues, and veins in and around the main stratified orebodies in Japan (Kase and Yamamoto, 1988). These may be metamorphosed and deformed alteration pipes.

2.10. Gangue mineralogy. The massive sulphide lenses generally contain <20% gangue minerals including quartz, muscovite ± carbonate (calcite, ankerite, siderite) ± albite ± chlorite ± amphibole ± tourmaline (Slack, 1993) with minor graphite, biotite.

2.11. Alteration mineralogy. Alteration pipes formed beneath some massive sulphide lenses, with a core zone of chalcopyrite, pyrite, and pyrrhotite veinlets or stockwork with quartz and sericite and local chlorite. The core zone can be surrounded by a chloritic outer margin. Some pipes contain talc. However, a number of deposits lack a well-defined alteration pipe, possibly in some cases because of significant deformation and masking by metamorphism. Semi-conformable alteration in the footwall is poorly documented for this type of VMS (Franklin et al., 2005). In strongly deformed and metamorphosed deposits, such as in the Besshi district, the orientation of the alteration pipes can be transformed from perpendicular to roughly concordant with the massive sulphide lens. This leads to descriptions of narrow, stratiform alteration zones around the ore bodies with the veins described under mineralogy (Kase and Yamamoto, 1988). Japanese geologists noted that the principal component of green schist in the Besshi district is amphibole with accessory chlorite. However, close to the orebodies, chlorite is more abundant than amphibole (Collins, 1950).

2.12. Weathering. Subaerial weathering of a massive sulphide lens produces a leached cap with mainly Fe oxides, clay minerals, and quartz overlying an oxidized zone with mainly secondary sulfates and a basal supergene enrichment zone with abundant chalcocite and other Cu-rich sulfides (Slack, 2012). The residual concentration of precious metals in the supergene enrichment zone can be economically important. For example, a gossan at the Windy Craggy deposit has enrichments of 8.5 times for gold and 3.4 times for silver relative to the underlying massive sulphide lens (Boyle, 1996). Studies of modern seafloor mineralization also reveal enrichment of gold in oxidized zones of massive sulfide deposits like the TAG (Hannington et al., 1998). Similar zones might be preserved in some older deposits.

2.13. Comments. This deposit profile is revised from Höy (1995), which was based on Hutchinson (1980), Franklin et al. (1981), Höy (1984; 1991), Fox (1984), Cox (1986), Singer (1986), and Slack (1993). Some Besshi deposits have been mistakenly classified as SEDEX deposits (e.g., Outokumpu) because, although both are hosted by sedimentary rocks, the significance of volcanism is not recognized. Besshi deposits have received less mineral exploration attention than other types of VMS with a more obvious spatial relationship to volcanic rocks.

3. Exploration and resource assessment guides

3.1. Geochemical signatures. Commonly used sample media are rocks and soils, stream and lake sediments, heavy mineral concentrates in regions with some relief, glacial till and, less commonly, water and soil gases. Altered wall rocks, particularly the footwall zones or pipes, provide important exploration guides and increase the potential cross-section of the deposit tested at surface or in drilling. Key pathfinder elements are Cu, Zn, Ag, and Co with Co/Ni ratios > 1. The sulphide mineralization has very little Pb; deposits can have Mn halos and Mg enrichment. The Besshi deposit has high Se and Te and low Ni, Mn, and Ba relative to crustal abundances (Kase and Yamamoto, 1988). Chemical deposits associated with the deposits may provide mineralogical and chemical vectors to orebodies. A positive europium (Eu) anomaly in iron formation is taken to reflect high-temperature fluid venting and may serve as a guide to mineralization (Peter, 2003). Altered wall rocks, particularly footwall zones or pipes, provide important exploration vectors and increase the potential cross-section of the deposit tested at surface or in drilling. Alteration is commonly indicated by Na_2O depletion, but multiple element ratios can sometimes distinguish more subtle anomalies. For example, the alteration box diagram of Large et al. (2001) plots the Ishikawa alteration index, 100 (K_2O

+ MgO)/(K_2O + MgO + Na_2O + CaO) against the chlorite-carbonate-pyrite index, 100 (MgO + FeO)/(MgO + FeO + K_2O). Increasing values of both parameters indicate increasing intensity of alteration in which sericite, chlorite, carbonate, and pyrite replace sodic feldspar and glass in volcanic rocks. The immobile major and trace elements, TiO_2, Al_2O_3, the HFSE (Zr, Hf, Nb, Ta, Y, Sc, Ti, V), and REE, can be used in most altered and metamorphosed rocks to better assess depletion and addition of mobile elements and provide insight into primary igneous processes and the tectonic settings of VMS deposit formation (Piercey, 2007). The geochemistry of the least altered mafic rocks can help with delineating prospective regions to consider for mineral exploration. Typically, these are mid-ocean ridge basalts and rarely boninites (Piercey, 2007).

3.2. Geophysical signatures. Airborne and ground geophysics are important tools because massive sulphide lenses, and local parts of footwall alteration pipes, have higher magnetic, conductivity and density properties than those of their host rocks (Ford et al., 2007). Besshi massive sulphides can contain magnetite and /or pyrrhotite in the massive sulphide lens and magnetite associated with iron formation, which will lead to strong responses to a magnetic survey. Sulphide lenses commonly show a strong electromagnetic response based on conductive sulphides. In cases where the sulfide grains are not electrically connected, such as in the disseminated and weak stockwork sulfides in the alteration pipe, induced polarization may be useful. Gamma-ray spectroscopy provides an indirect technique based on chemical contrasts associated with near-surface alteration, mostly as potassium enrichment or depletion near a deposit. Gravity surveys generally follow other geophysical and geochemical surveys to determine the mass and size of an ore body (Slack, 2012), but it is more common to proceed with diamond drilling instead. Gravimetry can delineate structural lineaments or faults and identify horst-graben structures that may control the location of ore bodies.

3.3. Other guides. At surface, red and orange gossans and iron-stained surface water from sulphide mineral oxidation. Magnetite iron formation and other hydrothermally precipitated chemical deposits, such as chert and Fe-Mn-rich rocks. Mafic volcanic rocks (tholeiitic, less commonly alkalic) associated with siliciclastic rocks. Manganese-rich garnets in metamorphosed exhalative horizons. In metamorphic terranes with abundant gneisses, diagnostic minerals may include cordierite, diopside, orthopyroxene, garnet, K-feldspar, biotite, and Al-silicates, especially kyanite and sillimanite (Slack, 2012).

4. Economic factors

4.1. Typical grade and tonnage. British Columbia deposits range from <1- to 300 Mt. The type-locality Besshi deposits in Japan average 0.22 Mt containing 1.5% Cu, 2 to 9 g/t Ag, and 0.4 to 2% Zn (Cox and Singer, 1986). Geometric mean metal contents for 90 global deposits are 1.23% Cu, 1.58% Zn, 0.75 g/t Au, and 19.29 g/t Ag with an average size of 4.7 Mt (Franklin et al., 2005). Slack (1993) mentioned that most Besshi deposits probably contain < 0.1% Pb and suggested crude correlations between higher Cu grades and predominantly volcanic rocks and Zn grades and predominantly sedimentary rocks. Besshi deposits have significant cobalt grades averaging ~0.05% Co in cobaltiferous pyrite and other minerals (Hitzman et al., 2017). The only significant production of cobalt to date from a Besshi deposit was during the Second World War from the Besshi mine with a resource of 30 Mt at 0.05% Co. Windy Craggy is the largest Besshi deposit and contains 138 Mt at 0.069% Co (Desautels, 2008). Cadmium has been recovered from zinc concentrates from the Ducktown deposit in Tennessee, USA at the smelter.

4.2. Economic limitations. Many deposits are small (millions of tonnes) and are generally only economic if they can be mined using an open pit or in combination with one or more other nearby lenses. As with other VMS deposits, the high concentration of sulphides in Besshi deposits can present environmental problems with acid water drainage and metal leaching.

4.3. End uses. An important source of Cu and Zn and usually contributing the precious metals Ag and Au. Cobalt is becoming increasingly important for use in batteries for electric vehicles.

4.4. Importance. Significant sources of Cu, Zn, Au and Ag and a potential important cobalt resource. Besshi deposits are some of the largest VMS deposits.

5. Genesis

5.1. Genetic model. The deposition of sulphides and related gangue minerals occurs at or just beneath the sea floor by metal-bearing hydrothermal fluids mixing with seawater. The heat to drive the convecting seawater systems that produces the hydrothermal fluid discharges along faults is provided by magmatic activity associated with a subduction-related spreading centre located near continental land masses. The hydrothermal fluids leach metals, such as copper and gold from terrigenous siliciclastic sedimentary and smaller volumes of volcanic rocks up to a 2 km beneath the seafloor. The accumulation of the massive suphide mounds requires a period of time without volcanic activity or significant sedimentation, which may be marked by deposition of a thin layer of chemical and/or pelagic sediments. The sulphide mounds must be covered by sediments or volcanic rocks to be preserved. At some later date, the assemblage of sedimentary and volcanic rocks is accreted to a continent. Modern analogues for the seafloor formation environment are the Guaymas Basin in the Gulf of California, Escanaba Trough on the southern Gorda Ridge, and Middle Valley on the northern Juan de Fuca Ridge (Koski, 1990).

Table 1. Tonnage and grade for Besshi deposits.

	Mt	Cu %	Pb %	Zn %	Au g/t	Ag g/t	Reference
British Columbia							
Goldstream	2.22	3.52		3.59		11.7	BC MINFILE 2004
Granduc	25.06	1.79	0.021	0.104	0.17	10.63	Franklin et al., 2005
Windy Craggy	297.4	1.38		0.25	0.22	3.83	Franklin et al., 2005
Canada							
Fyre Lake	8.5	2.1		1	0.73		Franklin et al., 2005
Westarm	1.64	3.7		1.58	1.4	16	Franklin et al., 2005
United States							
Ducktown	163.34	1		0.9	0.3	3	Franklin et al., 2005
Gossan Lead	40	0.5		1.5	<0.1	8	Slack, 1993
Namibia							
Otjihase	17	2.3		<0.3	0.3	9	Slack, 1993
Japan							
Besshi	29.95	2.6		0.3	0.7	21	Franklin et al., 2005
Besshi - Shinga	0.5	1.2				4	Franklin et al., 2005
Besshi - Shirataki	2.81	1.1		0.3	0.1	4	Franklin et al., 2005

5.2. Tectonic settings. Back-arc basins, mid-ocean ridges, and mafic alkalic terranes related to seamounts (Franklin et al., 2005) and possibly continental rifts such as considered by Pirajno et al. (2016) for several Australian Besshi deposits. The largest known Besshi-type deposit, Windy Craggy may have formed at a slab-window, perhaps related to subduction of a spreading centre, which allowed enriched magmas to reach the surface with only minimal interaction with subduction-modified mantle (Peter et al., 2014). Analogous deposits are in the present-day Gulf of California, and some argue, the Red Sea where relatively narrow rift arms are bounded by continental areas. Spreading centers that become close to continental margins through subduction of oceanic crust, ridge propagation, or development of a continental margin rift can receive volumes of sediment carried by rivers draining adjacent continental crust that overwhelm volcanic rock accumulation.

5.3. Associated deposit types. Cu-Zn veins, Noranda VMS, Kuroko VMS, Eskay Creek-Boliden hybrid VMS.

6. Mineral systems

The following mineral system summary draws from articles by Slack (1993), Franklin et al. (2005), Piercey (2011) and Shanks III (2012).

6.1. Source region. The mantle in a region of crustal extension and thinning.

6.2. Source driver. Crustal thinning from extension results in decompression melting of the upper mantle, which produces large volumes of mafic magma.

6.3. Source product. Commonly tholeiitic magmas with MORB geochemistry; local alkalic magmas.

6.4. Transport driver. Buoyant magmas migrate upwards initially by dike propagation and then primarily by following crustal faults and establishing a thermal corridor.

6.5. Transport path. Ascent of large magma volumes requires a long-lived, continuous supply of magma and melt paths that can be exploited by multiple magma pulses. Magmas may initially pond at mid-crustal levels until recharge leads to upward migration to the seafloor.

6.6. Transport termination. Dikes feed sills injected into wet, unconsolidated sediments several 100 m below the seafloor. The high rates of sedimentation at these sites result in thick sedimentary sequences that provide an effective density barrier to the eruption of relatively dense basalt on the seafloor. Heat from the intrusive rocks converts seawater within the sediments into convecting hydrothermal fluids that leach ore metals from the wall-rock and discharge onto the seafloor.

6.7. Deposit concentration. The rising hydrothermal fluids will commonly focus on near surface, vertical to sub-vertical faults to reach the seafloor. As the fluids approach the seafloor they will interact with seawater in the sediments and /or at the seafloor to cause the deposition of sulphides and gangue minerals due to the dramatic temperature drop and fluid mixing reactions. Fluids encountering more open faults and/or more permeable wallrock introducing seawater at deeper levels can lead to more pronounced and extended alteration pipes. Besshi deposits may have also formed from exhalations of hydrothermal fluids into dense brine pools. The Windy Craggy deposit, British Columbia, has well-preserved fluid inclusions that indicate formation from moderately saline fluids (9–17 wt% NaCl equivalent that could have formed negatively buoyant brine-pools on the seafloor (Shanks III, 2012). Brine pools may explain the formation of sheets and the presence of iron-formation at deposits like Granduc and in the Red Sea (Slack, 1993).

6.8. Deposit controls. The deposits typically form near faults and fault scarps and within basins created by the rift environment. Hydrothermal upflows may be related to the margins of sills. Although the sills may be partly responsible for driving hydrothermal circulation, high-temperature fluids mainly appear to originate from greater depths.

6.9. Deposit accumulation. As the sulphide mound builds, the hydrothermal fluids passing through it can heat the internal layers which can lead to zone refining from the base to the top. This will replace lower temperature minerals with higher temperature minerals over time. In the case of Besshi VMS deposits, pyrite is replaced by chalcopyrite, sphalerite and other minerals within the sulphide mounds. Larger deposits will have larger footwall pipes with more mineralization near the original seafloor beneath the mounds.

6.10. Post formation processes. Weathering of seafloor massive sulphide (SMS) deposits is an inevitable consequence of exposure to seawater unless the deposit is rapidly covered by sediment and/or volcanic material that shields sulfides from seawater contact. Bottom waters may contain a small amount of oxygen such that the weathering of the deposit may be slowed but not halted.

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G05: Cyprus volcanogenic massive sulphide Cu±Zn (back-arc mafic VMS)

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1. Identification

1.1. Synonyms. Cupreous pyrite, Cyprus massive sulfide (Singer, 1986), mafic backarc VMS (Franklin et al., 2005), back-arc mafic VMS (Galley et al., 2007). Volcanogenic massive sulphide (VMS) identifies a class of deposits related to volcanism. .

1.2. Commodities and by-products. Cu, Zn (Au, Ag, Co, Cd).

1.3. Examples. In British Columbia, Chu Chua (092P 140) and Lang Creek (104P 008); Ice (Yukon); Coronation and Konuto (Saskatchewan); Birch Lake (Manitoba); York Harbour, Whalesback, and Betts Cove (Newfoundland); Turner-Albright (Oregon, USA); Løkken (Norway); Mavrovouni, Apliki, and Skouriotissa (Cyprus); Al Ajal, Hayl-As-Safil, and Lasail (Oman).

2. Geological characteristics

2.1. Capsule description. Deposits comprise one or more stratabound lenses of massive pyrite and chalcopyrite that are typically hosted by basaltic flows, often pillowed, with minor associated sedimentary rocks. Ochres commonly mantle the sulphide mound. The lenses are underlain by a discordant, pipe-shaped stockwork zone; the top of this zone can contain recoverable copper. The deposits commonly occur near the top of an ophiolite sequence. The deposits form on the seafloor at significant water depths at back-arc spreading centres.

2.2. Depositional environment and geological setting. Deposits form in deep ocean waters in basaltic volcanic sequences with limited associated sediments. Modern Cyprus-type seafloor deposits are known but are not yet economic to exploit. On land, deposits are hosted in ophiolite and ophiolite-like basaltic sequences, commonly near a transition with overlying sedimentary rocks. Many lenses are structurally controlled and aligned near steep normal faults. Much of the sulfide mineralization in ophiolite terranes has undergone severe deformation and metamorphism along with the host strata.

2.3. Ages of mineralization. Most common age of mineralization is Paleozoic to Cenozoic. Proterozoic deposits are sparse and Archean deposits are rare (Franklin et al., 2005) despite the presence of rift basins with thick ophiolite sequences (Galley et al., 2007).

2.4. Associated rocks. Typified by ophiolite host sequences with less than 10% sedimentary and minimal felsic volcanic rocks that formed concurrently with the massive sulphides (Franklin et al., 2005). Typically, ophiolite sequences consist of a series of mafic effusive flows, mostly pillow lavas, with minimal interflow volcaniclastic material which host the mineral deposits. These rocks overly a thick section of sheeted dikes which continues downward into a thick sequence of layered gabbros and peridotite which are commonly harzburgite and dunite in older rocks. The igneous rocks consist of mid-oceanic ridge basalt (MORB), back-arc basin basalts and low-K arc tholeiitic through to picritic and boninitic pillow and flow basalts (Galley and Koski, 1997). Minor bimodal basalt and andesite-rhyolite suites can occur near the top of the volcanic sequence. The volcanic component of many ophiolites is overlain by an unrelated, thick sedimentary sequence marking the end of active magmatism.

2.5. Host rocks. Pillow lavas are commonly the predominant host for mineralization; flows can be vesicular and have phenocrysts of plagioclase, pyroxene and, less commonly, olivine. Mafic dikes are relatively common. Minor fine-grained, metalliferous sedimentary rocks consisting of manganese oxides, hydrated ferric oxide and silica ('umbers') may be at boundaries of major volcanostratigraphic units and also at the contacts of individual volcanic units (Gilgen et al., 2014). The massive sulphide horizons are associated with chert, magnetite iron-formation, coticule (fine-grained, quartz-spessartine rock), tourmalinite, and albitite and their metamorphosed equivalents, such as quartzite and metachert. The chert, coticule, and iron-formation are thin exhalative units, formed by chemical sedimentation, with interbedded detrital or volcanic material. They commonly occur in the immediate hanging wall on the edges of the deposit and typically cap the massive sulphide lens (Peter, 2003). They can extend 100s of m beyond the massive sulphide lens. The mafic rocks that host Cyprus deposits are typically boninite and low-Ti island arc tholeiite, which are commonly overlain or underlain by basalt of mid-ocean ridge or back-arc basin basalt geochemistry. These transitions from arc to non-arc volcanic rocks can be stratigraphic markers for VMS deposits

(Piercey, 2010). Boninitic rocks have high MgO, Ni and Cr and low TiO2 (<0.6%) contents, with high Al2O3/TiO2 (often >40) and low Ti/Sc and Ti/V ratios. The rocks have distinctive U-shaped REE and primitive mantle-normalized patterns.

2.6. Deposit form. Concordant, bulbous, and elongate massive sulphide lenses less than 4m thick up to 500m long usually overlying a well-defined alteration pipe that can extend to depths of 100 to >500m. Deposit and pipe location commonly controlled by synvolcanic faults, elongate lenses taper away from such structures. Many deposits are truncated by later faults. Some deposits are almost entirely discordant to semi-conformable stockwork mineralization (Galley and Koski, 1997). The Whalesback deposit is considered a type example of an Appalachian, stringer-dominated Cyprus-type VMS deposit by Cloutier et al. (2015).

2.7. Ore controls. The massive sulfide deposits are located throughout the basaltic section of an ophiolite which extends from the sheeted dikes to the upper pillow lavas and locally into overlying sedimentary rocks. Sulfide mounds form during periods of quiescence between magmatic events. The largest deposits (both in Cyprus and Oman) occur between major pillow sequences of slightly different composition, probably recording a hiatus between separate magmatic episodes (Hannington et al., 1998). Sulphide lenses cluster and align along early normal faults. The major mining districts in Cyprus are distributed along graben axes.

2.8. Ore texture and structure. The massive, fine-grained sulphide lenses are commonly brecciated. The associated chert layers are locally brecciated and can contain disseminated sulphides. Fragments of high temperature, ‘black smoker’ chimney walls can be preserved in younger deposits, such as those in Cyprus ore. Traces of fauna similar to that near present-day seafloor vents are also at Cyprus (Oudin and Constantinou, 1984). Remobilization of the sulfides during deformation and metamorphism may be significant, creating textures such as durchbewegung. Stockwork, vein and disseminated mineralization occurs in underlying alteration pipes and the upper portion commonly broadens below the massive sulphide lens with an increase in vein size and decrease in vein spacing producing a volcanic breccia that can be ore grade.

2.9. Ore mineralogy. Stratiform sulphide lens with pyrite, or less commonly pyrrhotite, chalcopyrite and usually less abundant sphalerite, locally with massive magnetite. Individual deposits contain minor concentrations of marcasite, cubanite, covellite, bornite, diginite, chalcocite, galena, pyrrhotite, idaite, bravoite, carollite, and mackinawite (Galley and Koski, 1997). Commonly strongly zoned with Cu and Zn concentrated in the upper half of a massive sulphide lenses. Zinc-rich deposits with high Au contents are known, such as Betts Cove and Tilt Cove (Newfoundland) and Turner -Albright (Oregon). A distinctive suite of Co- and Ni-bearing arsenides, sulfarsenides, and sulfides (e.g., skutterudite, safflorite, cobaltite, löllingite, millerite, and pentlandite) are found in massive sulfide deposits in ophiolitic terranes in Quebec, Morocco, Cyprus, and Finland (Koski, 2012). The massive sulphide lens can have a well-layered ochre cap consisting of mixtures Fe-rich and siliceous mudstones, hydrothermal sediments, and oxidized massive sulphides that contain copper mineralization and locally native gold. Ochers in Cyprus represent iron-rich gossans that formed contemporaneously on the surface of the massive sulphide mound. The alteration pipe has quartz-sulphide veins with chalcopyrite and pyrrhotite in the core that is usually enveloped by a larger, diffuse zone of quartz-pyrite veins and disseminated mineralization. Chalcopyrite veins are concentrated in the most silicified parts of some stockwork zones.

2.10. Gangue mineralogy. Gangue minerals are limited in the massive sulphide lens. Quartz is usually predominant, followed by jasper and gypsum; there can also be minor amounts of magnetite and hematite.

2.11. Alteration mineralogy. Alteration pipes are zoned with Fe-Mg chlorite in the core and a sericite ± paragonite rim, locally with an outer envelope of minor weak albite-illite alteration. The core of the pipe consists of in situ pyrite-quartz breccia grading down into quartz-pyrite stockwork and then into chlorite-pyrite stockwork (Galley et al., 2007). Semi-conformable alteration zones composed of epidote-albite-actinolite with local silicification that are metal depleted can occur at depth in the footwall rocks.

2.12. Weathering. Outcropping massive sulphides typically form Fe-oxide gossans. In suitable environments the gossans are intensely altered and leached with an underlying supergene enrichment zone containing precipitated Cu sulphides, such as chalcocite. The bedded ocher overlying massive sulfide at Skouriotissa, Cyprus has been reinterpreted as a submarine gossan (Herzig et al., 1991).

2.13. Comment. This deposit profile is revised from Höy (1995), which was based on Franklin et al. (1981), Cox and Singer (1986), and Höy (1991).

3. Exploration and resource assessment guides

3.1. Geochemical signatures. Soil, silt, till and rock sampling can show enhanced Cu and Zn values, locally with anomalous Au, Ag, Co and/or Cd values. Pb values are low. As, Sb, and Sn values are low compared to other VMS deposits. Cherts and umbers related to massive sulphide lenses can have anomalous base and precious metal concentrations that extend well beyond the deposit. Altered wall rocks, particularly the footwall zones or pipes, provide important exploration vectors and increase the potential cross-section of a deposit. These altered rocks are commonly indicated by major Ca-Na losses and Fe-Mg-K-Si-S enrichments relative to less altered volcanic rocks (Piercey, 2009). Rocks in the footwall and outside the alteration pipe are less altered, but exhibit generally similar changes in composition, particularly Na depletion. The immobile major and trace elements, TiO_2 , $Al2O_3$, the HFSE (Zr, Hf, Nb, Ta, Y, Sc, Ti, V), and REE, can be used in most altered and metamorphosed rocks to better assess depletion and addition of mobile elements and provide insight into primary igneous processes and the tectonic settings (Piercey, 2010). Multiple element ratios can distinguish more subtle anomalies. For example, the alteration box plot of Large et al. (2001) plots the Ishikawa alteration index, 100 (K_2O + MgO)/(K_2O + MgO + Na_2O + CaO) against the chlorite-carbonate-pyrite index, 100 (MgO + FeO)/(MgO + FeO + K_2O). Increasing values of both parameters indicate increasing intensity of alteration in which sericite, chlorite, carbonate, and pyrite replace sodic feldspar and glass in volcanic rocks. The geochemistry of the boninite and low-Ti tholeiite mafic rocks can help delineate prospective regions.

3.2. Geophysical signatures. Airborne and ground geophysics are important tools because massive sulphide lenses, and local parts of footwall alteration pipes, have higher density and positive magnetic and conductivity properties that differ significantly from those of their host rocks (Ford et al., 2007). Contrasts in magnetic, electromagnetic, and gravitational (density) properties are direct exploration guides; gamma-ray spectroscopy provides an indirect technique based on chemical contrasts associated with near-surface alteration. Sulphide lenses commonly show a strong electromagnetic response based on the presence of conductive sulphides. In cases where the sulfide grains are not electrically connected, such as in the disseminated sulfide stockwork below the main massive sulfide ore body, induced polarization can be useful. Gravity surveys can be used, generally following other geophysical and geochemical surveys, to determine the mass of the ore body as well as its size (Slack, 2012), but it is far more common in exploration programs to proceed with diamond drilling instead. Gravimetry can delineate structural alignments or faults and identify horst-graben structures that may control the localization of sulfide ore bodies.

3.3. Other guides. Favourable horizons are commonly marked by chemical deposits in older rocks and umbers in younger sequences like Cyprus. Multiple stratigraphic horizons are found in some regions. A small VMS lens can lead to finding other lenses nearby. If the stratigraphy is tilted, the alteration pipe provides a significant target for prospecting, geochemical sampling, and geophysical surveys. A broad zone of semiconformable alteration with epidotization and silicification located deeper in an ophiolite sequence can be a favourable indicator of major alteration system, potentially related to a VMS deposit.

4. Economic factors

4.1. Typical grade and tonnage. Deposits generally occur in clusters occupying an area of roughly 10 by 10 km. The smallest lenses can be only a few thousands of tonnes; some mines exploit multiple lenses. Geometric mean metal contents for 76 deposits are 1.82% Cu, 0.02% Pb, 0.84% Zn, 1.40 g/t Au, and 10.62 g/t Ag with an average size of 2.7 Mt (Franklin et al., 2005). Lenses have higher grades for copper, zinc, and gold than stockworks. Cyprus deposits have higher average copper and gold contents (Table 1) with lower Pb values and a smaller average tonnage than Besshi (G04), Noranda (G06) and Kuroko (G08) deposits. Gossans have been mined for Cu and Au in Cyprus and Oman where enhanced weathering due to warmer climates and limited erosion has produced relatively thick deposits. The Rakah mine in Oman has a resource figure of 400,000 tonnes grading 7.7 % Cu and 19 g/t Au (Batchelor, 1992).

4.2. Economic limitations. Sphalerite is underreported from older mines because it was not recovered. Currently, smaller massive sulphide lenses will only be economic if they are close to a larger lens. As with other VMS deposits, the high concentration of sulphides in Cyprus deposits can present environmental problems with acid water drainage and metal leaching.

4.3. End uses. These deposits have produced copper since pre-classical times and, more recently, zinc. In the past they have been a source for sulphuric acid produced from high-quality pyrite. The massive sulphide ore has produced gold and silver and, in some cases, cobalt and cadmium. Supergene alteration zones have been mined for gold and copper. The umbers in Cyprus have been a source of high-quality natural pigments; some of the cherts contain potentially exploitable manganiferous horizons (Gale et al., 1981).

4.4. Importance. Worldwide these deposits are more significant for their higher grades and polymetallic nature than their size. There are 200 ophiolite suites recognized throughout the world and at least 25 contain significant VMS mineralization (Galley and Koski, 1997). This suggests that new mining districts for Cyprus VMS deposits could be found.

5. Genesis

5.1. Genetic model. Deposition at or beneath the sea floor at water depths ranging from 2 to 4 km as hydrothermal fluids mix with seawater. The heat to drive the convecting sea-water systems and hydrothermal discharges along faults is provided by magmatic activity associated with a subduction-related spreading centre that is distal to the associated volcanic arcs (Monecke et al., 2014). The composition of the fluids is controlled by the mineral assemblages of the footwall mafic rock and the temperature of the circulating seawater. These fluids leach metals, such as copper and gold, from large volumes of volcanic rocks within a couple of km of the seafloor. The accumulation of massive suphide mounds requires a period without volcanic activity or

Table 1. Tonnage and grade figures for selected Cyprus deposits.

British Columbia	**Mt**	**Cu %**	**Pb %**	**Zn %**	**Au g/t**	**Ag g/t**	**Reference**
Chu Chua	1.04	2.98		0.3	0.54	10.2	Franklin et al., 2005
Canada							
Ice (YT)	4.56	1.48					Franklin et al., 2005
Konuto (SK)	1.44	6	0.001	3	2.5	10	Franklin et al., 2005
York Harbour (Nfld)	0.34	1.92		4.67			Franklin et al., 2005
Gullbridge (Nfld)	4.07	1.02					Franklin et al., 2005
Handcamp (Nfld)	2.27	2.62			13.4	56	Franklin et al., 2005
Tilt Cove (Nfld)	8.17	6					Franklin et al., 2005
Whalesback (Nfld)	3.79	0.95					Franklin et al., 2005
Norway							
Lokken	25	2.1	0.1	1.9	0.29	19	Franklin et al., 2005
Cyprus							
Kalavasos-Mousoulos	6.92	1	0.01	0.5	1.7	0.1	Franklin et al., 2005
Limni	4.22	1.41			3.39	2.7	Franklin et al., 2005
Mavrovouni	15	4		0.5	0.3	39	Franklin et al., 2005
Skouriotissa	5.44	2.35		0.5	11	69	Franklin et al., 2005
Oman							
Al Ajal	1	0.75	0.005	0.26	1.2	11	Franklin et al., 2005
Hayl-As-Safil	8	1.3	0.01	0.6	0.6		Franklin et al., 2005
Lasail	12	2.1		0.04	0.6	1.7	Franklin et al., 2005

significant sedimentation which may be marked by deposition of a thin layer of chemical and/or pelagic deposits. The sulphide mounds are then covered by volcanic rocks or, less commonly sedimentary rocks. At some later date, the ophiolitic assemblage of basaltic volcanic and intrusive rocks with minor sedimentary deposits was obducted onto continental crust. The TAG SMS deposit on the East Pacific Rise provides an example of an actively forming deposit that is similar to the Cyprus deposits (Hannington et al., 1998).

5.2. Tectonic settings. Cyprus type VMS deposits formed in mature back-arc or possibly fore-arc spreading centres with high-temperature submarine magmatism. Subsequent to their formation, the host ophiolitic strata were obducted onto an adjacent continent, such as the Troodos Complex in Cyprus and the Josephine ophiolite of California and Oregon. The Cyprus deposits formed in seafloor grabens (Martin et al., 2019) considered to have formed due to slab roll-back probably near a slab edge (Pearce and Robinson, 2010). Deep incursion of seawater into the crust occurs along rift-related faults which also localize hydrothermal fluid migration and discharge. These deposits form as the seafloor spreading rates change from an initial period of robust magmatic activity, steep geothermal gradients, and seawater convection to a magmatic lull, which allowed for accumulation of massive sulphide mounds and hydrothermal/pelagic sediments on the seafloor (Galley and Koski, 1997). Although modern seafloor massive sulphide (SMS) deposits exist at mid-ocean spreading ridges, few ancient deposits from this tectonic setting are known (Slack, 2012), because of the consumption of oceanic crust by subduction.

5.3. Associated deposit types. Cu-Au gossans; vein and stockwork Cu (±Au) mineralization; Mn- and Fe-rich cherts; massive magnetite (±talc) deposits..

6. Mineral systems

The following mineral system summary draws from Galley and Koski (1997), Galley (2003), Franklin et al. (2005), Piercey (2011), and Slack (2012). Rifting is a key element of all VMS deposits, influencing all aspects of the mineral system, including shallow-level magma generation, magma transport paths, and controlling deposition at and near the seafloor along and near faults in local basins.

6.1. Source region. The mantle source is ultra-depleted in incompatible trace elements and requires high temperatures to melt

(c. 1200–1500°C) at a relatively shallow depth of ~ 20 km.

6.2. Source driver. Rift-related extension in a crustal plate results in subsidence and thinning that produces decompression melting of the upper mantle.

6.3. Source product. A large volume of hot tholeiitic magmas is produced.

6.4. Transport driver. Buoyant magmas rise initially by dike propagation and then follow crustal faults establishing a thermal corridor that facilitates their upward movement.

6.5. Transport path. Ascent of large magma volumes requires a long-lived, continuous supply of magma and melt paths that can be exploited by multiple magma pulses. The melts may initially pond at mid-crustal levels until ongoing magma recharge leads to upward migration of a multi-phase magmas.

6.6. Transport termination. The magmas produce volcanic rocks on the seafloor and dikes and sills up to ~2 km below the seafloor. The size and concentration of these subvolcanic intrusions can indicate areas of higher heat flow that transform descending seawater into rising hydrothermal fluids that can form VMS deposits (Sangster, 1972).

6.7. Deposit concentration. The hydrothermal fluids leach metals, silica, and other elements from the enclosing rocks. As they rise and encounter cooler water and rocks, they initially deposit anhydrite, carbonate, silica or M-smectite which decreases porosity and permeability to focus flow. As the hot fluids approach and reach the seafloor they interact with seawater resulting in deposition of sulphides and gangue minerals due to the dramatic temperature drop and fluid mixing reactions. Fluids encountering more open faults and/or more permeable wallrock introducing seawater at deeper levels can lead to more pronounced and extended alteration pipes.

6.8. Deposit controls. The rising hydrothermal fluids will commonly follow major rift boundary listric faults to a depth of ~200m below the seafloor where subvertical extension fractures focussed the discharge at some distance from the surface trace of the major fault (Franklin et al., 2005). As the sulphide mound builds, the hydrothermal fluids passing through it can heat the internal layers which can lead to zone refining from the base to the top. This will replace lower temperature minerals with higher temperature minerals over time. In the case of Cyprus VMS deposits, pyrite is replaced by chalcopyrite, sphalerite, and other minerals within the sulphide mounds. Larger deposits will have larger footwall pipes with more mineralization near the original seafloor beneath the mounds.

6.9. Deposit accumulation. An ore deposit forms during a period of volcanic and sedimentary quiescence that allows prolonged deposition of sulphides. The large hydrothermal systems are considered to have remained active for up to a million years. Features that create depressions, like half-grabens, ensure the sulphides accumulate in one location.

6.10. Post formation processes. Massive sulphide deposits on the seafloor can be gravitationally unstable and subject to slumping. Until the massive sulphides are covered by younger sediment or volcanic unit, the deposit can be subject to dissolution, weathering and/or erosion that can reduce the size or change the composition of the massive sulphide mound. The land-based deposits are obducted onto a nearby continent, which leads to deformation and metamorphism. Subaerial exposure of the massive sulphides can create gossans with enriched gold and copper values or erode the deposits..

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G06: Kuroko volcanogenic massive sulphide Cu-Pb-Zn (bimodal-felsic VMS)

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1. Identification

1.1. Synonyms. Polymetallic volcanogenic massive sulphide, bimodal-felsic VMS (Franklin et al., 2005; Galley et al., 2007), felsic to intermediate volcanic type (Singer, 1986). Volcanogenic massive sulphide (VMS) identifies a class of deposits related to submarine volcanism.

1.2. Commodities and by-products. Cu, Pb, Zn, Ag, Au (Cd, S, Se, Sn, barite, gypsum).

1.3. Examples. In British Columbia, Lenora (092B 001), Myra (092F 072), Price (092F 073), H-W (092F 330), Britannia (092GNW003, and Tulsequah Chief (104K 002); Izok Lake (Nunavut); Mattabi (Ontario); Selbaie (Québec); Buchans (Newfoundland); Shasta King (California, USA); Hanaoka-Matsumine and Kosaka-Uwamuki (Kuroko district, Japan); Woodlawn (New South Wales, Australia), Roseberry and Mount Lyell (Tasmania, Australia).

2. Geological characteristics

2.1. Capsule description. Kuroko VMS deposits consist of one or more lenses of massive sulphides composed of Fe-sulphides (pyrite or pyrrhotite) and subordinate amounts of sphalerite, chalcopyrite, and galena with barite, tetrahedrite, bornite and other mineral phases. The lenses may be zoned, with a Cu-rich base and a Zn-Pb-Ag-Au rich top, commonly with overlying mineralized barite and/or chert layers. The deposits overlie semi-conformable alteration zones or discordant, sulphide-bearing alteration pipes (stringer or stockwork zones). The host rocks are predominantly felsic volcanic, with associated basaltic and minor sedimentary rocks.

2.2. Depositional environment and geological setting. The deposits form in submarine caldera and graben settings on and beneath the seafloor. They are hosted by felsic and mafic volcanic rocks interbedded with minor chemical or fine-grained sedimentary rocks. The deposits require a period of volcanic quiescence or limited volcanism and sedimentation to enable accumulation of the massive sulphide lens.

2.3. Ages of mineralization. These deposits formed since the Archean and continue to form today (Franklin et al., 2005); most formed in the Phanerozoic. In British Columbia they are typically Devonian and Late Triassic.

2.4. Associated rocks. Kuroko deposits are found within submarine volcanic successions with rock compositions similar to those in present-day continental and oceanic arcs. These are primarily volcanoclastic felsic and basaltic to basaltic andesite flows, dikes, and sills with only minor amounts of sedimentary strata. The bimodal-felsic VMS deposit type definition of a Kuroko deposit specifies that the stratigraphic succession consists of 35-70% felsic rocks, 20-50% mafic rocks and 10% terrigenous sedimentary rocks (Barrie and Hannington, 1999; Franklin et al., 2005). Some deposits and the enclosing rocks have subsequently been metamorphosed and deformed.

2.5. Host rocks. Rhyodacite, rhyolite and/or high-silica rhyolite typically directly underlie or host the mineralization and consist of pre- or syn-ore rhyolite and rhyodacite domes and cryptodomes with felsic volcaniclastic rocks. The deposits are overlain by siliciclastic rocks, such as mudstones, greywackes, and argillites or volcanic units, such as pumice tuff; more rarely basaltic volcanic rocks cover the massive sulphide lenses. The host mafic volcanic rocks generally have a composition that varies from arc to midocean ridge basalt affinities and locally ocean island basalt-alkalic basalt. Host rhyolites are designated as FII or, less commonly, FIII rhyolites and HFSE-enriched FV (Hart et al., 2004; Gibson et al., 2007). Ore horizons commonly grade laterally and vertically into thin, sulphidic chert, waterlain tuff. or chemical sedimentary layers, which can be interlayered. Thin bedded tuffs or sedimentary layers with minor pyrite and/or pyrrhotite, and locally sphalerite and/or galena, are also called exhalites in some mining districts. Exhalites form by the precipitation of mainly amorphous Fe ± Mn ± Si ± S ± Ba ± B phases from hydrothermal vents and plumes (Slack, 2012b) commonly with intermingled tuff or fine-grained sediment. They are from a few cm to as much as several m thick and can extend 100s to (rarely) 1000s of m from the massive sulphide lens. This distinctive rock type is referred to in Japan, as tetsusekiei (literally iron-quartz). The tetsusekei from the Fukazawa mine in Japan was found to be very similar to the ‘main contact tuff’ at the Millenbach mine, Quebec (Scott et al., 1983).

2.6. Deposit form. Concordant, massive to banded sulphide lens, typically m to 10s of m thick and 10s to 100s of m in long dimensions; locally with a peripheral apron of ‘clastic’ massive sulphides. The lens, also referred to as a mound, can be elongate along a fault structure or equidimensional at the intersection of major faults (Large, 1992). Locally, a well-developed alteration pipe underlies the massive sulphide lens and extends roughly 100m into the footwall (Ohmoto, 1996); other deposits have extensive footwall, stratiform alteration zones (Slack, 2012b). Significant permeable volcaniclastic rocks underlie many Kuroko VMS deposits, resulting in alteration zones larger than the deposit itself. The alteration zones can extend 50 to 200 m into the footwall volcanic rocks and may extend for 2 to 6 km along strike from the orebody (Large, 1992). The hydrothermal alteration can extend into the hanging wall rocks above the ore lenses.

2.7. Ore controls. The deposits form in the upper portions of volcanoes, associated with synvolcanic subsidence structures like calderas. A well-known example is in the Hokuroko district in Japan (Ohmoto, 1996). Individual ore bodies are on synvolcanic faults that were conduits for the hydrothermal fluids. The massive sulphides can only accumulate during periods of volcanic quiescence and limited sedimentation and will normally only be preserved if covered by barite-silica caps, sediments, or volcanic units.

2.8. Ore texture and structure. The ore is massive to well-layered in the lens and stockwork, vein and disseminated in the footwall. Massive sulfides are typically compact, fine-grained aggregates of intergrown minerals with irregular grain boundaries, with idiomorphic crystals projecting into cavities, colloform overgrowths, framboidal and botryoidal pyrite, pseudomorphic replacement, fine-scale replacement relationships, boxwork intergrowths, and internal mineral growth zoning (Koski, 2012). Coarser grained sulphides occur in strongly metamorphosed deposits.

2.9. Ore mineralogy. Abundant and variable amounts of pyrite, sphalerite, chalcopyrite and, along with significant galena and tetrahedrite, zones of mainly sphalerite and galena. The massive sulphide lenses are commonly zoned from top to bottom (Koski, 2012) as follows: barite with lesser sulphides > massive sphalerite-barite-pyrite-galena (Black ore) > sphalerite plus barite-pyrite-chalcopyrite (Semi-black ore) > chalcopyrite and pyrite (Yellow ore) > pyrite and chalcopyrite (Powdery yellow ore) > pyrite with minor chalcopyrite and sphalerite (Massive pyrite ore). This is produced by zone refining as high temperature fluids entering the base of the massive sulphide lens progressively deposit Cu in the base and interior of the lens, re-dissolve Zn, Pb, (+/-Au), and move them outward resulting in concentration of Zn, Pb and Au at the top of the lens (Gibson et al., 2007).

2.10. Gangue mineralogy. Barite, chert with subordinate gypsum, anhydrite, and carbonate near the top of lens, carbonate quartz, chlorite, and sericite near the base.

2.11. Alteration mineralogy. Stratabound or semi-conformable footwall alteration zones consist of quartz-sericite and locally pyrite with patchy development of chlorite and carbonate. Low-intensity hanging-wall alteration without sulphides can be found above the thickest portions of some massive sulfide lenses. Footwall alteration pipes are commonly zoned from a core with quartz, sericite, or chlorite to an outer zone of clay minerals, albite, and siderite or ankerite. The Hukuroko district alteration pipes consist of a central sericite/chlorite zone flanked by montmorillonite and zeolite zones. The sericite/chlorite zone coincides generally with the stockwork ore zone and the montmorillonite zone extends about 500 m outward from it (Ohmoto, 1996).

2.12. Weathering. Seafloor weathering at the time of deposit formation may occur without rapid burial by sediment and/ or volcanic material to shield the sulphides from seawater contact. Weathering forms insoluble Fe oxy-hydroxide minerals including goethite and hematite, and sulphates such as jarosite (Fallon et al., 2017). Sites containing significant pyrrhotite, marcasite, galena and secondary copper sulphide are predisposed to oxidation. Subaerial weathering by descending, acidic meteoric waters can produce supergene ore. Copper and other metals are mobilized from the primary massive sulfide ore and reprecipitated below (Koski, 2012b). This precipitation of Cu sulfides with high Cu/S ratios can produce an economically significant copper enrichment at the reactive redox boundary between massive sulfide protore and downward penetrating fluids. The supergene enrichment zone is overlain by an intensely altered and leached Fe oxide-rich gossan.

2.13. Comments. This deposit profile is revised from a combined Noranda/Kuroko mineral deposit profile by Höy (1995), which incorporated information from Sangster (1972), Hutchinson (1980), Franklin et al. (1981), Ohmoto (1983), Ohmoto and Skinner (1983), Lydon (1984), Singer, (1986), and Höy, (1991). In the last 20 years, the most prominent classifications of VMS deposits have separated Kuroko and Noranda types based on their associated host rocks or lithostatigraphic settings (Barrie and Hannington, 1999; Franklin et al., 2005; Galley et al., 2007). These assignments may be difficult to apply for less well-known mineral occurrences or deposits that occur in regions without sufficiently detailed geological maps.

3. Exploration and resource assessment guides.

Many of the exploration techniques used to find Kuroko VMS deposits are similar to those used for Noranda VMS deposits.

3.1. Geochemical signatures. Geochemical guides for VMS deposits are provided by sampling waters, tills, soils and soil gases, rocks, minerals, stream and lake sediments and heavy mineral concentrates (Slack, 2012c). Water sampling for Cu, Zn and sulphate combined with changes in surface water pH may be detected by regional surface water surveys (Lett et al., 1998). Soil and till geochemical surveys commonly use the ore-related elements (e.g., Cu, Pb, Zn, Ag, Au) to detect mineralization. Anomaly size can be increased, and the character of the sulphide mineral source better established by using the pathfinder elements like As, Ag, Au, Ba, Bi, Cd, Hg, In, Sb, Se, Sn, and Tl (Gill et al., 2015). Soil gases have also proven useful because of their mobility in the vadose zone and glacial overburden. Indicator minerals include the main ore minerals (galena, sphalerite, chalcopyrite, pyrite, and pyrrhotite), accessory minerals (native gold, electrum, cassiterite, cinnabar, and barite), and various minerals (sillimanite, andalusite, gahnite, staurolite, and spessartine) in a metamorphic terrain. Zonal alteration is a common feature in volcanic rocks underlying sea-floor massive sulfide deposits. Various ratios using whole rock geochemistry have been developed to characterize this alteration, including the Ishikawa alteration index (AI) and the chlorite-carbonate-pyrite index (CCPI). These were combined by Large et al. (2001) in the alteration box plot to characterize the different alteration trends related to massive sulfide ores and to assist in the distinction of VMS-related hydrothermal alteration from regional diagenetic alteration. Piché and Jébrak (2004) have devised a normative mineral alteration index that is less sensitive to lithological variations and better identifies ore-related hydrothermal mineral assemblages. The Portable Infrared Mineral Analyzer (PIMA) and more recently TerraSpec are examples of field tools used for mapping alteration mineral assemblages by detecting the chemical variations as manifested by subtle changes in their infrared spectra.

3.2. Geophysical signatures. Geophysical methods are widely used in VMS exploration. Airborne magnetic and ground gravity and seismic surveys are primarily used to constrain the regional geology and in ideal circumstances directly image ore bodies. Sulphide lenses usually show an electromagnetic signature due to the presence of conductive sulphides like chalcopyrite, pyrite and pyrrhotite. Note that the sphalerite-galena-barite zones will have little or no electromagnetic response. High-resolution and deeply penetrating electromagnetic surveys are extending search results to identify deeper targets (Gibson et al., 2007). Combined airborne electromagnetic and magnetic surveys were the primary tool in discovering many VMS deposits in the last century. Starting in the 1980s, borehole time domain electromagnetic surveys provided important directional information for locating conductive massive sulphides. More recently, ground gravity surveys have been successful for detecting and delineating the shape and size of undiscovered orebodies. Nontraditional geophysical techniques, such as magnetotellurics and deep induced polarization, are being used to search for deposits at greater depths. Seismic surveys can be useful in providing better constraints on geologic models by tracing important geologic features. Hyperspectral data with appropriate line spacing can be collected to identify larger alteration zones where there is minimal surface cover and good outcrop exposures (Agar and Coulter, 2007).

3.3. Other guides. Boulder tracing has been used effectively in Scandinavia and Canada for locating near-surface deposits covered by glacial till or soil. Identifying a favorable stratigraphic interval with an exhalite horizon and/or an abrupt change in lithofacies or composition that marks a hiatus in volcanism can provide prospecting and drilling targets. This correlation requires detailed mapping of lithofacies and structural elements, supplemented by systematic lithogeochemical sampling to fingerprint chemostratigraphic units and high-precision age dating to enable accurate correlations (Mercier-Langevin et al., 2014). Volcanic centres are prospective for ore formation (Gibson et al., 2007). The vent area of volcanic centres can be defined by the presence of felsic flows, domes, and or cryptodomes and/or swarms of mafic and felsic synvolcanic dikes and/or sills.

4. Economic factors

4.1. Typical grade and tonnage. The geometric mean tonnage and grades for 241 Kuroko VMS deposits are 3.32 million tonnes of 1.04% Cu, 1.14% Pb, 4.36% Zn, 1.06 g/t Au, and 56.35 g/t Ag (Franklin et al., 2005). These deposits generally contain more Zn, Pb and Ag and less Cu (Table 1) than Noranda VMS deposits. Some alteration zones have been selectively mined adjacent to the massive sulphide lens. Mosier et al. (2009) provide global grade and tonnage data for VMS deposits organized to assist in resource assessments. The residual concentration of precious metals in gossans, in the form of native gold, electrum, and a variety of silver minerals, can be economically important in some larger Kuroko and other types of VMS deposits (Boyle, 1996).

4.2. Economic limitations. Small massive sulphide lenses were mined in the past, but now are only recovered if they are near larger economic deposits. Metallurgical challenges, such as grain size and deleterious metal content, reduce the value of the ore (Gibson et al., 2007). Coarser grained sulphides occur in strongly metamorphosed deposits which can lead to higher metal recoveries in the milling process due to the enhanced size of mineral grains. Recrystallization can also affect metal recoveries, both negatively due to metal intergrowth and substitution of deleterious metals (e.g., Se and Tl) and positively following thermal and mechanical purification metals such as Hg, As, and Sb (Gibson, 2007).

4.3. End uses. Kuroko VMS deposits are an important source of Cu, Zn and Pb, with varying amounts of Ag and Au.

Table 1. Tonnages and grades for selected Kuroko VMS deposits.

British Columbia	**Mt**	**Cu %**	**Pb %**	**Zn %**	**Au g/t**	**Ag g/t**	**Reference**
Ecstall	4.54	0.86	0.2	2.3	0.69	24.34	Franklin et al., 2005
Kutcho Creek	17	1.6	0.06	2.3	0.37	29	Franklin et al., 2005
Myra Falls Group	29.32	1.83	0.55	6.25	2	49	Franklin et al., 2005
Tulsequah Chief	8.7	1.27	1.18	6.35	2.43	99.4	Franklin et al., 2005
Canada							
Izok Lake (Nunavut)	16.5	2.2	1.1	11.4	<0.10	60	Franklin et al., 2005
Marshall Lake (Ontario)	2	1.2		4.2	0.41	84	Franklin et al., 2005
Mattabi (Ontario)	12.78	0.74	0.85	8.28		110	Franklin et al., 2005
Buchans (Newfoundland)	16.2	1.37	7.73	14.97	1.58	127.89	Franklin et al., 2005
International							
Blue Moon (USA)	2.9	1.3	0.6	8.55	1.47	80	Franklin et al., 2005
El Cuale-La Prieta (Mexico)	13.7	0.3	1.27	4.89	1.28	188	Franklin et al., 2005
Kristineberg (Sweden)	11.8	1	0.3	2.4	0.9	23	Franklin et al., 2005
Udden (Sweden)	8	0.44	0.31	4.54	0.8	40	Franklin et al., 2005
Furutobe-Anai (Japan)	14.24	1.48	0.55	2.32	1.6	148	Franklin et al., 2005
Tsunokakezawa (Japan)	3	1.13	3.3	15.4	0.6	93	Franklin et al., 2005
Kosaka-Uwamuki (Japan)	19.86	1.99	1.54	5.31	0.88	110	Franklin et al., 2005
Scuddles (Australia)	10.5	1.2	0.8	11.7	1.1	89	Franklin et al., 2005
Rosebery (Australia)	32.7	0.58	4.4	14.5	2.7	145	Franklin et al., 2005
Woodlawn (Australia)	17.7	1.7	3.8	9.9	1.4	80	Franklin et al., 2005

4.4. Importance. Kuroko massive sulphide deposits are attractive exploration targets due to their abundance, high grades, and a well-developed exploration model.

5. Genesis

5.1. Genetic model. Both Kuroko and Noranda VMS deposits share a similar genetic model. According to Gibson et al., (2007), the seawater convection model envisages that VMS deposits form syngenetically as a product of seafloor hydrothermal systems that formed in spatial, temporal and genetic association with contemporaneous volcanism and/or plutonism. VMS deposits form on, and immediately below, the seafloor by the discharge of a high temperature, hydrothermal fluid that mixes with seawater. They require: 1) a heat source to initiate, drive, and sustain a long-lived, high temperature hydrothermal system; 2) a high-temperature reaction zone that forms through the interaction of seawater with volcanic and sedimentary strata during which metals are leached from the rocks; 3) deep synvolcanic faults that focus recharge and discharge of metal-bearing hydrothermal fluid; 4) footwall and locally hanging wall alteration zones that are produced by the interaction of near-surface strata with mixtures of high-temperature ascending hydrothermal fluid and ambient seawater; and 5) massive sulphides whose metal content was refined by successive hydrothermal events. The magmatic model (Large, 1992) is generally similar to the seawater convection model but incorporates input from an ore-forming process related directly to fractional crystallization of the magma and the release of metal-rich volatiles at specific times during its evolution that are contribute to the formation of the ore elements.

5.2. Tectonic settings. The plate tectonic setting for Kuroko VMS deposits is suprasubduction continental and oceanic arcs where shortening is interrupted by discrete periods of rifting (Mosier et al. (2009). The rifts provide thermal, magmatic, and structural corridors that focus magma ascent, heat flow, high-temperature convective hydrothermal systems, and emplacement of subvolcanic intrusions for the formation of VMS deposits (Hart et al., 2004).

5.3. Associated deposit types. Eskay Creek-Boliden hybrid VMS (G07); Noranda VMS (GO8).

6. Mineral systems

The following mineral system summary is largely derived from Galley (2003); Franklin et al. (2005); Gibson et al. (2007); Piercey (2011) and Shanks III (2012). It is the same as the mineral system described in the Noranda VMS deposit profile.

6.1. Source region. The source region is the mantle beneath a regional rift.

6.2. Source driver. Rift-related extension results in subsidence and crustal thinning that produces decompression melting of the upper mantle at >1300°C to produce a large volume of hot mafic melt.

6.3. Source product. Significant volumes of mid-ocean ridge basalt and locally boninite or low-Ti tholeiite magmas formed as a result of melting incompatible element-depleted mantle.

6.4. Transport drive. Buoyant magmas rise relatively rapidly which allows for heat retention.

6.5. Transport path. Rifts contain long-lived, thermal, magmatic, and structural corridors that focus magma ascent, heat flow and emplacement of subvolcanic intrusions (Hart et al., 2004).

6.6. Transport termination. The rising magmas evolve to an intermediate composition at a shallow crustal level (< 15km) by incorporating hydrated crust via low to moderate degrees of partial melting with subsequent crystal fractionation of the melt (Franklin et al., 2005) leading to high temperature melts emplaced as subvolcanic sills and dikes and erupted as basalts, andesites and rhyolites.

6.7. Deposit concentration.The rising hydrothermal fluids will commonly focus on near surface, vertical to sub-vertical faults to reach the seafloor. As the fluids approach the sea floor, they interact with seawater in the sediments and /or at the seafloor to cause the deposition of sulphides and gangue minerals due to the dramatic temperature drop and fluid mixing reactions. Fluids encountering more open faults and/or more permeable wallrock introducing seawater at deeper levels can lead to more pronounced and extended alteration pipes.

6.8. Deposit controls. The deposits are localized near faults and fault scarps. The upward movement of hydrothermal fluid is enhanced near the margins of contemporaneous sills. Although the sills are partly responsible for driving hydrothermal circulation, most high-temperature fluids originate in the volcanic basement where flow paths are intersected by basement highs and focused upward along growth faults or the margins of buried intrusions.

6.9. Deposit accumulation. As the sulphide mound builds, the hydrothermal fluids passing through it can heat the internal layers which can lead to zone refining from the base to the top. This will replace lower temperature minerals with higher temperature minerals. Larger deposits will have larger footwall pipes with more mineralization near the original seafloor beneath the mounds.

6.10. Post formation processes. Weathering of seafloor massive sulphide (SMS) deposits is an inevitable consequence of exposure to seawater unless the deposit is rapidly covered by sediment and/or volcanic material that shields sulfides from seawater contact. Bottom, mainly anoxic, waters may contain a small amount of oxygen such that the weathering of the deposit may be slowed but not halted. Outcropping VMS deposits will weather to produce a gossan in most climates.

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G07: Hybrid volcanogenic massive sulphide Ag-Au (hybrid bimodal-felsic)

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1. Identification

1.1. Synonyms. Epithermal massive sulphide, Eskay Creek subaqueous hot spring Au-Ag (Alldrick, 1999); bimodal felsic/ epithermal (Appendix, Table A1, Franklin et al., 2005), hybrid bimodal-felsic (Galley et al., 2007). Volcanogenic massive sulphide (VMS) identifies a class of deposits related to submarine volcanism.

1.2. Commodities and by-products. Two mineralization styles: Ag, Au (Zn, Pb, As, Sb, barite, Hg) and Au, Cu.

1.3. Examples. Low sulphidation. In British Columbia, Eskay Creek (104B 008), Lulu (104B 376), Dolly Varden (103P 188), Torbrit (103P 191), and Samatosum (082M 244); LaRonde (Quebec); Iron Dyke (Oregon, USA); Minas de Oro-Grandeza and El Cuale-La Pieta (Jaisco State, Mexico); Mungana (Queensland, Australia), Que River (Tasmania, Australia), Nimbus (Western Australia).

High sulphidation. Bousquet 2-Dumagami (Quebec); Morne Bossa and Grand Bois (Haiti); Boliden (Sweden); Kamikita-Honko and Oage (Japan); Lerokis and Kali Kuning (Indonesia), Mount Morgan (Queensland, Australia); Henty and Julia (Tasmania, Australia).

2. Geological characteristics

2.1. Capsule description. Hybrid VMS deposits are valued for their high silver and/or gold grades that are associated with massive sulphide, stockwork, and vein mineralization. They are hosted by volcanic and sedimentary rocks or their metamorphic equivalents.

Low sulphidation. Ag-Au-Zn-Pb- deposits, like Eskay Creek, contain sphalerite, galena, pyrite and generally minor subordinate chalcopyrite with associated arsenopyrite, tetrahedrite, stibnite, antimony and other minerals.

High sulphidation. Cu-Au-Ag deposits, such as Boliden, are more commonly veins and stockworks consisting of chalcopyrite-rich mineralization with bornite, enargite, luzonite, tennantite, covellite, native gold, Au-tellurides, low-Fe sphalerite, orpiment and realgar; sphalerite and galena are minor constituents

2.2. Depositional environment and geological setting. Submarine hydrothermal systems associated with volcanoes at water depths of up to 2 km exhibiting a number of features in common with subaerial epithermal systems (Monecke et al., 2014). The systems form in a variety of tectonic settings including intra-arc rifts, summits of seamounts, and unconsolidated shallow marine sediments on the flanks of emergent volcanic islands. Copper-rich massive sulfides typically occur at water depths exceeding ~1,000 m, whereas Zn- and Pb-rich occurrences may form up to ~2 km below the ocean surface (Monecke et al., 2014).

2.3. Ages of mineralization. Examples range from Archean to present day, with a number of modern analogues at active seafloor sites. Phanerozoic deposits are more common.

2.4. Associated rocks. Low sulphidation. Deposits are generally associated with interbedded volcanic and siliciclastic rocks, locally with carbonate units. The stratigraphic sequence hosting the ore deposit may be relatively limited in thickness and rest on an unconformity. The Eskay Creek mine is associated with pillow basalts and basalt breccias and conglomerates deposited near graben-bounding faults that grade laterally to distal turbidites with inter-layered felsic tuff, sandstone, and chert, and intervals of alternating rhyolite, mudstone, and basalt (Alldrick et al., 2005). The mafic volcanic rocks are tholeiitic, sub-alkaline to basaltic andesites, varying from MORB to arc-related (Barresi et al., 2015). The Nimbus deposit in Australia is in a generally similar sequence of rocks (Hollis et al., 2017). The LaRonde deposit regional stratigraphy consists of extensive tholeiitic basaltic flows overlain by tholeiitic to transitional, mafic to intermediate, effusive and volcaniclastic units at the base and transitional to calc-alkaline, intermediate to felsic, effusive and intrusive rocks on top (Mercier-Langevin et al., 2007).

High sulphidation. The Boliden deposit is associated with a mostly calc-alkaline sequence of rhyolitic to basaltic, subaqueous volcaniclastic rocks, porphyritic intrusions, and lavas with minor sedimentary rocks that is overlain by fine- and coarse-grained sedimentary strata that are intercalated with locally abundant felsic to mafic volcanic rocks and felsic volcaniclastic mass flow deposits (Mercier-Langevin et al., 2013). The Bousquet 2- Dumagami deposit is associated with a succession of tholeiitic basalt and basaltic andesite flows, cogenetic gabbroic sills, and local isolated rhyolite and rhyodacite flows overlain by basaltic to rhyolitic flows, domes, synvolcanic intrusions, and volcaniclastic strata (Dubé et al., 2014). A tholeiitic to transitional, rhyodacitic to rhyolitic, blue quartz-bearing sill-dike complex is in the stratigraphic footwall of the deposit.

2.5. Host rocks. Low sulphidation Eskay Creek deposit, mineralization is hosted by intermediate to felsic flows and tuffs and intercalated sedimentary rocks, such as mudstone and conglomerates. Pillow lavas, coarse epiclastic mass flows, and assorted subvolcanic feeder dikes can also be part of the local stratigraphic package. The LaRonde deposit is hosted by dacitic to rhyodacitic flow breccia deposits that are cut and overlain by rhyodacitic and rhyolitic domes and/or partly extrusive cryptodomes and by intermediate to mafic sills and dikes.

High sulphidation. The Boliden deposit mineralization is hosted by altered dacite in a sequence of intermediate to mafic and feldspar-phyric dacite to quartz-feldspar porphyritic rhyolite (Mercier-Langevin et al., 2013). The Bousquet 2-Dumagami deposit is hosted by basaltic to rhyolitic flows, domes, synvolcanic intrusions and volcaniclastic strata, including regionally atypical intermediate to calc-alkaline dacite and rhyodacite (Dubé et al., 2014).

2.6. Deposit form. The deposit form is variable, including massive sulphide pods, finely laminated stratiform sulphide layers and lenses, reworked clastic sulphide beds, footwall stockwork or stringer vein networks, epithermal-style veins, which can exhibit breccias, large vugs, and coarse sulphides. All types may coexist in a single deposit. The footwall mineralization commonly represents significant ore; locally the massive sulphide zones are not ore suggesting that subsea-floor replacement and depositional processes are important (Mercier-Langevin et al., 2011).

2.7. Ore controls. At the district scale, hybrid VMS deposits commonly occupy a stratigraphic position and/or volcanic setting that differs from other VMS deposits of the district (Mercier-Langevin et al., 2011). Some deposits in rifts are underlain by relatively limited stratigraphic sequences of sedimentary and volcanic rocks. This relationship can occur near boundary faults where structural features and moderate water depths are favourable, with hydrothermal fluids coming from more extensive volcanism elsewhere in the rift. VMS formation is favored in calderas during and immediately after caldera collapse and during post-caldera resurgence (Stix et al., 2003). For example, VMS solutions that emerge from the principal caldera fault at the bottom of a deep asymmetric caldera may undergo little or no boiling. These hydrothermal solutions and VMS deposits will be enriched in copper and zinc (Herzig and Hannington, 1995). Other solutions emanating from faults at structurally higher levels within the caldera, or even outside the caldera, are subjected to greater boiling at shallower water depths, and the resultant hybrid VMS deposit may be enriched in elements such as gold and mercury (Hannington et al., 1997; Hannington et al., 1999).

2.8. Ore texture and structure. Textures range from fine clastic sulphides and framboid-like chemical precipitates to very coarse grained sulphide aggregates in breccia veins. Structural styles include: stratabound and stratiform sulphide lenses and layers, vein stockworks, and breccia veins. Fragmental textures at all scales at the Nimbus deposit have been interpreted to record repeated crack and seal events (Hollis et al., 2017). The mineralization in the high sulphidation deposits appears to be largely restricted to the footwall stringers and veins.

2.9. Ore mineralogy. Low sulphidation. Wide range of minerals including sphalerite, tetrahedrite, boulangerite, bournonite, electrum, native silver, amalgam, galena, chalcopyrite, enargite, pyrite, stibnite, realgar, arsenopyrite, orpiment; subordinate metallic arsenic, Hg-wurtzite, cinnabar, aktashite, unnamed Ag-Pb-As-S minerals, jordanite, wurtzite, krennerite, coloradoite, marcasite, magnetite, scorodite, jarosite, limonite, anglesite, and native sulphur. Sulphosalts are found at Eskay Creek and Nimbus. Pyrargyrite, Ag-bearing tetrahedrite; subordinate marrite and rare owyheeite are also found at Nimbus (Hollis et al., 2017).

High sulphidation. Deposits consist of pyrite with some of the following minerals: bornite, enargite, luzonite, tennantite, covellite, native gold, electrum, Au-tellurides, low-Fe sphalerite, orpiment and realgar (Sillitoe et al., 1996; Hannington et al., 1997; Mercier-Langevin et al., 2011). The Lerokis and Kali Kuning Au-Ag barite deposits are intimately associated with zones of massive pyrite-marcasite containing abundant enargite and tennantite. The barite mineralization is underlain by Cu-bearing sulfides, which pass downward into silicified, pyritic stockworks associated with alunite-bearing alteration (Sillitoe et al., 1996).

2.10. Gangue mineralogy. Magnesian chlorite, muscovite (sericite), chalcedonic silica, amorphous silica, calcite, dolomite, pyrobitumen, gypsum, barite, potassium feldspar, alunite; carbon, graphite, halite and cristobalite are subordinate (Alldrick, 1999). Jasper and minor carbonate also in some deposits. In metamorphosed terranes, the gangue minerals may include quartz, sericite, andalusite, kyanite, pyrophyllite, Zn-rich staurolite, and Mn-rich garnet (Dubé et al., 2007).

2.11. Alteration mineralogy. Low sulphidation. Massive chlorite (clinochlore)-illite-quartz-gypsum-barite rock or quartz-muscovite-pyrite rock are associated with the near-footwall stockwork zones. Chlorite and pyrite are associated with the deep-footwall stockwork zones where these minerals are restricted to fractures. Stratabound mineralization is accompanied by magnesian chlorite, muscovite, chalcedonic silica, calcite, dolomite and pyrobitumen. At Eskay Creek an extensive zone of carbonate-kaolinite alteration in the carbonaceous mudstone hosting the stratiform clastic sulphide and sulphosalt orebodies is the most notable alteration (Meuzelaar, 2012). This style of alteration is largely restricted to areas overlying upflow zones of mineralizing hydrothermal fluids and associated discordant sulphide zones in the footwall rhyolite. Secondary potassium-feldspar formation and moderate silicification are in the periphery of the stratiform ores and in deeper parts of the footwall. Immediately underlying the stratiform ore zones, a tabular zone of more intense and texturally destructive chlorite and white mica alteration is recognized. An unusual hydrocarbon alteration is locally below the stratiform ore zones (Monecke et al., 2014).

High sulphidation. Alteration consists of advanced argillic mineral assemblages with intense silicification including quartz, kaolinite, pyrophyllite, diaspore, alunite, barite, and native sulfur. These assemblages may be represented by aluminosilicate minerals in metamorphosed deposits. The Tsuchihata, Kamikita-Honko and Oage VMS deposits in Japan consisted almost entirely of Cu-bearing pyritic stringer ore in silicified zones (Sillitoe et al., 1996). These were pipe or funnel-shaped zones of pyritic veinlet and disseminated mineralization, which contained appreciable amounts of enargite, luzonite, covellite, tetrahedrite, and native sulfur in association with silicification and/or advanced argillic alteration. Sericite-chlorite alteration surrounds the stockwork zone in two of the Tsuchihata pipes, immediately below barite-rich caps. The pyritic stockwork at Kamikita-Honko is hosted by a quartz-diaspore-kaolinite-pyrophyllite assemblage, whereas that at Oage is accompanied by quartz, alunite, diaspore, kaolinite, pyrophyllite, barite, and native sulfur.,

2.12. Weathering. Many of the intensely altered host rocks are easily eroded, which can limit outcrop exposure of mineralization; silicified zones will be more resistant. Iron sulphide-rich zones will form gossans in outcrop.

2.13. Comments. In the 1990s it was recognized that the Eskay Creek deposit was a different type of VMS (Alldrick, 1996; Alldrick, 1999; Roth et al., 1999). Exploration of modern seafloor hydrothermal systems with VMS mineralization increased the understanding of Eskay Creek and other related deposits (Hannington et al., 1997). Hybrid VMS deposits are rarer than their conventional counterparts, in part because some of them have been confused with other deposit types.

3. Exploration and resource assessment guides

3.1. Geochemical signatures. The epithermal suite of minerals and related elements (Ag, Au, Cu, Pb, Zn, As, Sb, Hg) can characterize submarine volcanogenic hydrothermal systems and is not unique to subaerial epithermal deposits (Mercier-Langevin et al., 2013). At Eskay Creek, elevated Sb, As, Hg, and Ba are characteristic of the high-grade ore (Roth et al., 1999).

3.2. Geophysical signatures. Airborne and ground geophysics are important because the massive sulphide lenses, and sometimes portions of footwall alteration pipes have higher density and positive magnetic and conductivity properties that differ significantly from those of their host rocks (Ford et al., 2007). Contrasts in magnetic, electromagnetic, and gravitational (density) properties are direct exploration guides; gamma-ray spectroscopy provides an indirect technique based on chemical contrasts associated with near-surface alteration, mostly as potassium enrichment or depletion near the deposit. Sulphide lenses commonly show a strong electromagnetic response based on the presence of conductive sulphides. In cases where the sulfide grains are not electrically connected, such as in the disseminated sulfide stockwork below the main massive sulfide ore body, induced polarization can be useful.

3.3. Other guides. Additional exploration guides include: broad hydrothermal systems marked by widespread alteration; the presence of a synvolcanic rift or volcanic caldera; and accumulations of felsic volcanic strata that formed in a local subaqueous setting in regional subaerial environment or along the near shore zone of a regional subaerial to subaqueous volcanic transition.

4. Economic factors

4.1. Typical grade and tonnage. These deposits are highly valued for Ag and /or Au and commonly contain significant base metals (Table 1). The low sulphidation hybrid VMS deposits typically have higher Pb and Zn contents than those that are high sulphidation. Base metals were not always recovered from some of these deposits and are not uniformly reported, as shown in Table 1. Eskay Creek has the highest gold grade at 26.4 g/t of any VMS deposit with an average Ag grade of 998 g/t. The Boliden deposit is the second largest gold-rich VMS with an unusually high arsenic content at 6.8% (Mercier-Langevin et al., 2013). The Bousquet 2-Dumagami deposit is the fourth largest Au-rich VMS deposit (Dubé et al., 2014).

4.2. Economic limitations. The generation of acid rock drainage and the possibility of elements like Hg escaping into the surrounding water systems may need to be addressed. In some deposits, Au is mainly hosted in commonly refractory arsenic-rich pyrite and arsenopyrite and present as submicroscopic inclusions or structurally bound to the crystal lattice (Dubé et al., 2007).

Table 1. Tonnage and grade data for selected hybrid VMS deposits.

	Mt	**Cu %**	**Pb %**	**Zn %**	**Au g/t**	**Ag g/t**	**Reference**
low sulphidation							
Canada							
Eskay Creek (British Columbia)	4	0.33	2.2	5.4	26.4	998	Galley et al., 2007
Samatosum (British Columbia)	0.35	1.07	1.44	2.7	1.80	1210.00	Franklin et al., 2005
Torbrit (British Columbia)	1.185					278.0	Turner and Nicholls, 2019
Selbaie (Quebec)	29.90	1.21		1.91	0.63	37.02	Galley et al., 2007
Hackett River (Nunavut)	25.0	0.5	0.6	4.2	0.2	100	Grant et Al., 2016
Australia							
Mungana (Queensland)	1.6	1	2.3	2.3	2.1	106	Franklin et al., 2005
Nimbus (Western Australia)	12.1			0.9	0.2	52	Hollis et al., 2017
Que River (Tasmania)	3.3	0.7	7.4	13.3	3.3	195	McGoldrick et al., 1992
high sulphidation							
Canada							
Bousquet #2-Dumagami (Quebec)	15.55	0.67		0.31	7.8	12.8	Mercier-Langevin et al., 2013
Laronde (Quebec)	88.1	0.32		1.71	5.07	40.9	Galley et al., 2007
Rambler–Ming (Newfoundland)	5.45	2.53			1.00	8.00	Franklin, 2005
International							
Iron Dyke (California)	0.51	2.84			6.99	29.5	Franklin, 2005
Boliden (Sweden)	8.4	1.4	0.3	0.9	15.9	50.0	Mercier-Langevin et al., 2013
Tsuchihata (Japan)	>4.50	1.17					Sillitoe, 1996
Lerokis (Indonesia)	2.9				3.3	106	Sillitoe, 1996
Australia							
Mt Morgan (Queensland)	50	0.7	0.1	0.05	4.7	0.6	Galley et al., 2007
Henty (Tasmania)	0.52	0.1	0.1	0.05	27.61	10	Franklin et al., 2005
Mt Lyell (Tasmania)	98.57	1.17	0.01	0.04	0.39	7.2	Franklin et al., 2005

4.3. End uses. A source of Ag and Au; less commonly Cu, Zn and Pb.

4.4. Importance. These deposits are attractive because of their bonanza precious metal grades, polymetallic character, and tendency to occur in clusters.

5. Genesis

5.1. Genetic model. Deposits are formed where epithermal-type fluids circulate beneath and vent on the seafloor. Hydrostatic pressure, as dictated by water depth, is the main control on the maximum temperature of hydrothermal fluids discharging on the seafloor. The composition of the mineralizing fluids and water depth governs the character of the mineralization. Fluid conduits are fissures generated by: seismic shock; volcano inflation over an expanding magma chamber; and fracturing in response to regional shortening. A near-surface subvolcanic magma body is the likely source of heat and possibly metal-rich fluids (Sillitoe, 2020). Hybrid VMS deposits may form distal to the main eruptive centres or subvolcanic heat sources. Modern seafloor vent sites demonstrate that boiling of hydrothermal fluids is common at volcanic arcs and in arc-related rifts. A hybrid VMS system can gradually evolve from creating neutral Au-Cu-Zn-Ag-Pb ore to acidic advanced argillic alteration and Au ± Cu ore (Mercier-Langevin et al., 2007).

5.2. Tectonic settings. Transitional arc and back-arc settings (both oceanic island arcs and continental margin arcs), near-trench volcanoes, rifted fore-arcs, rifted continental margins. The Eskay rift belt includes at least 12 sub-basins that formed as en-echelon, transtensional graben as a result of oblique collisional tectonics between Stikinia and adjacent terranes (Barresi et al., 2015). An abrupt change in magmatic affinity in response to changes from arc volcanism to arc rifting and back-arc volcanism resulted in the Eskay Creek deposit.

5.3. Associated deposit types. Noranda VMS (G08), Kuroko VMS (G06), Besshi VMS (G04), epithermal Au-Ag-Cu: high sulphidation (H05), epithermal Au-Ag: low sulphidation (H04), hot spring Au-Ag (H03).

6. Mineral systems

The following mineral system summary draws from Sillitoe et al. (1996); Galley (2003); Franklin et al. (2005); Galley et al. (2007), and Barresi et al. (2015). A hybrid VMS system can gradually evolve from creating neutral Au-Cu-Zn-Ag-Pb ore to acidic advanced argillic alteration and Au ± Cu ore (Mercier-Langevin et al., 2007).

6.1. Source region. The source region is the mantle beneath a region of rift-related crustal thinning.

6.2. Source driver. Rift-related extension results in subsidence and crustal thinning that produces decompression melting of the upper mantle at > 1300°C to produce a large volume of hot mafic melt. An alternative theory is that a magmatic plume drives the extension and starts the upward migration of magma into the crust.

6.3. Source product. Significant volumes of mid-ocean ridge basalt and locally boninite or low-Ti tholeiite magmas formed as a result of melting incompatible element-depleted mantle.

6.4. Transport driver. Buoyant magmas rise relatively rapidly, which allows for heat retention.

6.5. Transport path. Rift environments contain long-lived, thermal, magmatic, and structural corridors that focus magma ascent, heat flow, and emplacement of subvolcanic intrusions (Hart et al., 2004).

6.6. Transport termination. The rising magmas evolve to an intermediate composition at a shallow crustal level (< 15km) through incorporation of hydrated crust via low to moderate degrees of partial melting, with subsequent crystal fractionation of the melt (Franklin et al., 2005) leading to high-temperature melts emplaced as subvolcanic sills and dikes and erupted as basalts, andesites, and rhyolites. An important element for some of these deposits can be a relatively shallow emplacement of subvolcanic intrusions, which leads to greater magmatic fluid input (Sillitoe, 2020).

6.7. Deposit concentration. The rising hydrothermal fluids will commonly focus on near surface, vertical to sub-vertical faults to reach the seafloor. The hydrothermal fluids rise until descending seawater interacts with the mineralizing fluids to deposit mineralization beneath and at the seafloor (Mercier-Langevin et al., 2007). Fluids encountering more open faults and/or more permeable wallrock introducing seawater at deeper levels can lead to more pronounced and extended alteration pipes with more pronounced mineralization closer to massive sulphide lenses. In low sulphidation deposits, descending seawater evolves to produce heated, near neutral to weakly acidic fluids that leach metals from the wall rocks and transports them upwards towards the seafloor. In high sulphidation deposits, the parental magma contributes Au, SO2-rich volatiles, and metalliferous brines to the seawater, changing its composition to an oxidized, low-pH fluid and providing heat, resulting in more Au and Cu being transported and more metals being leached from the wall-rock.

6.8. Deposit controls. The deposits are localized near faults and fault scarps and massive sulphides are deposited within local basins..

6.9. Deposit accumulation. Larger deposits form when the hydrothermal fluids continue to deposit mineralization for a longer time with limited deposition of sediments and volcanic rocks and produce massive sulphides and other styles of mineralization at different stratigraphic levels.

6.10. Post formation processes. VMS deposits formed in shallow-water settings are more prone to erosion, perhaps explaining the relatively limited number of silver and gold-rich VMS deposits in the geologic record (Mercier-Langevin et al., 2011).

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G08: Noranda volcanogenic massive sulphide Cu-Pb-Zn (bimodal-mafic VMS)

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1. Identification

1.1. Synonyms. Polymetallic volcanogenic massive sulphide, bimodal-mafic VMS (Barrie and Hannington, 1999). Volcanogenic massive sulphide (VMS) identifies a class of deposits related to submarine volcanism.

1.2. Commodities and by-products. Cu, Pb, Zn, Ag, Au (Cd, S, Se, Sn, In, barite, gypsum).

1.3. Examples. Flin Flon, Trout Lake, and Callinan (Manitoba); Kidd Creek (Ontario); Ansil, Corbett, Millenbach and Matagami Lake (Québec), Tambo Grande (Peru); Skorovas (Norway); 50Let Oktyabrya (Kazakhstan); Hongtoushan and Xiqui (China).

2. Geological characteristics

2.1. Capsule description. Noranda VMS deposits consist of one or more lenses of massive sulphides containing abundant Fe-sulphides (pyrite or pyrrhotite), subordinate amounts of chalcopyrite and sphalerite, and minor galena, barite, tetrahedrite, bornite, and other mineral phases. The lenses may be zoned, with a Cu-rich base, a Zn-rich top, and a cap of chert layers and/or barite. The deposits overlie discordant, sulphide-bearing stringer or stockwork zones called alteration pipes. The mineralization is hosted by felsic domes and flows, and/or mafic flows with minor sedimentary rocks, in predominantly mafic volcanic sequences.

2.2. Depositional environment and geological setting. The deposits form in submarine grabens related to volcanic edifices, such as calderas, on and immediately beneath the seafloor. The deposits require a period of volcanic quiescence or limited volcanism and sedimentation to enable accumulation of the massive sulphide lens. Many older VMS deposits have been deformed and metamorphosed.

2.3. Ages of mineralization. These deposits formed since the Archean and are most common in the Archean and Paleoproterozoic. In the Canadian Shield, many of these deposits are Neoarchean and formed in a comparatively narrow time interval, between 2740 and 2690 Ma (Franklin et al., 2005).

2.4. Associated rocks. Noranda VMS are in sections of pillowed and massive basaltic flows and felsic flows and domes with greywacke, sandstone, and argillite and local mass flow deposits flows (Franklin et al., 2005). Mafic dikes and sills intrude the sequence. Large subvolcanic intrusions composed of quartz diorite–tonalite–trondhjemite are recognized in most Precambrian VMS camps. The quartz-diorite and possibly tonalite phases follow tholeiitic fractionation trends whereas the trondhjemites are in the composition field for primitive crustal melts. Geochemical and geochronological studies indicate that the most voluminous phases were emplaced later than the nearby VMS deposits (Gibson et al., 2007).

2.5. Host rocks. Basaltic rocks form the bulk of stratigraphy. The rock sequence may display a shift from basalt with an arc affinity to a midocean ridge basalt composition (±boninite) at the stratigraphic position of the deposits (Franklin et al., 2005). The VMS deposits are typically close to rhyolite domes and flows and, locally in an unusual association with andesite. In particular, high-silica rhyolites with specific compositions (as defined by Hart et al. 2004) as typically FIII, but locally FIV or FII type (Gibson et al., 2007) are spatially related to some deposits. Ore horizons commonly grade laterally and vertically into thin, sulphidic chert, waterlain tuff or chemical deposits (exhalites). Exhalites form by the precipitation of mainly amorphous Fe ± Mn ± Si ± S ± Ba ± B phases from hydrothermal vents and plumes (Slack, 2012b) commonly with intermingled tuff or fine-grained deposits. They are from a few cm to as much as several m thick and can extend 100s to (rarely) 1000s of m from the massive sulphide lens. Thin bedded tuffs or sedimentary layers with minor pyrite and/or pyrrhotite, and locally sphalerite and/or galena, are also called exhalites in some mining districts.

2.6. Deposit form. A concordant, massive to banded sulphide lens or multiple lenses, typically m to 10s of m thick and 10s to 100s of m in long dimensions, locally with a peripheral apron of ‘clastic’ massive sulphides. The lens, also referred to as a mound, can be elongate along a fault structure or equidimensional at the intersection of major faults (Large, 1992). Many deposits have an underlying alteration pipe or 'stringer' zone that crosscuts the host stratigraphy and may reach ore grades close to the overlying sulphide lens. Such a pipe flares towards to the base of the massive sulphide lens. If flows are predominant, a well-defined alteration pipe may extend ~20 to 500m into the footwall with a width to depth ratio of ~ 1.10, which is smaller in maximum diameter than the massive sulphide lens (Franklin et al., 2005). If the deposit is underlain by volcaniclastic rocks, the pipe is moderately to poorly developed or there is a weaker, stratiform alteration zone, which is generally significantly larger than the VMS deposit, is developed instead.

2.7. Ore controls. The deposits form on and in volcanic structures like domes and calderas. A well-known example is the Noranda caldera structure with intracaldera deposits having formed with onset of renewed volcanism following two periods of caldera subsidence (Gibson and Galley, 2007). Individual ore bodies are located on synvolcanic faults that were conduits for hydrothermal fluids. The massive sulphides can only accumulate during periods of volcanic quiescence and limited sedimentation and will normally only be preserved if covered by slightly younger volcanic or sedimentary rocks.

2.8. Ore texture and structure. The ore is massive to well-layered sulphides in the lens and stockwork, vein and disseminated sulphides in the footwall. Massive sulfides are typically compact, fine-grained aggregates of intergrown sulfide minerals with irregular grain boundaries with idiomorphic crystals projecting into cavities, colloform overgrowths, framboidal and botryoidal pyrite, pseudomorphic replacement, fine-scale replacement relationships, boxwork intergrowths, and internal mineral growth zoning (Koski, 2012a). Coarser grained sulphides occur in strongly metamorphosed deposits.

2.9. Ore mineralogy. The massive sulphides are typically mostly pyrite, and locally pyrrhotite, marcasite, or magnetite interbedded with the ore minerals chalcopyrite and sphalerite with minor galena. These deposits commonly have an upper massive zone consisting of fine-grained pyrite, sphalerite, galena, chalcopyrite with pyrrhotite, tetrahedrite-tennantite, bornite, and arsenopyrite overlying a lower massive zone of pyrite, chalcopyrite, and sphalerite, locally with pyrrhotite and/or magnetite. This relationship is produced by zone refining that develops as high temperature fluids entering the base of the massive sulphide lens progressively deposit Cu within the base and interior of the lens and redissolve Zn, Pb, (+/-Au) and move them upward and outward resulting in concentration of Zn, Pb, and Au at the top of the lens (Gibson et al., 2007).

2.10. Gangue mineralogy. Barite, chert, gypsum, anhydrite, and carbonate minerals occur near the top of a lens and carbonate minerals, quartz, chlorite, and sericite near the base.

2.11. Alteration mineralogy. Footwall alteration pipes are commonly zoned from a central core of quartz, sericite, or chlorite to an outer zone of clay minerals, albite, and siderite or ankerite. The hydrothermal alteration can extend into the hanging wall rocks above some VMS deposits. In highly metamorphosed terranes the alteration zonation is mineralogically enhanced through the development of distinctive, coarse-grained metamorphic assemblages (Gibson et al., 2007).

2.12. Weathering. Seafloor weathering at the time of deposit formation may occur without rapid burial by sediment and/or volcanic material to shield the sulphides from seawater contact. Weathering forms insoluble Fe oxy-hydroxide minerals including goethite and hematite, and sulphates such as jarosite (Fallon et al., 2017). Sites containing significant pyrrhotite, marcasite, galena, and secondary copper sulphide are predisposed to oxidation. Subaerial weathering of deposits by descending, acidic meteoric waters can produce supergene ore. Copper and other metals are mobilized from the primary massive sulfide ore and reprecipitated below (Koski, 2012b). This precipitation of Cu sulfides with high Cu/S ratios can produce an economically significant copper enrichment at the redox boundary between massive sulfide protore and downward penetrating fluids. The supergene enrichment zone is overlain by an intensely altered and leached Fe oxide-rich gossan. The residual concentration of precious metals in gossans, in the form of native gold, electrum, and a variety of silver minerals, can be economically important in some larger VMS deposits of various types (Boyle, 1996).

2.13. Comments. This deposit profile is revised from a combined Noranda/Kuroko mineral deposit profile by Höy, (1995) which incorporated information from Sangster (1972); Hutchinson (1980), Franklin et al. (1981), Lydon (1984), Singer, (1986), and Höy (1991). In the last 20 years, the prominent classifications have separated the most common types of VMS deposits (Kuroko and Noranda) based on lithostratigraphic settings (Barrie and Hannington, 1999; Franklin et al., 2005; Galley et al., 2007). These assignments can be difficult to apply accurately for little known mineral occurrences or in regions with less detailed geological maps. The two deposit types share a number of characteristics in common which can add to the confusion.

3. Exploration and resource assessment guides

Many of the exploration techniques used to find Noranda VMS deposits are similar to those used for Kuroko VMS deposits.

3.1. Geochemical signatures. Geochemical guides for VMS deposits are provided by sampling waters, tills, soils and soil gases, rocks, minerals, stream and lake sediments and heavy mineral concentrates (Slack, 2012c). Water sampling for Cu, Zn, and sulphate combined with changes in surface water pH may be detected by regional surface water surveys (Lett et al., 1998).

Soil and till geochemical surveys commonly use the ore-related elements (e.g., Cu, Pb, Zn, Ag, Au) to detect mineralization. Anomaly size can be increased, and the character of the sulphide mineral source better established by using the pathfinder elements like As, Ag, Au, Ba, Bi, Cd, Hg, In, Sb, Se, Sn, and Tl (Gill et al., 2015). Soil gases have also proven useful because of their mobility in the vadose zone and glacial overburden. Indicator minerals include the main ore minerals (sphalerite, chalcopyrite, galena, pyrite, and pyrrhotite), accessory minerals (native gold, electrum, cassiterite, cinnabar, and barite), and others (sillimanite, andalusite, gahnite, staurolite, and spessartine) formed from VMS alteration minerals in a metamorphic terrain. Zonal alteration is a common feature in volcanic rocks underlying sea-floor massive sulfide deposits. Various ratios using whole rock geochemistry have been developed to characterize this alteration, including the Ishikawa alteration index (AI) and the chlorite-carbonate-pyrite index (CCPI). These were combined by Large et al., (2001) in the alteration box plot to characterize the different alteration trends related to massive sulfide ores and to assist in the distinction of VMS-related hydrothermal alteration from regional diagenetic alteration. Piché and Jébrak (2004) have devised a normative mineral alteration index that is less sensitive to lithological variations and better identifies ore-related hydrothermal mineral assemblages. The Portable Infrared Mineral Analyzer (PIMA) and more recently TerraSpec are the first field tools used for mapping alteration mineral assemblages by detecting the chemical variations as manifested by subtle changes in their infrared spectra.

3.2. Geophysical signatures. . Geophysical methods are widely used in VMS exploration. Airborne magnetic and ground gravity and seismic surveys are primarily used to constrain the regional geology and, in ideal circumstances, directly image ore bodies. Sulphide lenses usually show either an electromagnetic or induced polarization signature depending on the style of mineralization and presence of conductive sulphides. Combined airborne electromagnetic and magnetic surveys were the primary tool in discovering many VMS deposits in the last century. Starting in the 1980s, borehole time-domain electromagnetic surveys provided important directional information for locating massive sulphides. More recently, ground gravity surveys have been successful for detecting then delineating the shape and size of undiscovered orebodies. High-resolution and deeply penetrating electromagnetic surveys are extending search results to identify deeper targets (Gibson et al., 2007). Nontraditional geophysical techniques, such as magnetotellurics and deep induced polarization, are being used to search for deposits at greater depths. Seismic surveys have proven useful in providing better constraints on geologic models, as shown in the Noranda mining camp by tracing a number of important geologic features, including favorable stratigraphic intervals to depth (Mercier-Langevin et al., 2014a). Hyperspectral data with appropriate line spacing can identify larger alteration zones where there is minimal surface cover and good outcrop exposures (Agar and Coulter, 2007).

3.3. Other guides. Boulder tracing has been used effectively in Scandinavia and Canada for locating near surface deposits covered by glacial till or soil. Identifying a favorable stratigraphic interval that marks a hiatus in volcanism with an exhalite horizon and/or an abrupt change in lithofacies or in lithofacies composition can provide prospecting and drilling targets. This correlation requires detailed mapping of lithofacies and structural elements, supplemented by systematic sampling to fingerprint chemostratigraphic units, and high-precision age dating to enable accurate correlations (Mercier-Langevin et al., 2014). The vent area of volcanic centres are defined by the presence of felsic flows, domes, and or cryptodomes and/or swarms of mafic and felsic synvolcanic dikes and/or sills. These volcanic centres are prospective for ore formation (Gibson et al., 2007). Large, multiphase subvolcanic intrusions indicate long-lived thermal corridors in which repeated rift-related volcanism and intrusive activity can generate suitable and episodic VMS environments (Galley, 2003; Hart et al., 2004; Franklin et al., 2005). These intrusions can be readily recognized during regional reconnaissance for potential greenfields VMS exploration (Gibson et al., 2007). Locating regional, semi-conformable alteration zones with up to 10s of km of strike length that extend downwards from the paleoseafloor to a subvolcanic intrusion (Gibson et al., 2007) is another exploration guide. These display vertical mineralogical and compositional variations that are divisible into an upper (e.g., diagenetic-zeolitic, carbonate, spilitic alteration) and lower zone (e.g., epidote-quartz alteration).

4. Economic factors

4.1. Typical grade and tonnage. The geometric mean grade and tonnage for 291 Noranda VMS deposits is 3.42 million tonnes grading 1.82% Cu, 0.30 % Pb, 2.3 % Zn, 0.81 g/t Au, and 21.14 g/t Ag (Franklin et al., 2005). Mosier et al. (2009) also provided global grade and tonnage data for VMS deposits. Noranda VMS deposits generally contain more Cu and less Zn, Pb and Ag than Kuroko VMS deposits. Some alteration pipe stockworks have been selectively mined adjacent to the massive sulphide lens like Kidd Creek (Slack, 2012a) and some deposits in the Noranda mining camp.

4.2. Economic limitations. Small massive sulphide lenses were mined in the past, but now are only recovered if close to economic deposits. Metallurgical challenges, such as grain size and deleterious metal content, can reduce the value of ore (Gibson et al., 2007). Coarser grained sulphides in highly metamorphosed deposits, which can lead to higher metal recoveries during milling due to the enhanced size of mineral grains. Recrystallization can also affect metal recoveries, both negatively due to metal intergrowth and substitution of deleterious metals (e.g., Se and Tl) and positively following thermal and mechanical purification of deposits of metals such as Hg, As, and Sb (Gibson, 2007).

4.3. End uses. Important sources of Cu and Zn with varying Ag, Au and Pb. Some mines produce other commodities. For example, Kidd Creek has also produced indium, silver-bearing slimes, nickel-copper carbonate, liquid SO_2, and sulphuric acid.

Table 1. Tonnages and grades for selected Noranda VMS deposits.

	Mt	Cu %	Pb %	Zn %	Au g/t	Ag g/t	Reference
Canada							
Trout Lake (Manitoba)	10.18	2.11		4.79	1.41	15.43	Franklin et al., 2005
Flin Flon (Manitoba)	62.93	2.2		4.1	2.85	43.20	Franklin et al., 2005
Kidd Creek (Ontario)	147.88	2.31	0.22	6.18	0.01	87	Franklin et al., 2005
Ansil (Quebec)	1.58	7.22		0.94	1.6	26.5	Franklin et al., 2005
Corbet (Quebec)	2.78	2.92		1.62	1	21	Franklin et al., 2005
Horne - No. 5 (Quebec)	144	1		0.9	1.4		Franklin et al., 2005
Millenbach (Quebec)	3.56	3.46		4.33	1	56.2	Franklin et al., 2005
Matagami Lake (Quebec)	25.6	0.42	5.1	0.3		21.6	Franklin et al., 2005
International							
Tambo Grande 3 (Peru)	82	1	0.3	1.4	0.8	25	Franklin et al., 2005
Skorovas (Norway)	6.62	0.73		1.65	0.1	10	Franklin et al., 2005
Shermskoye Novy (Russia)	36.2	1.01		1.32	0.25	8.7	Franklin et al., 2005
50Let Oktyabrya (Kazakhstan)	49.40	1.8		0.5	0.06	51.00	Franklin et al., 2005
Xiqiu (China)	31	1.03		1.83	0.49	10.96	Franklin et al., 2005
Hongtoushan (China)	40	1.75		2.4	0.77	32.4	Franklin et al., 2005

4.4. Importance. Noranda VMS deposits are major producers of Cu, Zn, Ag, Au, and minor Pb. Their high grade and precious metal contents make them attractive exploration targets.

5. Genesis

5.1. Genetic model. Similar genetic models are proposed for the formation of Noranda and Kuroko VMS deposits as a product of hydrothermal systems that formed in spatial, temporal and genetic association with contemporaneous volcanism and/or plutonism. Massive sulphides form on, and immediately below, the seafloor by the discharge of a high temperature, hydrothermal fluid. They require the following elements: 1) a heat source to initiate, drive and sustain a long-lived, high temperature hydrothermal system; 2) a high-temperature reaction zone that forms through the interaction of evolved seawater with volcanic and sedimentary strata during which metals are leached from the rocks; 3) deep synvolcanic faults that focus recharge and discharge of metal-bearing hydrothermal fluid; 4) footwall and locally hanging wall alteration zones that are produced by the interaction of near-surface strata with mixtures of high-temperature ascending hydrothermal fluid and ambient seawater; and 5) massive sulphide lenses that form when seawater mixed with hydrothermal fluids at or near the seafloor and whose metal content was refined by successive hydrothermal events (Gibson et al., 2007). An alternative source of the metals for this model could be fractional crystallization of intrusive magma and the release of metal-rich volatiles at specific times during its evolution that contribute to the formation of the ore elements (Large, 1992).

5.2. Tectonic settings. The plate tectonic setting for Noranda VMS deposits is suprasubduction oceanic and continental arcs when shortening is interrupted by discrete periods of rifting (Mosier et al. (2009; Palin et al., 2020). Most authors interpret that the Noranda VMS deposits, which are abundant in the Archean and Paleoproterozoic (Goldfarb et al., 2010), formed in a plate tectonic regime similar to the Phanerozoic. However, others consider that early Earth geodynamics differed (Stern, 2020; Palin et al., 2020; Condie, 2021).

5.3. Associated deposit types. Kuroko VMS (G06), Hybrid VMS (G07), Algoma-type iron formation (G01), and volcanogenic Mn (G02).

6. Mineral systems

The following summary is largely derived from Galley (2003); Franklin et al. (2005); Gibson et al. (2007); Piercey (2011) and Shanks III (2012). It is the same as the mineral system described in the Kuroko VMS deposit profile.

6.1. Source region. The source region is the mantle beneath a regional rift.

6.2. Source driver. Rift-related extension results in subsidence and crustal thinning that produces decompression melting of the upper mantle at >1300°C to produce a large volume of hot mafic melt.

6.3. Source product. Significant volumes of mid-ocean ridge basalt and locally boninite or low-Ti tholeiite magmas formed as a result of melting incompatible element-depleted mantle.

6.4. Transport drive. Buoyant magmas rise relatively rapidly which allows for heat retention.

6.5. Transport path. Rifts contain long-lived, thermal, magmatic, and structural corridors that focus magma ascent, heat flow and emplacement of subvolcanic intrusions (Hart et al., 2004).

6.6. Transport termination. The rising magmas evolve to an intermediate composition at a shallow crustal level (< 15km) by incorporating hydrated crust via low to moderate degrees of partial melting with subsequent crystal fractionation of the melt (Franklin et al., 2005) leading to high temperature melts emplaced as subvolcanic sills and dikes and erupted as basalts, andesites and rhyolites.

6.7. Deposit concentration.The rising hydrothermal fluids will commonly focus on near surface, vertical to sub-vertical faults to reach the seafloor. As the fluids approach the sea floor, they interact with seawater in the sediments and /or at the seafloor to cause the deposition of sulphides and gangue minerals due to the dramatic temperature drop and fluid mixing reactions. Fluids encountering more open faults and/or more permeable wallrock introducing seawater at deeper levels can lead to more pronounced and extended alteration pipes.

6.8. Deposit controls. The deposits are localized near faults and fault scarps. The upward movement of hydrothermal fluid is enhanced near the margins of contemporaneous sills. Although the sills are partly responsible for driving hydrothermal circulation, most high-temperature fluids originate in the volcanic basement where flow paths are intersected by basement highs and focused upward along growth faults or the margins of buried intrusions.

6.9. Deposit accumulation. As the sulphide mound builds, the hydrothermal fluids passing through it can heat the internal layers which can lead to zone refining from the base to the top. This will replace lower temperature minerals with higher temperature minerals. Larger deposits will have larger footwall pipes with more mineralization near the original seafloor beneath the mounds.

6.10. Post formation processes. Weathering of seafloor massive sulphide (SMS) deposits is an inevitable consequence of exposure to seawater unless the deposit is rapidly covered by sediment and/or volcanic material that shields sulfides from seawater contact. Bottom, mainly anoxic, waters may contain a small amount of oxygen such that the weathering of the deposit may be slowed but not halted. Outcropping VMS deposits will weather to produce a gossan in most climates.

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L03: Alkalic porphyry Cu-Au

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1. Identification

1.1. Synonyms. Porphyry Au-Cu, diorite porphyry copper, volcanic (alkalic) porphyry (Osatenko et al., 2020).

1.2. Commodities and by-products. Cu, Au (Ag, PGE).

1.3. Examples. New Afton (092INE023), Ajax (092INE012), Mount Polley (Cariboo Bell, 093A 008), Copper Mountain/ Ingerbelle (092HSE001, 004), Galore Creek (104G 090), Lorraine (093N 002) in British Columbia; Allard Stock (Colorado, USA); Skoures (Greece); Cadia Hill, Cadia Quarry, Cadia East, Ridgeway, E22, E26, E27 E48 and GRP314 (New South Wales, Australia); Ok Tedi (Papua New Guinea); Tai Parit and Dinkidi (Philippines).

2. Geological characteristics

2.1. Capsule description. Alkalic porphyry Cu-Cu deposits consist of stockworks, veinlets, breccias, and disseminations of pyrite, chalcopyrite, bornite, and magnetite in large zones of bulk-mineable mineralization in or adjoining multiple and commonly pipe-like diorite to syenite porphyritic intrusions. The mineralization is spatially, temporally, and genetically associated with hydrothermal alteration of the intrusive bodies and host rocks. Potassic and propylitic alteration is most common. This deposit type was first described by geologists working in British Columbia (Barr et al., 1976) and was not recognized as a distinct type globally until grouped with similar mines in New South Wales, Australia.

2.2. Depositional environment and geological setting. High-level (epizonal) emplacement of small stocks and dikes in magmatic arcs that intrude cogenetic volcanosedimentary sequences. They commonly form in oceanic volcanic island arcs with alkalic (shoshonitic) basic flows to intermediate and felsic pyroclastic rocks. Aplitic vein dike, comb quartz layering, and pegmatite at some deposits are interpreted to indicate that the early stages of mineralization formed at the transition between magmatic and hydrothermal conditions. The deposit characteristics vary with depth of emplacement of the host intrusive rocks. Mount Polley and the Cadia district deposits formed at shallower depths with breccias. The Lorraine deposit appears to represent the deepest known level of ore formation in the alkalic porphyry environment, with some magmatic segregation of mineralization and elevated PGE contents (Chamberlain, et al., 2007).

2.3.Ages of mineralization. Deposits in the Canadian Cordillera are restricted to the Late Triassic to Early Jurassic (215-180 Ma) with two clusters around 205-200 and ~ 180 Ma. In New South Wales the deposits are Late Ordovician to early Silurian ranging from ~455 to 435 Ma and young eastwards. In southwest Pacific island arcs, deposits are Miocene to Pleistocene.

2.4. Associated rocks. Numerous intrusions range from fine through coarse grained, equigranular to coarsely porphyritic, locally pegmatitic stocks and dike complexes that intrude volcanic flows and pyroclastic rocks with varying amounts of sedimentary rocks. The metamorphic grade is generally low for deposits in British Columbia, typically prehnite-pumpellyite facies. Successive intrusive phases are common, from pre to post mineralization. Breccias can be important and vary in fragment composition; some include wispy juvenile fragments sourced from magma (Micko et al., 2014). Porphyry-cemented breccias are common. Associated rock compositions range from gabbro and diorite through monzonite to syenite, low-silica, although individual deposits generally show a more limited range. K-feldspar (± feldspathoid) megacrystic (phenocrysts > 1 cm) monzonitic rocks are common to many alkalic porphyry Cu-Au districts. Coeval volcanic rocks are mafic to intermediate alkalic varieties of the high-K basalt and shoshonite series and rarely, phonolites. Picrite can be spatially associated with alkalic porphyry deposits, such as New Afton (Logan and Mihalynuk, 2014).

2.5. Host rocks. Alkalic porphyry deposit host rocks can be subdivided into a silica-undersaturated group that contains >10% feldspathoids and a silica-saturated suite with <5% quartz or <10% feldspathoid (i.e., “quartz-free”). The silica-saturated suite may become weakly silica oversaturated in late stages of formation. Silica-undersaturated suites in British Columbia have pyroxenite and syenite, which can be locally zoned (Chamberlain et al., 2007). Aegirine-augite, potassium feldspar, biotite, melanite, titanite, and apatite are common minerals; hornblende, magnetite, plagioclase and vishnevite-cancrinite are local. Garnet can occur both as an igneous mineral and hydrothermal alteration phase. The most undersaturated nepheline normative rocks contain modal nepheline and, more commonly, pseudoleucite. Examples are Galore Creek and Mount Polley, although Mount Polley also has some silica-saturated phases (Pass et al., 2014). Silica-saturated suites are commonly diorite and monzonite. Augite, biotite, magnetite, plagioclase, K-feldspar and apatite are the major mineral phases; quartz is rare (Chamberlain et al., 2007). Examples are Afton, Copper Mountain and the Cadia district and North Parkes deposits.

2.6. Deposit form. Mineralization is in vertical intrusive pipes or small elongate stocks that are generally less than several 100 m across. Older deposits are commonly tilted. In some cases, mineralization is at pipe margins and apices. Ore zones can extend vertically for more than 1 km. Stockworks and veinlets, minor disseminations, and replacements throughout large areas of hydrothermally altered rock commonly coincide with hydrothermal or intrusion breccias. Deposit boundaries are determined by economic factors that outline ore zones within larger areas of low-grade, laterally zoned mineralization. Cordilleran porphyry deposits can be subdivided according to their morphology into three classes: volcanic (most common form for alkalic porphyry Cu-Au deposits), classic, and plutonic (Sutherland Brown, 1976; McMillan and Panteleyev, 1988). The volcanic class (e.g., Galore Creek) is associated with multiple intrusions of small subvolcanic stocks, sills, dikes, and diverse intrusive breccias. Reconstruction of volcanic landforms, structures, vent-proximal deposits, and subvolcanic intrusive centres is possible in some cases.

2.7. Ore controls. Mineralization occurs at igneous contacts, both internal between intrusive phases and external with wallrocks, and in the cupolas and the uppermost, bifurcating parts of stocks, dike swarms and volcanic vents. Intrusive and hydrothermal breccias are an important host for ore. Zones of most intensely developed fractures have the potential for ore-grade vein stockworks. Chemically distinct magmatism, with alkalic intrusions varying from gabbro, diorite, and monzonite to nepheline syenite and coeval shoshonitic volcanic rocks, takes place at certain times in segments of some island arcs. Multiple intrusive events that can generate complex overprints of alteration and mineralization assemblages are relatively common. The magmas are often introduced at cross-arc structures that coincide with deep-seated faults. Mineralization can be controlled by features such as hostrock, alteration, density of veining, and location (margins or central area).

2.8. Ore texture and structure. Mineralization occurs as veinlets, stockworks and breccias with sulphide and magnetite grains in fractures and along fracture selvages or as disseminated sulphides. Hydrothermally altered rocks can contain coarse-grained mineral assemblages including feldspathic and calcsilicate replacements ('porphyroid' textures) and open-space filling with fine to coarse, granular, and rarely pegmatitic textures.

2.9. Ore mineralogy. Chalcopyrite, pyrite, and magnetite with generally subordinate bornite, chalcocite (primary) and rare galena, sphalerite, tellurides, tetrahedrite, gold and silver. Pyrite is less abundant than chalcopyrite in ore zones. Sulfides are typically zoned from bornite-rich cores to bornite + chalcopyrite and pyrite + chalcopyrite zones, with an outer barren zone where pyrite is the predominant sulfide. Overall, the sulfide content, especially pyrite, is low compared to calc-alkalic porphyry deposits. Sulfides may occur as breccia cements, disseminated, or in veins with gangue minerals. Quartz gangue is restricted to the alkalic porphyry deposits related to silica-saturated magmatism (Bissig and Cooke, 2014). At the Skouries deposit in Greece, PGE are hosted by platinum-group minerals in quartz-chalcopyrite–bornite ± magnetite veins and in potassic alteration assemblages (McFall et al., 2018).

2.10. Gangue mineralogy. Gangue minerals in mineralized veins are mainly quartz with lesser biotite, sericite, K-feldspar, magnetite, chlorite, calcite, epidote, anhydrite, and tourmaline. Many of these minerals are also pervasive alteration products of primary igneous mineral grains.

2.11. Alteration mineralogy. Quartz, sericite, biotite, K-feldspar, albite, anhydrite/gypsum, magnetite, actinolite, chlorite, epidote, calcite, clay minerals, tourmaline. Early formed alteration can be overprinted by younger assemblages. Typically, fewer well-developed alteration types than those found in calc-alkaline porphyry deposits (L04). Central and early formed potassic zones (K-feldspar and biotite) commonly coincide with ore. The potassic alteration assemblage typically contains abundant biotite and magnetite in basaltic host rocks, whereas secondary K-feldspar is more abundant in more felsic intrusions. Secondary K-feldspar in several alkalic porphyry deposits has hematite dusting; the zone of reddening can provide a useful vector to mineralization (Bissig and Cooke, 2014). An outer zone of propylitic alteration, which consists of epidote, chlorite and pyrite is typical and is commonly fracture controlled in low-permeability rocks. Particularly in the core zone, alkalic porphyry deposits can also include calcic and calc-potassic alteration assemblages consisting of primarily albite and/or sodic-plagioclase, actinolite, chlorite, and epidote. This alteration can be flanked in volcanic hostrocks by biotite-rich rocks that grade outward into propylitic rocks. The biotite is a fine-grained, 'shreddy' looking secondary mineral that is commonly referred to as an early developed biotite (EDB) or a 'biotite hornfels'. At Galore Creek, a silica-undersaturated deposit, an alteration assemblage of orthoclase ± hematite ± specular hematite ± garnet ± anhydrite is associated with gold-bearing bornite. The older alteration assemblages in cupriferous zones can be partially to completely overprinted by later biotite and K-feldspar and then phyllic (quartz-sericite-pyrite) alteration, less commonly argillic, and rarely, in the uppermost parts of some ore deposits, advanced argillic alteration (kaolinite-pyrophyllite). Late-stage alteration is more variable between deposits with varying types of veins and veinlets. Weakly developed, sericite-anhydrite-calcite alteration is a common characteristic in the alkalic porphyry deposits of British Columbia and New South Wales, usually along the margins of late-stage faults.

2.12. Weathering. In the Northparkes region, well-developed, surficial oxide ore zones are up to 80 m thick with uppermost Cu phosphate minerals passing down through Cu carbonate minerals to a small supergene enrichment zone with native Cu, cuprite and chalcocite (Pacey et al., 2019). In temperate climates leaching and supergene enrichment effects are generally modest and surface outcrops normally have little of the copper remobilized. Secondary minerals are malachite, azurite, lesser copper oxide, and rare sulphate minerals; in some deposits native copper is economically significant (e.g., Afton, Kemess).

2.13. Comments. The best-known districts are the Quesnel and Stikine terranes in British Columbia and the MacQuarrie arc in New South Wales (Cooke et al., 2007). Subdivision of porphyry deposits can be made on the basis of metal content, mainly ratios between Cu, Au and Mo. This economically based criterion may fail to match with the geological differences between deposits with similar metal contents. Differences in composition between the host rock alkalic and calc-alkaline intrusions and variations in alteration mineralogy and zoning patterns provide fundamental geologically based contrasts between porphyry deposit model types. Porphyry copper deposits associated with calc-alkaline host rocks are described in mineral deposit profile L04. The calc-alkaline porphyries, such as Red Chris and Bingham, with higher gold contents typically belong to a high-K calc-alkalic suite of rocks (Lang et al., 1995; Wolfe and Cooke, 2011) and are considered a different porphyry deposit type by some (Riedell et al., 2020). These Cu-Mo-Au deposits may correspond to the volcanic (calc-alkaline) porphyry classification described by Osatenko et al. (2020). As well, Sillitoe (2000) refers to small number of gold-only porphyries (L02).

3. Exploration and resource assessment guides

3.1. Geochemical signatures. Alkalic cupriferous systems contain elevated Au (> 0.3 g/t) and Ag (>2 g/t) grades but sub-economic values of Mo, possibly <0.0030% (Osatenko et al., 2020). Cu grades vary widely but commonly exceed 0.5 % and rarely 1%. Many contain elevated values for Ti, V, P, F, Ba, Sr, Rb, Nb, Te, Pb, Zn, PGE and have a high CO_2 content. Soil and till sampling for Cu, Au and other elements are effective and commonly used exploration techniques in British Columbia (Plouffe et al., 2016). The occurrence of resistate minerals such as apatite, titanite, garnet, and rutile in the surficial environment near mineralized and altered portions of British Columbia alkalic porphyry copper deposits can also be used as exploration tools, especially in terrains covered by glacial till (Celis et al., 2013). Detrital gold collected from fluvial placers nearby four alkalic porphyry deposits in British Columbia exhibit a strong Pd and Hg signature, both in the alloy and as mineral inclusions, related to late stage veining (Chapman et al., 2017). Micron-scale Cu-rich gold grains formed in alkalic porphyry deposits are generally too small to be recovered during routine sediment sampling. Sulfur isotope analyses have exploration potential, with zones of depleted delta 34S sulfide values generally the most prospective for high-grade mineralization in the Cadia district (Wilson et al., 2007), but more work is needed (Deyell and Tosdal, 2014).

Propylitic alteration is now being tested for indications of deposit fertility and proximity to a deposit (Pacey et al., 2020). So called ‘green rock alteration’ can have enrichment and depletion patterns of the trace elements Mn, Sr, Zn, Pb, As, and Sb in epidote, and chlorite. Prehnite minerals in propylitic zones are affected by co-existing mineral phases, temperatures of formation, and distance from porphyry deposits Cu centres (Lee et al., 2020). These geochemical tools can potentially detect porphyry copper deposits at 1-5 km from their centres. Because the different intrusive phases in alkalic intrusive complexes are not always easily distinguished during drill core logging, crosscutting relationships at intrusive contacts can be guided by geochemical breaks portrayed in graphical strip logs.

3.2. Geophysical signatures. Ore zones, particularly those with high Au content, are commonly found in association with magnetite-rich rocks and can be located by airborne, ground, and drill hole magnetic surveys. Induced polarization chargeability anomalies of moderate intensity correspond to mineralized zones with low concentrations of pyrite (Osatenko et al., 2020). The more intensely hydrothermally altered rocks produce resistivity lows. Airborne electromagnetic (AEM) data has been used with an improved Airborne Induced Polarization (AIP) mapping algorithm to map subtle electromagnetic signatures of disseminated sulfides around intrusive porphyry stocks at Mt. Milligan (Kwan and Müller, 2020). Gravity anomalies can identify larger intrusions underlying a mineralized region and help suggest the boundaries to a particular prospective area. A 7 by 7 km gravity anomaly with a –20 mGal Bouguer gravity anomaly has been identified at the Northparkes deposit (Pacey et al., 2019). Radiometric airborne surveys are useful for identifying potassic alteration zones. Remote sensing can be used to identify alteration zones using satellite or airborne systems, particularly in areas with limited vegetation.

3.3. Other guides. Porphyry deposits are marked by large-scale, markedly zoned metal and alteration assemblages. The central parts of mineralized zones generally have higher Au/Cu ratios than the margins. Hydrothermally altered clasts in coarse pyroclastic deposits can be used to locate mineralized intrusive centres. Alkalic porphyry deposits are more likely to be preserved in older rocks than their calc-alkaline counterparts due to burial in back-arc basins. Thus, areas of fragmented intraoceanic arc terranes should be considered prospective for Au-rich alkalic porphyry deposits (Harris et al., 2013). Early exploration for alkalic porphyry deposits in the Quesnel terrane of British Columbia keyed in on small limestone units in largely volcanic sequences as indicators of emergent Triassic volcanoes and related magmatic centres.

4. Economic factors

4.1. Typical grade and tonnage. Alkalic porphyry deposits contain elevated Au (> 0.3 g/t) and Ag (>2 g/t) grades but sub-economic values of Mo of <0.0030% (Osatenko et al., 2020). Cu grades vary widely but commonly exceed 0.5 % and rarely 1 % (Table 1). Gold is an important coproduct at grades as low as 0.2 g/t Au (Sinclair, 2007), and silver can be a by-product. Cox and Singer (1988) divided 55 global porphyry copper deposits into Cu-Mo, Cu-Au-Mo and Cu-Au subtypes according to metal ratios to determine median values for porphyry Cu-Au of 160 Mt with 0.55 % Cu, 0.003 % Mo, 0.38 g/t Au and 1.7 g/t Ag. Their porphyry Cu-Au subtype would include alkalic porphyry (L03) and some members of the porphyry Cu±Mo±Au (L04) deposits. As more exploration leads to porphyry discoveries and expanded reserves at operating mines, there is more recognition that alkalic porphyry deposits can be large and high grade (Osatenko et al., 2020). Galore Creek and Copper Mountain exceed 1Bt and ten deposits from the northern Cordillera have media values of 0.38% Cu, 0.280 g/t Au and 1.35 g/t Ag. Alkalic porphyry deposits are PGE enriched with Pd and Pt concentrations generally two to three orders of magnitude lower than Au (Thompson et al., 2002). The Skouries deposit in Greece has some of the highest reported values, with Pd contents between 52 and 610 ppb and Pt contents up to 150 ppb in whole rock samples (McFall et al., 2018). Other PGE-enriched porphyries in British Columbia include Galore Creek, Lorraine, and Mt. Polley. The PGEs in these deposits may form both during a first stage associated with the growth Co-Ni-As-rich pyrite and a second stage involving precipitation of platinum group metal (PGM) phases containing As, Sb, Te and Hg (Hanley et al., 2020). The platinum-bearing pyrite and PGM phases are not necessarily the most abundant in the Cu-Au mineralized zones.

Table 1. Tonnage and grade figures for alkalic porphyry Cu-Au deposits. For Sinclair (2007), resource figures include production plus measured, indicated and/or inferred reserves.

British Columbia, Canada	**Mt**	**Cu %**	**Ag g/t**	**Au g/t**	**Reference**
Afton	91.7	1.04	2.8	0.8	Sinclair, 2007
Ajax	24.7	0.46		0.37	Sinclair, 2007
Copper Canyon	164	0.35	7.154	0.54	Sinclair, 2007
Copper Mountain	318	0.42	1.66	0.14	Sinclair, 2007
Galore Creek	930.2	0.52	4	0.36	Sinclair, 2007
Lorraine	31.9	0.66	4.7	0.17	Sinclair, 2007
Mount Polley	71.6	0.36		0.35	Sinclair, 2007
New South Wales, Australia					
Cadia East	2300	0.28		0.44	Kreuzer et al., 2015
Cadia Hill	352	0.16		0.63	Kreuzer et al., 2015
Ridgeway	150	0.37		0.71	Kreuzer et al., 2015
Cadia Quarry	50	0.23		0.46	Kreuzer et al., 2015
Endeavour 26 (E26)	65.3	1.37		0.39	Kreuzer et al., 2015
Endeavour 48 (E48)	33.4	1.04		0.59	Kreuzer et al., 2015
Endeavour 22 (E22)	18.6	0.71		0.61	Kreuzer et al., 2015
Endeavour 27 (E27)	14.4	0.71		0.73	Kreuzer et al., 2015
International					
Dinkidi (Philippines)	110	0.5		1.2	Sinclair, 2007
Ok Tedi (Papua New Guinea)	443	0.87		0.9	Sinclair, 2007

4.2. Economic limitations. The relatively small ore zones for many deposits compared to other types of porphyry deposits can be both more expensive to locate and challenging to mine. The potential for acid generation is generally low for alkalic porphyry deposits compared to calc-alkaline types due to their abundant primary and secondary feldspars and comparatively low pyrite contents, and in some cases, abundant carbonate veining.

4.3. End uses. Production of chalcopyrite or chalcopyrite-bornite concentrates with significant Au credits.

4.4. Importance. Some of the world's highest-grade porphyry gold resources and much more common than gold-only porphyry deposits. They are a potential future source of PGE. They are commonly more attractive for underground block caving than calc-alkaline porphyry deposits due to their significant gold-contents. Given their generally smaller size and less distinct alteration zones, it is likely that mineral exploration has been less successful in discovering alkalic porphyries compared to calc-alkaline porphyries. Therefore, there is probably more potential to find the former in the appropriate metallogenetic belts.

5. Genesis

5.1. Genetic model. According to the magmatic-hydrothermal or orthomagmatic model, alkalic porphyry Cu-Au deposits are thought to form from magmas generated after subduction beneath an arc has ceased. The magmas result from remelting of subduction-modified arc lithosphere and migrate upwards to the upper crust following the cessation of convergent plate motion. Large volumes of highly saline aqueous fluids develop in the magma at higher crustal levels under high pressure and eventually fracture the carapace and the country rock, migrating upwards and outwards from a magmatic centre. The extensive fracturing (± brecciation) is associated with ore formation. Mineralization and alteration, along with associated intrusive activity, occur in multiple stages. Magmatic waters are the predominant control during the early stages of ore formation; during the waning stages the predominant control is alteration by influx of meteoric waters.

5.2. Tectonic settings. Alkalic porphyry deposits form in orogenic belts at convergent plate boundaries, commonly in oceanic volcanic island arcs. This is a complex, postsubduction magmatic setting with both extensional and compressional environments, in some cases involving reversals in subduction polarity, possibly induced by collision with an arc or oceanic plateau, and incipient back-arc extension parallel to the arc (Bissig and Cooke, 2014). The magmas tend to be relatively small volume, spatially isolated, and mildly alkaline to strongly alkaline (John et al., 2010). In several districts of British Columbia (e.g., Galore Creek, Mount Polley), mafic to intermediate silica-undersaturated potassic magma compositions may be followed by mafic dike swarms. Overall, this is consistent with tectonic reorganization resulting in a temporally restricted contractional regime which favors intrusive over extrusive magmatism followed by arc rifting, a situation also observed in modern examples of alkalic ore deposits (Bissig and Cooke, 2014). Picrites occur locally in the Iron Mask batholith area of British Columbia that may be the result of heating of the mantle wedge by inflow of hot asthenoshperic mantle after slab tearing (Logan and Mihalynuk, 2014). The picrites may be the precursor of potentially mineralizing alkalic magmatism. Similar broad coincidence of slab break-off and alkalic porphyry mineralization has been suggested for the Macquarie arc (Vos et al., 2007).

5.3. Associated deposit types. Cu skarns (K01); Fe skarns (K03); epithermal Au-Ag low sulphidation (H05); alkalic intrusion-associated Au-Ag (H08), polymetallic veins Ag-Pb-Zn±Au (I05), surficial placers (C01), buried-channel placers (C02); iron oxide Cu±Au±P±REE (D07).

6. Mineral systems

Holwell et al. (2019) proposed "that a trans-lithospheric continuum exists whereby post-subduction magmas transporting metal-rich sulfide cargoes play a fundamental role in fluxing metals into the crust from metasomatised lithospheric mantle". The following mineral system generally adopts this approach for the source and transport characteristics.

6.1. Source region. Post-subduction magmatism generally comprises <10% partial melting of subduction-metasomatized sub continental lithospheric mantle (SCLM) and/or lower crustal melts.

6.2. Source driver. The heat engine for post-subduction melting can be asthenospheric upwelling (due to lithospheric extension and/or slab drop-off and delamination) and/or post-collisional thermal rebound.

6.3. Source product. This process produces small volume, hydrous, alkali-enriched melts. The melts range from high-K-calc-alkaline, through silica-saturated to silica-undersaturated alkaline compositions. The preferential association of alkalic magmatism with Au mineralization may be related to post-subduction magmatism with melting of Au-rich residue from subduction-modified lithosphere (Richards, 2009).

6.4. Transport driver. The hydrous alkali melts are buoyant and given the opportunity will rise through denser, overlying crust.

6.5. Transport path. Any crustal extension can facilitate magma movement, such as when crustal compression stops at a convergent plate margin. This extension is particularly important at shallow levels.

6.6. Transport termination. During ascent through the lithosphere, magmas may incorporate variable amounts of crustal material, differentiate, and start to crystallize. They can pond at a range of depths which can trigger the steps leading to different styles of mineralization. At lower and mid-crustal levels, zoned alkaline intrusions can form, whereas at upper crustal levels, smaller volume, alkali-enriched stocks can host magmatic–hydrothermal porphyry Cu–Au deposits. Hydrothermal fluids may produce epithermal Au–Ag (Te) epithermal veins (H08) near surface.

6.7. Deposit concentration. The mineralizing fluids in alkalic porphyry Cu-Au deposits, as in their calc-alkaline counterparts, are largely derived from a progenitor porphyritic intrusive complex. Relatively high volatile contents and oxidation states in post-subduction magmas could suppress early sulfide segregation. This process could create the conditions for a chalcophile metal-rich volatile phase to be released upon ascent, thus explaining the enrichment of Cu and Au in the shallow crustal porphyry systems. Elevated CO_2 contents have been documented for some alkalic-related ore fluids, which is consistent with high CO_2 solubility in mantle-derived alkalic magmas (Bissig and Cooke, 2014). The incorporation of crustal carbonate into the rising magma has also been considered as a contributing factor to CO_2 contents for some deposits (Pass et al., 2014).

6.8. Deposit controls. Arc transverse and arc parallel regional and basement structures can control the locations of these deposits. For example, the Endeavour Linear, a structural corridor for the North Parkes porphyry Cu-Au deposits is close to the Lachlan transverse zone, which is at a high angle to the arc. Intrusion of a crystallizing camp scale magma by a later magma of different composition can lead to the onset of fertile fractionation creating a porphyritic phase rich in Cu sulphides which can be emplaced as a series of pipe-like stocks at higher crustal levels with porphyry style mineralization (Pacey et al., 2019).

6.9. Deposit accumulation. Mineralizing fluids are associated with multiple pulses of volumetrically restricted but compositionally varied alkaline porphyry intrusions (Bissig and Cooke 2014). Economic deposits may consist of a cluster of discrete hydrothermal systems.

6.10. Post formation processes. For these deposits to be preserved, uplift and erosion must have been minimal at the time of ore formation.

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L04: Calc-alkaline porphyry Cu ± Mo

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1. Identification

1.1. Synonyms. Calc-Alkalic porphyry Cu±Mo±Au (Panteleyev, 1995), porphyry copper-molybdenum (John et al., 2010). The acronym PCD for porphyry copper deposits (John et al., 2010) includes the two related mineral deposit profiles, calc-alkaline porphyry Cu±Mo (L04) and alkalic porphyry Cu-Au (L03).

1.2. Commodities and by-products. Cu, Mo (Ag, Au).

1.3. Examples. Bell (093M 001), Granisle (093L 146), Brenda (092HNE047), Highland Valley Copper (092ISE012), Huckelberry (093E 037), Island Copper (092L 158); Mitchell (104B 103), Schaft Creek (104G 015), and Gibraltar (093B 012) in British Columbia; Casino, (Yukon); Gaspé Copper and R-2 Chibougamau (Quebec); Inspiration, Morenci, Ray, Sierrita-Experanza, Kalamazoo, and Santa Rita (Arizona, USA); Chuquicamata, La Escondida and Quebrada Blanca (Chile); Far Southeast (Lepanto/Mankayan), Dizon, Guianaong, Taysan and Santo Thomas II (Philippines), Frieda River and Panguna (Papua New Guinea.

2. Geological characteristics

2.1. Capsule description. Calc-alkalic porphyry Cu±Mo deposits consist of stockworks of quartz veinlets, quartz veins, closely spaced fractures and breccias containing pyrite and chalcopyrite with lesser molybdenite, bornite and magnetite that form large zones of economically bulk-mineable mineralization in or adjoining porphyritic intrusions and related breccias. Disseminated sulphide minerals are generally subordinate. Porphyry intrusions may be plug-like or consist of steeply dipping, dike-like bodies of differing ages. The mineralization is spatially, temporally, and genetically associated with hydrothermal alteration of the host rock intrusions and wall rocks, which can extend up to 10 km from the centre of the mineralized zone. Weathered zones can be ore and include exotic copper deposits, leached caps, supergene enrichment blankets, and in situ oxide copper deposits.

2.2. Depositional environment and geological setting. High-level (epizonal) stocks in volcano-plutonic arcs, commonly continent-margin and oceanic volcanic island arcs. Most porphyry intrusions are emplaced at depths from 1 to 6 km, a few at deeper levels; source plutons are generally at depths of 3-10 km. Virtually any type of country rock can be mineralized, but commonly the stocks and related dikes intrude coeval and cogenetic volcanic piles. Faults can figure prominently in preservation of porphyry copper deposits by down dropping the mineralized zones so that they are preserved from erosion.

2.3. Ages of mineralization. Porphyry deposits usually form from late magmatic-hydrothermal processes that last up to one million years for more complex systems to less than a few hundreds of thousands of years for others. Globally these deposits are mainly Jurassic, Cretaceous, Eocene, and Miocene, but can range from Archean to Quaternary (Panteleyev, 1995). In the Canadian Cordillera, the deposits formed in two main periods: the Triassic/Jurassic (210-180 Ma) and Cretaceous/Tertiary (85-45 Ma). Precambrian deposits are unusual, and their classification can be contentious (Sinclair, 2007). The Coppin Gap Cu-Mo deposit in Australia, dated at approximately 3.3 Ga, is the oldest known porphyry deposit in the world. The small number of old porphyry deposits may result from shallow emplacement levels reducing preservation potential.

2.4. Associated rocks. The intrusions are hosted by volcanic rocks, such as dacite and andesite, sedimentary rocks, and more rarely, metamorphic rocks. The wall rocks can be cut by intrusions that pre-date or post-date the mineralizing intrusive phases. The intrusions may crosscut related volcanic rocks that were erupted during initial phases of magmatism. Intrusions hosting porphyry Cu deposits are rare compared to ubiquitous, barren, silicic upper-crustal intrusions that can occur in the same magmatic district (Large et al., 2018).

2.5. Host rocks. Multiphase intrusions of moderately evolved granitic rocks range from coarse-grained phaneritic to porphyritic stocks, batholiths, dike swarms, breccias and rarely, pegmatites. They are commonly steeply dipping, sheeted, parallel vein, and dike-like intrusions, unless the rocks have been tilted. The causal intrusion is commonly small. Almost all deposits are associated with a strongly porphyritic, hypabyssal intrusive rock typically containing 35 to 55% fine- to medium-grained phenocrysts (commonly plagioclase, commonly hornblende and/or biotite, less commonly pyroxene with more mafic compositions; John et al., 2010) with a characteristic aplitic quartz-feldspar groundmass. The groundmass grain size tends to coarsen with increasing depth. Magnetite, ilmenite and/or titanite, apatite, and zircon are common, primary accessory minerals.

Compositions range from calc-alkaline quartz diorite to granodiorite and quartz monzonite and monzonite (60-72 wt. % SiO2; Sinclair, 2007). John (2010) noted that "…the mineralizing stocks are oxidized (high whole-rock values of Fe2O3/ FeO), magnetite-series rocks. Porphyry copper deposits related to calc-alkaline magmas are enriched in large ion lithophile and fluid-mobile elements (for example, Cs, Rb, Ba, U, K, Pb, and Sr) and are relatively depleted in Nb, Ta, P, and Ti compared to primitive mantle. They also are commonly depleted in manganese and thorium. Mineralized intrusions have highly fractionated rare earth element (REE) patterns, commonly with heavy rare earth element (HREE) and yttrium depletions relative to barren intrusions. Mineralized intrusions commonly have high lanthanum/ytterbium (40–60), high strontium/yttrium (mostly greater than 20), and chondrite-normalized REE patterns that have small negative or positive europium anomalies."

2.6. Deposit form. Mineralization is centered around subvertical stocks or swarms of dikes that are generally cupolas of larger underlying plutons or batholiths. Mineralization occurs in zones less than 1 km wide and deep within enveloping hydrothermally altered wall rock in areas of up to 10 km2. Deposits are commonly circular to elliptical in plan view if not faulted or steeply tilted. Deposit boundaries are determined by economic factors that outline ore zones within larger areas of low-grade, concentrically zoned mineralization. Cordilleran porphyry deposits can be subdivided according to their morphology into three classes: volcanic, classic, and plutonic (Sutherland Brown, 1976; McMillan and Panteleyev, 1988); these classes were used by Osatenko et al.(2020) to subdivide calc-alkaline porphyry deposits into plutonic, classic and volcanic (calc-alkalic) types.

Volcanic deposits (e.g., Island Copper) are spatially related to multiple subvolcanic intrusions, including small stocks, sills, dikes, and diverse intrusive breccias. Reconstruction of volcanic landforms, structures, vent-proximal extrusive deposits, and subvolcanic intrusive centres is possible in many cases. Mineralization is at depths of < 1 km and is mainly associated with breccias or with lithologically controlled preferential replacement of host rocks with high primary permeability. Classic deposits (e.g., Huckleberry) are shallow (1-2 km), generally equant, cylindrical porphyritic stocks. Numerous dikes and breccias of pre, intra, and post-mineralization age modify the stock geometry. Orebodies occur along margins of intrusions and within adjacent wall rocks as annular ore shells. Lateral outward zoning of alteration and sulphide minerals from a weakly mineralized potassic/propylitic core is usual. Plutonic deposits (e.g., Highland Valley Copper) are in large plutonic to batholithic intrusions at relatively deep (2-4km) levels. Related dikes and intrusive breccia bodies can be emplaced at shallower levels. Host rocks are coarse grained to porphyritic. The intrusions can display internal compositional differences as a result of differentiation, with gradational to sharp boundaries between different phases. Local swarms of dikes, many with breccias, and fault zones are sites of mineralization. Orebodies around silicified alteration zones tend to occur as diffuse vein stockworks carrying chalcopyrite, bornite, and minor pyrite in intensely fractured rocks.

2.7. Ore controls. Mineralization is commonly associated with intrusive cupolas and the uppermost, bifurcating parts of stocks or dike swarms. It is more common at igneous contacts, both internal between intrusive phases and external with wallrocks. Breccias, mainly early formed intrusive and hydrothermal types, can be important ore hosts. The zones of most intensely developed fracturing give rise to ore-grade vein stockworks, notably where multiple sets intersect. Globally, porphyry deposits define relatively narrow, linear metallogenic provinces (Sinclair, 2007). Reactivation of basement faults is a recurring theme and deposits may form at intersections of arc-parallel and transverse faults, which permit crustal transit of uncontaminated magmas and later preservation in down-dropped basins (John et al., 2010). Superposition of multiple structures leads to higher grade zones and the characteristic large size of porphyry deposits.

2.8. Ore texture and structure. Quartz, quartz-sulphide and sulphide veinlets and stockworks with sulphide grains in fractures generally < 1 mm to several cm wide and in adjacent alteration selvages. Minor disseminated sulphides as discrete 1 mm or smaller anhedral to subhedral crystals, commonly replacing primary mafic minerals or in clot-like aggregates with other hypogene minerals (quartz, pyrite, potassium feldspar, potassium-mica, anhydrite, and biotite). Quartz phenocrysts can be partially resorbed and overgrown by silica.

2.9. Ore mineralogy. Hypogene ore minerals are chalcopyrite, molybdenite, lesser bornite and rare (primary) chalcocite. Subordinate minerals are tetrahedrite/tennantite, and enargite, and minor gold, electrum, and arsenopyrite. Some deposits have covellite, enargite, and digenite are in advanced argillic alteration assemblages (John et al., 2010). Gold and silver are thought to reside in bornite and chalcopyrite, and rare by-product rhenium is derived from molybdenite. Pyrite is the predominant sulphide mineral; in some deposits the Fe-oxide minerals magnetite, and rarely hematite, are abundant. In many deposits late veins commonly contain galena and sphalerite in a gangue of quartz, calcite, and locally barite, typically of no economic interest. Supergene ore, rarely > 200 m thick, consists of chalcocite, covellite, and other $Cu\sim_2S$ minerals e.g., digenite, djurleite), chrysocolla, native copper and copper oxide, and carbonate and sulphate minerals with copper grades up to three times those of underlying copper-mineralized rocks (Sillitoe and Perello, 2005). Supergene ore is best developed above pyrite-rich zones; other controls are faults and fractures providing permeability, topography, erosion and oxidation rates, and sufficient time to form economic deposits.

2.10. Gangue mineralogy. Gangue minerals in mineralized veins are mainly quartz with lesser biotite, sericite, K-feldspar, magnetite, chlorite, calcite, epidote, anhydrite, and tourmaline. Many of these minerals are also pervasive alteration products of primary igneous minerals. Supergene gangue consists of primary rock-forming minerals, hydrothermal minerals, and minerals formed by weathering including silica phases (chalcedony, opal), kaolinite, illite, montmorillonite, alunite, limonite (goethite, hematite, and jarosite), and manganese oxides.

2.11. Alteration mineralogy. Quartz, sericite, biotite, potassium feldspar, albite, anhydrite/gypsum, magnetite, actinolite, chlorite, epidote, calcite, clay minerals, and tourmaline. These minerals form different alteration assemblages in zones that extend beyond the economic mineralization, up to 10 km below the paleosurface, 5 km or more below the top of the porphyry system, and 3 km below the base of economic copper mineralization (John et al., 2010). Early formed alteration can be overprinted by younger assemblages. Central and early formed potassic zones (potassium feldspar and biotite) commonly host ore. This alteration can be flanked in volcanic host rocks by biotite-rich rocks that grade outward into propylitic rocks. The biotite is a fine-grained, 'shreddy' looking secondary mineral that is commonly referred to as an early developed biotite (EDB) or a 'biotite hornfels'. These older alteration assemblages can be partially to completely overprinted by later biotite and potassium feldspar and then phyllic (quartz-sericite-pyrite) alteration, less commonly argillic (clay-bearing assemblages), and rarely, in the uppermost parts of some ore deposits, advanced argillic alteration (kaolinite-dickite-pyrophyllite). The potassic and phyllic alteration may also form selvages up to a few cm wide along veins. Greisen with muscovite, quartz, and minor pyrite-chalcopyrite forms sets of sheeted veins with potassium feldspar-muscovite selvages in some root zones. Sodium and calcium alteration occurs at deeper levels, commonly with selective replacement of primary K-feldspar by albite ± fine-grained white mica (D'Angelo et al., 2017). The chemical compositions and spectral characteristics of hydrothermal minerals such as epidote, chlorite, and alunite, are being used to predict the likely direction and approximate distance to mineralized zones (Cooke et al., 2020).

2.12. Weathering. In temperate climates and glaciated terrains, the oxidized and leached zones overlying outcrop are marked by ferruginous caps with supergene clay minerals, limonite (goethite, hematite and jarosite) and residual quartz. More intense weathering, particularly in arid regions, can lead to near-surface, enriched zones referred to as supergene oxide deposits, chalcocite enrichment blankets and, less commonly, distal exotic copper deposits. These minerals are precipitated from descending, low-pH groundwaters that dissolve hypogene copper minerals and redeposit copper in minerals stable in low-temperature, oxidizing environments. Extensive supergene mineralization is rare for porphyry deposits in recently glaciated areas like British Columbia.

2.13. Comments. Subdivision of porphyry copper deposits can be made on the basis of metal content, mainly ratios between Cu, Mo and Au. This is an economically based criterion that is influenced by metal prices and metallurgy and can include deposits with different geological characteristics in the same family. Most classifications of porphyry deposits combine the compositional differences between host rocks with other criteria. Porphyry copper deposits associated with alkalic host rocks are described in mineral deposit profile L03. Some Cu-Mo-Au deposits are hosted by high-K calc-alkaline rocks, such as Red Chris and Bingham, which may be a different porphyry deposit type (Riedell et al., 2020). A small number of porphyries contain only gold (L02; Sillitoe, 2000).

3. Exploration and resource assessment guides

3.1. Geochemical signatures. Calc-alkaline porphyry systems can be zoned with a cupriferous (± Mo) ore zone having a barren, low-grade pyritic core and surrounded by a pyritic halo with peripheral base and precious metal-bearing veins. Distal signatures may extend 10 km or more away from the center of large porphyry deposits along structures. Overall, the deposits are large-scale repositories of sulphur, mainly in the form of metal sulphides, chiefly pyrite.

Soil sampling has been a key exploration tool in many regions. In areas covered by thick surficial materials, till sampling and geochemical methods to test soil gases, or biogeochemical methods are being used. K-feldspar staining of hand samples and drill core can help outline the key potassic alteration phase and identify albitic alteration. Porphyry indicator minerals, such as zircon, plagioclase, and apatite, in surficial materials or related rocks can lead to mineralization based on their chemistry. Recent work is demonstrating compositions of hydrothermal minerals such as epidote, chlorite, and alunite, can help determine proximity to copper porphyry systems (Cooke et al., 2014). For example, epidote near a porphyry deposit contains traces of Cu, Mo, Sn, Bi, light REEs, and Zr, but is depleted in As, Sb, and Pb relative to more distal epidote. The rocks from central porphyry zones commonly have coincident Cu, Mo, Au, and Ag with possibly Bi, W, B and Sr, accompanied by depletion of Mn, Pb, Zn, As, Tl and Li (Garwin, 2019). Peripheral enrichment in Pb, Zn, Mn, V, Sb, As, Se, Te, Co, Ba, Rb and possibly Hg is documented. Halley et al. (2015) reviewed the distribution of trace elements at different levels of a porphyry system and described a complex pattern that may be revealed by short-wave infrared (SWIR) spectroscopy analytical techniques. Some key elements form stable oxides that can provide exploration vectors in weathered rocks and soils.

Island arc rocks of adakitic composition may typify porphyry igneous complexes with precious and base metal mineralization (Chamberlain et al., 2007) and include enrichment in Sr, Na, and Eu and depletion in Y and heavy rare earth elements. Propylitic alteration is being tested for indications of deposit fertility and proximity to a deposit (Pacey et al., 2020). Enrichment and depletion patterns of the trace elements Mn, Sr, Zn, Pb, As, and Sb in epidote, chlorite, and prehnite minerals in propylitic zones ('green rock alteration') can be used as exploration vectors (Lee et al., 2020) that can potentially detect porphyry copper deposits at distances of 1 km to possibly more than 5 km.

3.2. Geophysical signatures. Aeromagnetic, seismic, gravity, and remote-sensing surveys can define the broad crustal structure and magmatic framework that hosts porphyry mineralization, and magnetic and induced polarization (IP) detailed surveys can help define the mineralized zones. Pyritic haloes surrounding cupriferous rocks respond well to IP surveys, but in sulphide-poor systems the ore itself provides the only significant IP response. Magnetic surveys can be used to outline porphyry Cu and Cu-Au deposits with abundant hydrothermal magnetite and pyrrhotite- and/or magnetite-bearing skarn and hornfels zones around porphyry-related intrusive rocks. Conversely, some deposits have magnetic lows due to the destruction of magnetite in the phyllic alteration zones. Magnetotelluric (MT) surveys can exhibit a major resistivity low with some large porphyry deposits (Garwin, 2019). Gavity signatures are variable but can be used to interpret the general geology at depth. Gamma ray spectrometry surveys have been used to outline potassic alteration zones closely related to mineralization. Remote sensing imaging systems can be used in areas with good bedrock exposure with limited vegetation to map sericitic, intermediate, and advanced argillic alteration zones, as well as iron oxide and hydroxide and silica alteration mineral associations (John et al., 2010).

3.3. Other guides. Porphyry deposits are marked by large-scale, zoned metal and alteration assemblages. Ore zones can form in certain intrusive phases and breccias or are present as vertical 'shells' or mineralized cupolas around particular intrusive bodies. In some terrains, the topography will reflect the varying hardness of the altered rocks and their different weathering characteristics. Weathering can produce a pronounced vertical zonation with an oxidized, limonitic leached zone at surface (leached cap), an underlying zone with copper enrichment (supergene zone with secondary copper minerals) and a zone at depth of primary mineralization (the hypogene zone). Porphyry deposits are most likely to be preserved in areas where the average depths of erosion from the paleosurface are less than 8 km and more abundant if erosional depths are roughly half that figure.

4. Economic factors

4.1. Typical grade and tonnage. Alkalic porphyry deposits contain elevated Au (> 0.3 g/t) and Ag (>2 g/t) grades but sub-economic values of Mo of <0.003Copper grades range from >0.2% Cu to more than 1%, whereas Mo ranges from ~0.005 to 0.03%. Hypogene copper grades are usually lower than those for the enriched supergene ore. However, supergene oxide ore grades are both higher and lower than hypogene copper grades. The porphyry deposit grade and tonnage data presented below (Table 1) includes hypogene and supergene ore. Many global porphyry deposits have significant supergene portions with no molybdenum recoveries. Cox and Singer (1988) determined median values for porphyry Cu-Au-Mo from 55 deposits worldwide of 390 Mt with 0.48 % Cu, 0.015 % Mo, 0.15 g/t Au and 1.6 g/t Ag. Singer et al. (2008) used 422 mainly calc-alkaline porphyry copper deposits to calculate values for median copper (0.44%), molybdenum (0.013%), silver (2.0 g/t) and gold (0.21 g/t) . Silver was recovered from roughly one third of the deposits, and gold from about two thirds.

4.2. Economic limitations. Globally, the median copper grades being mined are gradually declining due to more efficient extraction and recovery techniques enabling exploitation of lower grade ore coupled with smaller mined tonnages of supergene sulfide-enriched ore and increased mining of lower grade copper oxide ores by heap leaching. Although porphyry copper deposits have been mined almost exclusively as large open pits in the last fifty years to enable efficiencies of scale to reduce mining costs, block caving of subsurface deposits is becoming more attractive for higher grade deposits with favourable mining characteristics. Mine production in British Columbia has been largely from primary (hypogene) ores. Rare exceptions are the Afton and South Kemess mines where native copper was recovered from an oxide zone, and the Gibraltar and Bell mines where incipient supergene enrichment provided some economic benefits.

4.3. End uses. Porphyry copper deposits produce mineral concentrates of chalcopyrite, bornite, and other copper minerals from hypogene mineralization that is shipped to smelters and refineries to be converted into the metal. For some mines, the hypogene ore can also be used to produce Mo mineral concentrates and Mo. Byproduct gold and/or silver can be recovered from some copper concentrates and rarely, rhenium can be a byproduct from a molybdenum concentrate (e.g., 0.08 g/t Re from Island Copper).

4.4. Importance. Porphyry Cu±Mo±Au deposits are the world's largest (~70%) source and resource of copper (Singer, 2017) and can be significant Mo resources. Some porphyry Cu-Mo deposits, such as those in the Highland Valley, British Columbia, only produce a molybdenum concentrate when prices are high. About 80% of the world's Re, and nearly all of the Se and Te, are produced from porphyry copper deposits (John and Taylor, 2016).

5. Genesis

5.1. Genetic model. According to the magmatic-hydrothermal or orthomagmatic model (Sinclair 2007), felsic to intermediate magmas migrate to high crustal levels, with border zone crystallization along the walls and roof of the magma chamber. This crystallization leads to supersaturation of trapped volatile phases within the liquid magma which is enhanced by large volumes of non-degassed magma from underlying, magma bodies. Fluid separation from the rising magma occurs at shallow depths,

Table 1. Tonnage and grade figures for calc-alkalic porphyry Cu ± Mo deposits. Geological resource includes production plus measured, indicated and/or inferred reserves.

British Columbia	**Mt**	**Cu%**	**Mo%**	**Ag g/t**	**Au g/t**	**Reference**
Bell Copper (Newman)	148.9	0.42		0.42	0.2	Sinclair, 2007
Granisle	171.3	0.41		0.4	0.144	Sinclair, 2007
Bethlehem	136.6	0.47	0.0034	1.36	0.012	Sinclair, 2007
Highland Valley Copper	1,356	0.37	0.006	0.976	0.0062	Sinclair, 2007
Highmont	121	0.23	0.021		0.003	Sinclair, 2007
Island Copper	390.1	0.335	0.01	0.826	0.1	Sinclair, 2007
Mitchell	1,795	0.10	0.0058	3.0	0.60	Febbo et. al, 2020
Huckleberry	73.5	0.49	0.014	1.8	0.04	Sinclair, 2007
Gibraltar	1,440	0.28	0.009			Van Stratten et al., 2020
Schaft Creek	465	0.359	0.04	0.25	1.99	Sinclair, 2007
Canada						
R-2 (Quebec)	10.9	0.36	0.015			Sinclair, 2007
Gaspé Copper (Quebec)	350	0.75				Sinclair, 2007
Casino (Yukon)	559	0.25	0.025		0.31	Sinclair, 2007
International						
Pebble Copper (Alaska, USA)	2,083	0.85				Sinclair, 2007
Butte (Montana, USA)	2,740	0.27	0.015		0.3	Sinclair, 2007
Ann-Mason (Nevada, USA)	495	0.4		0.17	0.03	Sinclair, 2007
Cerro Colorado (Panama)	2210	0.6	0.009	4.7	0.07	Sinclair, 2007
Cerro Colorado (Chile)	204	1.02				Sinclair, 2007
Chuquicamata (Chile)	10,837	0.56	0.024			Sinclair, 2007
Collahuasi (Chile)	3,487	0.79				Sinclair, 2007
El Teniente (Chile)	2,850	1.3				Sinclair, 2007
Marcopper (Philippines)	195	0.57	0.003	1	0.1	Sinclair, 2007
Santo Tomas II (Philippines)	328	0.34	0.001	1.5	0.61	Sinclair, 2007
Dexing (China)	1,500	0.43	0.017	1.9	0.16	Sinclair, 2007

focusing volatiles near the top of the magma column; the resulting degassed magma descends through the non-degassed magma because of its lower volatile content and greater density. At some point volatiles separate due to resurgent, or second, boiling. Ore metals are strongly partitioned into these volatile phases, which become concentrated in the carapace of the magma chamber. Increasing fluid pressures eventually exceed the lithostatic pressures and the tensile strength of the overlying rocks permitting rapid escape of hydrothermal fluids into newly created fractures. Ore deposition results due to the pronounced adiabatic cooling of the ore fluids due to their sudden expansion into fracture and/or breccia systems. Typically, more than one cycle of magmatic/hydrothermal processes produces significant mineralized fracture and/or breccia systems.

5.2. Tectonic settings. These porphyry deposits typically occur in orogenic belts at convergent plate boundaries, commonly linked to subduction-related magmatism. The deposits may be related to arc-type continental and oceanic magmatism close to a trench but, in regions of flat subduction, may form more than 150 km inboard of a plate boundary. Magma emplacement may be controlled by relaxation of regional contraction, back-arc extension, or transtension related to strike-slip faults. Less well known, and more restricted in extent, are porphyry Cu-Mo deposits in continental collision settings in Tibet and the central Tethys region of Turkey, Iran, Pakistan, and Afghanistan (Zürcher et al., 2019). These deposits may have formed from hydrous magmas derived by partial remelting of metasomatized lithospheric roots and hydrous cumulate zones of former arc systems, possibly due to lithospheric thickening and thermal rebound, subcontinental lithospheric mantle delamination, or lithospheric extension (Richards, 2009).

5.3. Associated deposit types. Cu skarns (K01), Fe skarns (K03), Au skarns (K04), Pb-Zn skarns (K02), porphyry Au (L02), epithermal Au-Ag-Cu, high-sulphidation (H04), polymetallic veins Ag-Pb-Zn±Au (I05), polymetallic manto Ag-Pb-Zn (J01), sulphide manto Au (J04). Less commonly epithermal Au-Ag, low sulphidation (H05), carbonate-hosted disseminated Au-Ag (Carlin-like, E03), surficial placers (C01), buried-channel placers (C02). Surface weathering of porphyry deposits can result in exotic copper oxide deposits

6. Mineral systems
The magmatic-hydrothermal (orthomagmatic) model for calc-alkaline porphyry Cu±Mo deposits is well understood for upper crustal levels but for deeper levels is still developing. The following descriptions are taken largely from Cooke et al. (2005); Sinclair (2007); Richards (2009), and John et al. (2010).

6.1. Source region. The most common magmas are generated beneath volcanic arcs where partial melting of hydrated upper mantle above subducted ocean crust and sediments takes place. Some authors have suggested that large porphyry copper deposits formed when buoyant oceanic structures such as ridges, ocean plateaus, and seamounts were subducted or during episodes of low-angle subduction. Alternatively, the source could be remelting of subcontinental lithospheric mantle or lower crustal hydrous cumulate zones in collisional, delamination or post-subduction environments. The Cu, Mo, and precious metals are derived primarily from the mantle.

6.2. Source driver. Hot, hydrous magma is buoyant and will move upwards to the base of the crust where it migrates to the overlying plate margins.

6.3. Source product. Hydrous, oxidized, basaltic, calc-alkaline arc magmas are predominantly formed by partial melting of the metasomatized wedge of asthenospheric mantle between the downgoing oceanic and overriding oceanic or continental plate.

6.4. Transport driver. Magma would have accumulated at the base of the lithospheric mantle, eventually leading to the ascent of a buoyant batch of melt to be emplaced into the middle to upper crust where intrusions formed incrementally through the amalgamation of smaller volume batches.

6.5. Transport path. The rifted edges of old lithospheric blocks provide settings where deep, Moho-penetrating faults may be reactivated, and where dense mafic, underplated material is likely to be present at the base of the crust. Ascent of large magma volumes through established crack networks requires a long-lived, continuous supply of magma and an established melt pathway that is amenable to reopening and exploitation by subsequent magma pulses without substantial fractionation. These basaltic magmas can interact with the upper plate lithosphere as they ascend to evolve into hybrid andesitic magmas with relatively high oxidation states and water contents (≥4 wt% H2O). The high oxidation state suppresses the formation of magmatic sulphides, which would strip the magma of chalcophile and siderophile metals and the water content results in saturation of the magma in an aqueous fluid phase upon ascent into the upper crust, into which these metals will efficiently partition.

6.6. Transport termination. Because crustal density decreases significantly in the upper 10 km of crust, the buoyancy forces fall off and the magmas may pond to form plutonic or batholithic chambers.

6.7. Deposit concentration. With ongoing influxes of gas-rich magma, fluid pressures grow and eventually exceed lithostatic pressures and the tensile strength of the overlying rocks to fracture them and permit rapid escape of hydrothermal fluids into newly created open spaces. The escaping highly saline fluids (up to 60% NaCl equivalent) commonly separate into a vapour phase carrying some Cu and Au and a dense, hypersaline liquid with the bulk of the metal content as they flow from lithostatic to near-hydrostatic pressure conditions in the open fractures. Permeability in the column of rock from the cupola to the surface can be maintained as long as temperature and pressure gradients cause magmatic-hydrothermal fluids to ascend. When these fluids cease to flow, fracture permeability decreases by precipitation of minerals, predominantly quartz, in fractures to form veins, veinlets and stockworks. Ore minerals may precipitate with these minerals due to adiabatic expansion and fluid cooling, chemical effects of phase separation, interacting with wall rocks. or mixing with meteoric water.

6.8. Deposit controls. Regional faults can influence magma migration; for subduction-related deposits, these faults can be arc parallel and transverse. Within the broadly convergent plate setting, strike-slip faults can generate zones of transpression and transtension to encourage magma intrusion. Permeability in the column of rock from the cupola to the surface can be maintained as long as temperature and pressure gradients cause magmatic-hydrothermal fluids to ascend and precipitate minerals, predominantly quartz, in fractures to form veins, veinlets and stockworks. Ore minerals may precipitate due to adiabatic expansion and fluid cooling, chemical effects of phase separation, interacting with wall rocks or mixing with meteoric water or seawater.

6.9. Deposit accumulation. Multiple intrusive phases can produce overlapping and/or more extensive mineralized zones. One model suggests small intrusions near the site of ore deposition my remain largely liquid and act as conduits for large volumes of ore-forming fluids produced by degassing of large, subjacent magma bodies.

6.10. Post formation processes. Preservation of supergene enrichment zones can be important to form economic deposits.

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M02: Gabbroic-associated Ni-Cu±PGE

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1. Identification

1.1. Synonyms. Gabbroid associated* (Marston and others, 1981), gabbroid-associated nickel-copper-PGE – stock type (Eckstrand, 1984), synorogenic-synvolcanic Ni-Cu (Page, 1986), gabbroic Cu* (Nokelberg et al., 2005), gabbroic-hosted mineralization (Nixon et al., 2015).* Broader classifications that include gabbroic-associated Ni-Cu±PGE deposits.

1.2. Commodities and by-products. Cu, Ni (Pd, Pt, Ag).

1.3. Examples. Nickel Mountain (E&L, 104B 006; British Columbia); Lynn Lake (Manitoba); Great Lakes Nickel and Marathon (Ontario); Lac Kelly, Lorraine and RM Nickel (Quebec); Funter Bay (Mertie Lode) and Yakobi Bay (Alaska); Kotalahti (Finland); Selebi-Pikwe (Botswana); Carr-Boyd, Manchego, Nebo-Babel, Nova-Bollinger and Savannah (formerly Sally Malay; Australia); Kalatongke and Yueyawan (China).

2. Geological characteristics

2.1. Capsule description. Gabbroic-associated deposits are hosted by small to moderate-sized stocks with multiple phases of gabbro, norite, diorite, and rarely ultramafic rocks with massive and/or disseminated pentlandite, chalcopyrite, and pyrrhotite. Most mines have exploited massive to semi-massive lenses or pipes for Ni and Cu, locally with PGE byproducts.

2.2. Depositional environment and geological setting. These orthomagmatic deposits are hosted by intrusions emplaced into volcanic and sedimentary rocks, or their metamorphosed equivalents. They are found in orogenic terranes, including Archean greenstone belts.

2.3. Ages of mineralization. Most deposits are Archean and Proterozoic; some are Phanerozoic. This age distribution may reflect the limited exploration for nickel deposits of this type in Phanerozoic convergent margins.

2.4. Associated rocks. The host intrusions are emplaced into volcanic and sedimentary rocks and their metamorphic equivalents; less commonly they cut older intrusions. The gabbroic intrusions typically have a metamorphic aureole that extends 10s of m into the country rock.

2.5. Host rocks. Mineralization is hosted by magnesium-rich tholeiitic gabbro, olivine gabbro, gabbronorite norite, and norite, but locally extends into other intrusive phases like pyroxenite, hornblende pyroxenite, wehrlite, troctolite, and tonalite. Ultramafic rocks are uncommon and typically peridotite. A few intrusions have associated anorthositic or granitic rocks. Older intrusions are commonly metamorphosed metagabbro and metapyroxenite. Cumulate and intercumulate textures can be highly deformed and metamorphosed making primary textures difficult to recognize.

2.6. Deposit form. Semi-massive and massive sulphide ore bodies occur as steeply plunging or dipping shoots or pipes and horizontal to shallowly dipping lenses that can be broken up by faults (Marston et al., 1981). They are locally accompanied by downward penetration of m-scale vertical sulphide dikes into the footwall (Barnes et al., 2016). Disseminated mineralization generally forms irregular zones measuring 10s to 100s of m in the longest dimension.

2.7. Ore controls. Mineralization is best developed where large volumes of mafic magma moved through vertical or lateral conduits interacting with wall rock and xenoliths to produce sulphide-related slurries and liquids, which descend to physical traps where they accumulated to form potentially economic mineralization (Ripley, 2010). The magma chambers can propagate laterally as blade-shaped bodies, with sulphides accumulating in the keels (Barnes et al., 2016). Mineralization is generally near or adjacent to contacts with country rock, particularly basal contacts in the case of dikes or sills.

2.8. Ore texture and structure. Massive and breccia-hosted sulphides have typically been the most economically important concentrations of pentlandite and chalcopyrite, with up to 90% sulphides. Silicate inclusions in the massive sulphides consist of recrystallized country rock rather than gabbro. Semi-massive sulfide mineralization can occur along the fringes of the massive sulfide orebodies and in separate zones. It is semi-net to net-textured sulfide mineralization characterized by a semi-continuous to continuous matrix of sulfides (typically >5 modal %) containing a framework of silicate crystals. Some intrusions have generally stratabound or irregular zones of lower-grade, disseminated or blebby copper and nickel sulfide, with rare patches of matrix sulfide and thin veins or lenses of massive and breccia-hosted sulfide. The disseminated sulfide mineralization typically has elevated Cu, Pd, and Au contents relative to the massive sulphide and is typically hosted by specific gabbroic phases. Minor veins are present in some deposits. Minor mineralization can occur in the adjacent country rock but is rarely economic.

2.9. Ore mineralogy. Pyrrhotite, pentlandite, and chalcopyrite with associated titaniferous or possibly chromian varieties of magnetite, and subordinate pyrite and chrome-bearing spinel are the main ore minerals. However, the detailed ore mineralogy of these deposits is complex. More than 50 species of metal minerals are identified in the Kalatongke deposits, including violarite and magnetite with subordinate noble metal minerals of melonite, michenerite, sperrylite, hessite, and electrum (Han et al., 2019). At Nickel Mountain, the most common trace ore minerals are sphalerite and electrum, and most of the platinum group minerals are tellurides or bismuthotellurides, predominantly subordinate merenskyite, moncheite, and melonite (Vandenburg, 2020). Sperrylite is also relatively common, and a significant proportion exhibits an unusually Sb-rich composition. The rare platinum group minerals (PGMs) containing osmium, iridium, and ruthenium, such as rhodium telluride, increase in abundance towards the middle of the sulfide orebodies at Nickel Mountain. Other uncommon PGMs include michenerite, vincentite, and telargpalite.

2.10. Gangue mineralogy. Gangue minerals include magmatic silicates and oxides formed by the ore-hosting mafic intrusions, minerals resulting from contact and regional metamorphism, and minerals in partially ingested xenoliths and hornfelsed country rock (Schulz et al., 2010). Silicate minerals include plagioclase, clinopyroxene, orthopyroxene, olivine and minor hornblende, biotite, and quartz.

2.11. Alteration mineralogy. No alteration is directly related to the primary magmatic mineralization. However, younger metamorphic and/or hydrothermal alteration assemblages, including carbonate, serpentine, chlorite, garnet, amphibole, biotite, quartz, and graphite, can overprint older mineralization. For example, olivine is partially altered to serpentine plus magnetite, whereas orthopyroxene and plagioclase are partially altered to talc plus sericite, and clinopyroxene is partially altered to actinolite and chlorite in the Kalatongke intrusions (Li et al., 2012).

2.12. Weathering. Rusty gossans after sulphides are common in temperate climates. Massive sulfides are generally more deeply weathered than disseminated sulfides. In deeply weathered terranes in hotter climates, a near surface zone of earthy and soft goethite, chlorite, and clay-rich gossan overlies a thicker, less intensely altered zone. In some cases, uplift and tilting can erode much of the deeply weathered material and siliceous hard pans can develop. Above the water table, sulfide minerals are replaced by gossans of hydrated ferric oxides and various carbonate, and silica minerals (Marston et al., 1981). Below the water table, the weathering profile consists of a violarite-pyrite supergene zone where pyrrhotite and pyrite are altered to marcasite, magnetite to hematite, chalcopyrite to chalcocite, and covellite and pentlandite to fine-grained violarite. Gossans developed from the weathering of magmatic Ni-Cu±PGE hypogene minerals typically will retain immobile PGE (Schulz et al., 2010).

2.13. Comments. Three types of nickel deposits are found in convergent margin settings (Nixon et al., 2015): gabbroic-hosted Cu-Ni (PGE), Ural-Alaskan-type PGEs/Ni-Cu-Co, and Giant Mascot-type Ni-Cu-Co-(PGEs). The relatively recent discovery of nickel deposits like Horsetrail (Turnagain) and Huangshanxi coupled with research efforts related to gabbroic-associated deposits (Han et al., 2019, Nixon et al., 2015; Nixon et al., 2020a;) has highlighted the potential to find nickel deposits in orogenic regions. New discoveries and more research are required to more clearly define the boundaries between the gabbroic-hosted Cu-Ni (PGE) and Giant Mascot-type Ni-Cu-Co-(PGEs) deposit types.

3. Exploration and resource assessment guides

3.1. Geochemical signatures. Ni, Cu, and PGEs are the key pathfinder elements in rocks, stream sediments, soils, and silts. Anomalous Cr and locally Co concentrations can be expected as well. Gabbroic rocks with higher MgO contents are more prospective. A magma series that has segregated sulfides is expected to have Ni depletion in the rock and olivine crystals, which could indicate a Ni-Cu sulfide deposit in the area (Barnes et al., 2016). Pd has a much higher partition coefficient into sulfides than Ni and is thus a more sensitive indicator of sulfide segregation. However, Pd is an incompatible element during silicate fractionation and collects in the liquid during crystal fractionation in preference to being incorporated into minerals in cumulate rocks, so using the absolute Pd contents of the rocks to determine whether the magma is depleted in Pd produces ambiguous results. This problem is solved by considering the Cu/Pd ratio, because if no sulfide segregation occurs, Cu behaves similar to Pd, and the Cu/Pd ratio of both fractionated liquids and cumulates should be the same as that of the parental magma (Barnes et al., 1993).

3.2. Geophysical signatures. Airborne, ground, and drill hole surveys can be used; the following is based largely on a presentation by Peters (2017). Electromagnetic (EM) surveys are the most widely used and successful geophysical method to identify massive sulphide with pyrrhotite, chalcopyrite, and pentlandite mineralization. Downhole EM works to depths of 3 km or more and can be used for down-dip testing of prospective contacts. Induced polarization (IP) surveys are effective for identifying disseminated sulphides. Magnetic surveys are important for interpreting the geology and a useful addition to geophysical logging of drill holes, but they rarely lead to direct detection of massive sulphides. Gravity surveys are used primarily for mapping to locate dense host rocks, regional margins, sutures, feeder zones, and magma chambers. They are most effective as ground-based surveys. Seismic surveys are used as a tool for mapping lithology and structure and can locally detect massive sulphides. Passive seismic survey methods are improving and cheaper than conventional seismic methods but deliver lower resolution results. Refraction tomography enables regional mapping of deep structure, crustal thickness, and prospective mantle-tapping zones. Magnetotellurics (MT) uses natural magnetic and electric fields to identify weak resistivity contrasts at significant depths. Audio magnetotellurics (AMT) is faster but can only test shallower depths. Controlled source audio magnetoltellurics uses an active transmitter so it is superior at shallow depths and can also identify deep regional subsurface structures. Airborne magnetotellurics provide rapid coverage but can only measure the vertical field. Satellite spectral data has identified jarosite, a hydrous sulfate mineral with potassium and iron $(KFe_3+3(OH)_6(SO4)_2)$, down slope of Cu-Ni mineralization at Nickel Mountain. This sulfate mineral is formed close to ore deposits by the oxidation of iron sulfide.

3.3. Other guides. Regional areas of interest are near ancient cratonic boundaries and long-lived, trans-crustal structures with a relationship to voluminous mafic magmatism, typically with high Mg and low Ti contents. At the property scale, it is important to identify high volume magma pathways and the petrographic and geochemical signals of accumulation or extraction of sulphide liquid (Barnes et al., 2016). Identifying a sulphur source, such as sulphide-rich sedimentary rocks, can help with targeting exploration efforts, but recent isotopic research has shown the source can be several km from the mineralization site. Many deposits in Western Australia were discovered by recognition of siliceous, limonitic caps or gossans containing anomalous concentrations of Cu and locally Ni (Thornber et al., 1981). Gossans developed from the weathering of magmatic Ni-Cu±PGE hypogene minerals typically retain immobile PGE (Schulz et al., 2010).

4. Economic factors

4.1. Typical grade and tonnage. The grade and tonnage figures for deposits listed in this profile range between 0.6 and 49.4 Mt with grades of 0.2 to 1.4% Cu and 0.27 to 2.6% Ni (Table 1). As noted by Barnes et al. (1993) for eight occurrences in Quebec, mineralization occurs both as massive sulphide zones and larger, lower grade zones. Sixteen samples of semi-massive to massive sulphides at the Lorraine mine averaged 2.23% Ni, 7.26% Cu, 805 ppb Pd, 552 ppb Pt, 736 ppb Au and 30 ppm Ag. The disseminated zones occur close to the margins of the intrusions with lower metal contents and Ni/Cu ratios of ~1, associated with strongly anomalous Pd and Pt. Median tonnage and grades for gabbroic-associated Ni-Cu±PGE deposits, described by Page (1986) as synorogenic-synvolcanic Ni-Cu deposits, are 2.1 Mt grading 0.77% Ni and 0.47% Cu for 32 deposits (Singer et al., 1986) with by-product grades for only two or three deposits of 0.017% Co, 0.025 ppm Au, 63 ppb Pd and 16 ppb Pt.

4.2. Economic limitations. A smaller, high-grade zone of massive or semi-massive sulphides may require other similar zones nearby to make mining economically feasible. Lower grade, disseminated mineralization zones are only economic at present if they are larger deposits associated with other positive factors, such as easy site accessibility or existing mining-related infrastructure.

4.3. End uses. Copper and nickel are important industrial metals; byproduct PGEs are important for use in new technologies.

4.4. Importance. Gabbroic-associated Ni-Cu±PGE deposits are much smaller than the layered intrusive and flood basalt Ni-Cu deposits that have produced much of the world's nickel and a significant amount of the global copper supply. The high-grade massive sulphide zones are attractive economically, whereas the larger, low-grade deposits contain significant metal resources that have only been mined in a relatively few cases (e.g., Kotalahti and Selbie-Pikwe). The future may see development of low-grade deposits such as Mirabela in Brazil and Kevitsa in Finland, which have high-tenor, low-grade disseminated ores in zones that are 10s to 100s of m thick (Barnes et al., 2016). As well, advances in hydrometallurgical techniques, particularly pressure leach methods, are making the extraction of Cu, Ni and PGEs from low-grade, but larger tonnage deposits more economically promising (Ripley, 2010).

5. Genesis

5.1. Genetic model. Tholeiitic magma from the mantle following regional faults to reach conduits and forming small, multi-phase intrusions in the upper crust; hydrous magmas enriched in Ni, Cu and/or PGEs. The source of the sulphur to form sulphide mineralization droplets in the magma can be derived from the wall rocks, particularly from xenoliths, although an alternative source could be the subducted slab. Conduits and laterally flowing dikes are particularly favourable locations for concentrating ore sulphide droplets by gravitational settling and/or absorption onto existing liquid sulphides. Percolation of dense, low-viscosity sulfide liquid into pore space and fractures within partially molten (or melting) silicate rock is a unifying theme that links sulfide matrix ore breccias and emulsion-textured ores (Barnes et al., 2018).

Table 1. Tonnages and grades for selected gabbroic-associated Ni-Cu±PGE deposits.

	Mt	Cu %	Ni %	Pt g/t	Pd g/t	Ag g/t	Reference
Canada							
Nickel Mountain (E&L) (British Columbia)	2.9	0.62	0.8				Sharp, 1966
Lynn Lake (Manitoba)	20.2	0.54	1.02				Eckstrand, 1996
Marathon (Ontario)	37	0.38	0.03	0.27	1.1	0.21	Eckstrand and Hulbert, 2007
Lac Kelly (Quebec)	1.1	0.65	0.59				Barnes et al., 1993
Lorraine (Quebec)	0.6	1.08	0.62				Barnes et al., 1993
International							
Tunnel & Tripod (Alaska)	10.3	0.2	0.37				Kennedy and Walton, Jr, 1946
Muskeg & Side Hill (Alaska)	8.1	0.2	0.27				Kennedy and Walton, Jr, 1946
Kotalahti (Finland)	23.2	0.7	0.3				Eckstrand, 1996
Selebi-Pikwe (Botswana)	49.4	1.12	1.04				Eckstrand, 1996
Kalatongke-Y1 (China)	18	1.4	0.88				Li et al., 2012
Kalatongke-Y2 (China)	10	1.1	0.6				Li et al., 2012
Carr Boyd (Australia)	1.2	0.43	1.52				Eckstrand and Hulbert, 2007
Savannah (Australia)	2	0.66	2.6				Eckstrand and Hulbert, 2007

5.2. Tectonic settings. Arc magmatism at a convergent margin with partial melting of the mantle wedge overlying the subduction zone can produce hydrous, Ni-Cu bearing magmas that rise through the crust to form staging chambers that can expel large volumes of magma to form small, higher level intrusions or lava flows. Structural corridors may be important for these deposits (Lightfoot and Evans-Lamswood, 2015). Back-arc rifting has been proposed for the Nickel Mountain deposit in northwest British Columbia (Vandenburg, 2020). Ferguson Creek is another example of Ni–Cu–PGE mineralization considered to have been emplaced in a back-arc basin setting (Acosta-Góngora et al., 2018). Numerous gabbroic-associated Ni-Cu±PGE deposits occur in Archean greenstone belts that may have formed at convergent margins. Some gabbroic mineral deposits may also be related to large igneous provinces (Kalatongke, China; Lightfoot and Evans-Lamswood, 2015).

5.3. Associated deposit types. Komatiitic Ni-Cu, dunitic Ni-Cu (Page, 1986).

6. Mineral systems

The following description of a mineral system for gabbroic-associated Ni-Cu±PGE deposits is derived largely from Barnes et al. (2016) and Barnes and Robertson (2019).

6.1. Source region. The magma sources are sub-lithospheric and derived from the mantle wedge overlying a subduction zone. The metals in magmatic ores are sourced overwhelmingly from the magmas themselves.

6.2. Source driver. Higher temperatures in the mantle melt the mantle wedge and produce hot buoyant magma.

6.3. Source product. Hydrated mafic magmas are produced with moderate MgO contents and significant Ni, Cu, and/or PGE. Although Ni contents can be higher for recycled oceanic crust owing to the predominance of pyroxene, evidence of fertile source regions for these metals is generally lacking.

6.4. Transport driver. Buoyancy transports the melts upwards along crustal faults and via dike propagation.

6.5. Transport path. Deep, Moho-penetrating faults provide the initial path into the crust. Ascent of large magma volumes through established crack networks to the upper crust requires a long-lived, continuous supply of magma and established melt pathways that can be exploited by subsequent magma pulses.

6.6. Transport termination. Stocks, dikes and sills form as a vertically migrating magma reaches a level of neutral buoyancy and then propagates laterally due to a minimum compressive stress that is horizontal.

6.7. Deposit concentration. Massive sulphide ore deposition is favoured by high-volume flow over a horizontal floor. This floor may take the form of the base of a sill, tube, or dike (Barnes and Mungall, 2018). The very dense sulphide liquid accumulates by sedimentation of transported droplets higher in the magma conduit, then subsequently flows downwards to its site of deposition as sulphide liquid + crystal + magma gravity currents. The essential feature of this model is the presence of floors in parts of any magma chamber or conduit.

6.8. Deposit controls. At upper crustal levels, magma flows through dikes and sills where it interacts with country rocks to incorporate sulphur as the sulfate or sulfide that is necessary to form sulfide liquid or droplets. The liquid or droplets can extract and concentrate chalcophile elements such as Ni, Cu, Co, PGEs, Au and Ag from the magma. Driven largely by gravity, the dense sulphide liquid or droplets will accumulate in the conduit in physical traps. A key factor is that the partition coefficient for Ni from silicate into sulphide liquid increases rapidly with falling temperature and MgO content, such that Ni-rich sulphides can still form from relatively cool, Ni-poor magmas.

6.9. Deposit accumulation. Economic sulphide deposits require prolonged interaction between sulfide accumulations and many times their own volume of silicate magma. Repeated influxes of magma can interact with the sulphide liquid or droplets to upgrade their metal contents and increase the overall volume of the mineralized zone. The new magma can also remobilize the sulphide liquid or droplets multiple times.

6.10. Post formation processes. Because the deposit formed at some depth below the earth's surface, a favourable history of uplift and/or erosion may be required to bring it to a suitable location for economic recovery.

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M05: Ural-Alaskan-type PGE-Cu-Ni±Co

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1. Identification

1.1. Synonyms. Alaskan PGE (Page and Gray, 1986), Alaska-type Pt±Os±Rh±Ir (Nixon, 1996), Uralian-type (Naldrett, 2004), NC-7 Ural-Alaskan type (Naldrett, 2010).

1.2. Commodities and by-products. Three subtypes of deposits with differing commodities similar to a classification outlined by Laznicka (1985, p. 248): 1) Pt (Ir, Os, Rh); 2) Ni ± Cu ± Co and 3) Cu±PGE-Ag-Au.

1.3. Examples. Listed by the three subtypes: 1) Dunite-clinopyroxenite Pt (Ir, Os, Rh), Nizhny Tagil (Urals, Russia), Owendale (New South Wales, Australia 2) Dunite-wehrlite±clinopyroxenite Ni ± Cu ± Co: Turnagain complex BC, Horsetrail (104I 119), Polaris complex BC, GL Zone (094C 165), Xiarihamu (China); and 3) Clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au, Tulameen complex BC, Champion zone (Nixon et al., 2018), Turnagain complex BC, DJ/DB Zone (104I 125,126), Polaris complex BC, HB Zone (094C 168), Salt Chuck mine and Duke Island exploration property (Alaska); Volkovsky (Urals, Russia).

2. Geological characteristics

2.1. Capsule description. Ural-Alaskan-type orthomagmatic deposits are hosted by alkaline to subalkaline, ultramafic to mafic intrusive complexes located in linear belts at convergent plate margins. The complexes form transgressive sills, stocks, or irregular bodies intruded into weakly to strongly metamorphosed sedimentary and volcanic sequences. Larger complexes generally have crude concentric zoning from a dunitic core outwards through successive shells of olivine clinopyroxenite, magnetite-rich clinopyroxenite, hornblendite and locally gabbro or diorite. However, individual zones can be discontinuous or missing. Later stage hydrothermal processes can remobilize this mineralization, particularly near faults.

Ural-Alaskan complexes host three styles of mineralization. In the **dunite-clinopyroxenite Pt (Ir, Os, Rh)** style (Nizhniy Tagil type; Laznicka, 1985, Nixon, 1996, Nixon et al., 1997, Naldrett, 2004), chromite or magnetite segregations occur as veinlets and schlieren typically several m to 10s of cm thick and up to several m long with up to 100% chromite or magnetite (Naldrett, 2004). This style was mined for Pt from intrusions in the Urals in the 1800s and early 1900s. It is also the source of the prolific platinum placer deposits in the region, some of which are still being mined today. In the **dunite-wehrlite±clinopyroxenite Ni ± Cu ± Co style** (Scheel et al., 2005; Song et al. 2016), disseminated grains and net-textured aggregations of pyrrhotite, pentlandite, and less commonly chalcopyrite, occur near the margins of the intrusive complex. In the **clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au** style (PGE-4 - Volkovsky type, Naldrett, 2010, Nixon et al., 2020c), chalcopyrite, bornite, and pyrrhotite mineralization can form as disseminations and veinlets near the margins of the intrusive complexes or near contacts between intrusive phases.

2.2. Depositional environment and geological setting. Ural-Alaskan complexes are emplaced along major crustal faults in shallow-level subvolcanic environments. Intrusive margins are commonly faulted placing unrelated rocks adjacent to the intrusion. The larger intrusions have multiple phases that were emplaced in time spans of millions of years (Nixon et al., 2020b). Least evolved crystallization phases produce dunite and wehrlite that can form layered sequences of olivine-rich cumulates and chromitite or magnetite horizons, which are commonly disrupted in response to gravitational instability, influxes of magma, or tectonic activity. More evolved crystallization phases are clinopyroxenite, wehrlite, gabbro, and diorite, which can interact with the country rock to produce sulphide mineralization.

2.3. Ages of mineralization. Mineralization is syngenetic with intrusive phases and some Ural-Alaskan intrusions host different styles of mineralization that formed at different times. Mineralization may be modified by later hydrothermal or deuteric processes that can enhance the economic attractiveness of a deposit. The intrusions are predominantly Phanerozoic (Nixon, 1996, Naldrett, 2010): Urals (Silurian-Devonian); Alaska (Silurian-Devonian and Cretaceous); New South Wales (Devonian); Inagli and Konder (Carboniferous); and British Columbia (Late Triassic and Jurassic). A small group of 2.7 Ga, zoned, intrusive mafic and/or ultramafic pipes containing PGE-rich magmatic sulfides in the Quetico subprovince in northwestern Ontario resemble Phanerozoic Ural-Alaskan bodies (Pettigrew and Hattori, 2006, Nixon et al., 2015).

2.4. Associated rocks. . Intrusive complex rock types are dunite, wehrlite, olivine clinopyroxenite, clinopyroxenite, hornblende clinopyroxenite, clinopyroxene hornblendite, and hornblende- and/or clinopyroxene-bearing gabbro/diorite (Nixon, 1996). Syenite occurs in some intrusions. In the International Union of Geological Sciences classification scheme for ultramafic rocks, Ural-Alaska-type intrusive phases are confined to the olivine-clinopyroxene join with variable amounts of hornblende because they lack orthopyroxene (Nott et al., 2020). This is an important mineralogical distinction because other types of magmatic nickel deposits are associated with orthopyroxene-bearing host rocks. Minor rock types include chromitite, magnetitite, olivine-hornblende clinopyroxenite, and hornblendite. The complete range of rock units is rarely present in a single intrusive complex. Lithological contacts are gradational to sharp. Variations in grain size and crystal habit occur on cm to m scales. The host intrusions commonly have maximum dimensions of less than 10 km. Many are elongate and formed largely as sills. Intrusions can occur in belts extending 100s of km. The country rock generally consists of metamorphosed sedimentary and/or volcanic rocks. Locally, the complexes have well-developed metamorphic contact aureoles.

2.5. Host rocks. Key rock types are dunite, wehrlite, olivine clinopyroxenite, clinopyroxenite, hornblende clinopyroxenite, and gabbro. The Mg/(Mg+Fe^{2+}) ratio of olivine and clinopyroxene generally decreases systematically from dunite to more differentiated rocks. The $A1_20_3$ content of clinopyroxene, which shows a marked enrichment with differentiation, suggests crystallization from progressively more hydrous melts like those characteristic of arc magmas. The hydrous nature of the magma is also indicated by the common occurrence of phlogopite and hornblende in wehrlite and clinopyroxenite and by hornblendite being part of the differentiation sequence. In the **dunite-clinopyroxenite Pt (Ir, Os, Rh)** style, chromitite is hosted by dunite, wehrlite and olivine clinopyroxenite and in some instances clinopyroxenite. In the **dunite-wehrlite±clinopyroxenite Ni ± Cu ± Co** style, mineralization is hosted by olivine and clinopyroxene-rich rocks, such as dunite, wehrlite and clinopyroxenite. In the **clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au** style, mineralization is hosted by more differentiated intrusive phases, such as clinopyroxenite, hornblendite and gabbro. The contacts between clinopyroxenite and gabbro rocks can be favourable sites for mineralization.

2.6. Deposit form. In the **dunite-clinopyroxenite Pt (Ir, Os, Rh)** style, thin chromitite layers originate as cumulates. However, these layers are commonly disrupted to form thin discontinuous layers or schlieren, pods and nodular masses seldom more than 1 m long. Small platiniferous pipes have been mined in the Urals (Laznicka, 1985, p. 249). In the **dunite-wehrlite±clinopyroxenite Ni ± Cu ± Co** style, zones of sulphide mineralization at the margins of the intrusions can extend for more than 1 km with interspersed, variable amounts of barren or sparsely mineralized rock. In the **clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au** style, zones of sulphide mineralization at the margins of Ural-Alaskan intrusions that can extend for dimensions of 100s of m.

2.7. Ore controls. Processes fundamental to the production of economic Ni-sulphide deposits in the oxidized and hydrous primitive magmas at subduction zones are similar to those that produced magmatic nickel deposits in other tectonic settings (Nixon et al., 2015). Mineralization forms within alkaline to subalkaline intrusions emplaced above subduction zones. Pt (Ir, Os, Rh) mineralization is restricted to chromitite layers hosted by dunite, and rarely wehrlite, that formed by primary magmatic crystallization. Because most Alaskan-type magmas are sulphur-deficient, wall-rock assimilation of sulphur and/or carbon is required to form an immiscible sulphide liquid to produce Ni ± Cu ± Co or Cu±PGE-Ag-Au mineralization.

2.8. Ore texture and structure. Tectonic deformation, commonly ductile shear zones, is locally superimposed on magmatic textures and is prevalent at intrusive contacts. In the **dunite-clinopyroxenite Pt (Ir, Os, Rh) style**, cumulus and intercumulus textures are most common; poikilitic textures may predominate locally, especially in hornblende-bearing rocks. Dunite and wehrlite host disseminated chromite grains. Macroscopic layering is relatively rare, but inclusions of layered chromitites attest to the origin of the more common isolated chromitite schlieren (Nixon et al., 2020a). Layers are commonly disrupted, and the mineralization occurs in discontinuous zones, lenses, or schlieren. Euhedral to subhedral chromite concentrations form only in dunite as networks around olivine or discrete wispy or thin layers. Chromitites typically form nodular masses and narrow, small schlieren that may be more than 1m long, and display ductile fabrics of formerly layered chromitite-dunite sequences. Pegmatitic, biotite- and magnetite-poor clinopyroxenites, known only from Fifield, Australia, form irregular lenses and vein-like bodies within biotite- and magnetite-rich, fine grained clinopyroxenites (Johan et al., 1989). The Pt mineralized "P-units" are not enriched in base metal sulphides with respect to the surrounding barren clinopyroxenites. In the **dunite-wehrlite±clinopyroxenite Ni ± Cu ± Co** style, such as at the Horsetrail deposit (Turnagain complex, British Columbia) mineralized zones consist of broadly dispersed, disseminated to intercumulus pentlandite, pyrrhotite, and chalcopyrite in both dunite and wehrlite and serpentinized equivalents (MINFILE 104I 119). Sulphide grains range from 0.5 to 5 mm and commonly occupy interstices between olivine grains. Semi-massive and massive sulphide layers not exceeding a few 10s of cm were also noted in drill core (Thompson et al., 2020). In the **clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au** style, mineralization forms disseminated to blebby, net-textured, semi-massive to massive sulphides with local layering and veins (e.g., Salt Chuck, Alaska; Loney and Himmelberg, 1992). Bornite and chalcopyrite occur as largely irregular, interstitial grains in the intrusive rocks. The mineralization at the Duke Island intrusion is typically net-textured with pyrrhotite, chalcopyrite, and pentlandite, commonly with magnetite, although some massive sulphide zones are 2-3 m thick (Thakurta et al., 2008).

2.9. Ore mineralogy. Mineralogy in the **dunite-clinopyroxenite Pt (Ir, Os, Rh)** style is chromitite-PGM, principally chromite and Pt-Fe(-Cu-Ni) alloys (e.g., tetraferroplatinum, isoferroplatinum, rare native platinum, tulameenite) and minor Os-Ir and Pt-Ir alloys, Rh-Ir sulpharsenides (hollingworthite-irarsite series), sperrylite ($PtAs_2$), geversite ($PtSb_2$), and laurite (RuS_2). At Fifield, Australia there are pegmatoidal clinopyroxenites within olivine clinopyroxenites with cooperite, erlichmanite (OsS_2), Pt-Fe alloys (isoferroplatinum-tetraferroplatinum), sperrylite and geversite (Johan et al., 1989; Keays et al., 2020). In the **dunite-wehrlite±clinopyroxenite Ni ± Cu ± Co** style, the sulphides are mainly pentlandite and pyrrhotite with minor amounts of chalcopyrite, bornite, and/or pyrite, and trace Ni±Co±Cu sulphides (Thompson et al., 2020). In the **clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au** style, pyrrhotite and chalcopyrite are the most common sulphides, along with pyrite, pentlandite, and magnetite (Jackson-Brown et al, 2015). A variety of trace sulphide, antimonide, and platinum group minerals form disseminated grains associated with either pyrrhotite or chalcopyrite. At the Salt Chuck mine, bornite is the predominant copper mineral and the platinum group metals occur as isolated grains and free aggregates or within sulphide grains (Watkinson and Melling, 1992).

2.10. Gangue mineralogy. The principal gangue minerals include: olivine, chrome spinel, clinopyroxene, and hornblende in ultramafic rocks; hornblende, clinopyroxene, and plagioclase in gabbroic and dioritic rocks; and hornblende, quartz (rare), and alkali feldspar in leucocratic differentiates. Orthopyroxene is characteristically absent as a cumulus phase but may form very rare intercumulus grains. Accessory magnetite and apatite are generally common, and locally abundant in hornblende clinopyroxenite; phlogopite-biotite is an accessory phase in British Columbia intrusions.

2.11. Alteration mineralogy. Ural-Alaskan deposits are unaltered but are commonly serpentinized due to metamorphism and locally due to interaction with hydrothermal fluids (e.g., Salt Chuck mine).

2.12. Weathering. Tertiary laterites form above most of the Ural-Alaskan complexes in New South Wales, Australia. The laterite is preferentially developed over the ultramafic rock types, and the leached B-soil horizon contains locally well-developed nodular magnesite, which was mined in the Cincinnatti and Fifield magnesite mines (Johan et al., 1989). Deep weathering of ultramafic rocks at the Owendale complex produced a lateritic cap with a Pt resource and highly anomalous Ni and Sc values (Keays et al., 2020). Pt–Fe alloys, sperrylite, and most PGE-sulfides survive weathering of the ores, whereas the base metal sulfides and (Pt, Pd)-bismuthotellurides can be transformed into ill-defined (Pt, Pd)-oxides or -hydroxides (Oberthür, 2018). In addition, elevated contents of Pt and Pd can be found in Fe/Mn/Co-oxides/hydroxides and smectites. Placer platinum deposits are produced by mechanical degradation of magmatic lode occurrences. Although some argue that the PGE found in placer occurrences result from hydromorphic dispersion and precipitation of PGE during fluvial transport, deposition, and weathering, a variety of textural, mineralogical and isotopic (Re-Os) data indicate that most placer occurrences are detrital. In placer deposits, the PGE-sulfides experience further modification, whereas sperrylite largely remains a stable phase and grains of Pt–Fe alloys and native Pt are more durable and commonly increase in relative proportion.

2.13. Comments. Ural-Alaskan intrusions are well known for their chromite-associated platinum contents. These intrusions have given rise to important platinum placer deposits that are still mined and historic lode production, mainly from deposits in the Ural Mountains in Russia before the mid-1900s when the supply of platinum switched to the more economically attractive Merensky Reef mineralization of the Bushvelde Complex and other large layered intrusions. More attention is now being given to the potential of Ural-Alaskan intrusions for Ni and Cu deposits with PGEs (Naldrett, 2010, Nixon et al., 2015).

3. Exploration and resource assessment guides

3.1. Geochemical signatures. Sampling rocks, soils, stream sediments, and tills for elevated values of ore elements can be effective. Heavy mineral concentrate samples of these types of media are also useful. Whole rock and petrographic analyses can be used to help identify favourable host rocks that have high-Mg olivine, diopsidic clinopyroxene, and phlogopitic mica, high LILE and low HFSE, and fractionated REE. For the **dunite-clinopyroxenite Pt (Ir, Os, Rh)** style, panning stream sediments for platinum and magnetite nuggets and analyzing silt samples from streams for Pt, Os, Rh, and Ir is useful. PGE geochemistry and platinum mineralogy of nuggets may help find lodes. Geochemical pathfinder elements for PGE, such as As and Sb, may also be important. Similar analyses for Cu, Pd, Ag and Au and possibly Cu and Pt can be carried out for the c**linopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au** style.

3.2. Geophysical signatures. Ural-Alaskan intrusive complexes and their zonation can be identified by regional magnetic, gravity, and seismic surveys. Airborne, ground, and drill hole electromagnetic surveys are useful for identifying Cu and Ni more massive sulphide zones. Disseminated sulphide zones are best tested with induced polarization surveys.

3.3. Other guides. Mapping of Ural-Alaskan intrusive complexes may identify prospective host rocks and their contact relationships. Ni and Cu mineralization is likely to be close to contacts with country rocks, particularly those able to contribute sulphur or carbon to a magma. Contacts between magmatic phases within the complexes can be important for localizing magmatic and later remobilized mineralization.

4. Economic factors

4.1. Typical grade and tonnage. Platinum deposits were mined as lodes in the Ural Mountains from the 1800s until the 1930s (Garuti, 2011) from small bodies of platinum-bearing chromitite. For example, in the Nishniy-Tagil area, they range in length from roughly 30 cm to rarely more than 100 m. The highest grade was mined from the "Krutoy Log lode," a 2 m long mass of chromite that yielded 965 ounces of platinum metals (Mertie, 1976). Examples of Alaskan intrusions with nickel, copper, cobalt, and PGE production or resources are listed in Tables 1 and 2.

Table 1. Grades and tonnages for selected dunite-wehrlite±clinopyroxenite Ni ± Cu ± Co deposits.

	Mt	Ni %	Cu %	Co %	Reference
Horsetrail (British Columbia)	1073	0.22		0.013	Thompson et al., 2020
Xiarihamu (China)	157	0.65	0.14	0.013	Han et al., 2020

Table 2. Grades and tonnages for selected clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au deposits.

	Mt	Cu %	Ni %	Pd g/t	Pt g/t	Au g/t	Ag g/t	Reference
Polaris (British Columbia)	n/a	1.2	0.25		<1.3	<1.8		Nixon et al., 2015
Salt Chuck (Alaska, USA)	0.27	0.9		1.5		0.6	3	Gault and Wahrhaftig, 1992
Duke Island (Alaska, USA)		<2.8	<0.25	<1 Pd + Pt				Nixon et al., 2015
Volkovsky (Urals, Russia)	11.3	0.3-0.7		0.12	1-7	0.1	3.35	Anikina et al., 2014

4.2. Economic limitations. The PGE-chromitite lode occurrences are not currently viable for mining.

4.3. End uses. Nickel is an alloy metal found in nickel steels and nickel cast irons. Cobalt is important for creating modern batteries. Copper is used as a conductor of heat and electricity, as a building material, and as a constituent of various metal alloys. PGE are used as high-temperature catalysts in a variety of industries, perhaps the most familiar being platinum for automobile catalytic converters. Other uses include medical and electronic (fuel cells, thermocouples), and platinum is used in jewelry.

4.4. Importance. Nickel and copper are key metals for modern society. PGE are classed as a strategic commodity and their consumption has increased dramatically in the last three decades.

5. Genesis

5.1. Genetic model. Ural-Alaskan-type complexes originate from highly oxidizing magma derived from subduction zones that ascend to crustal levels. Platinum-rich minerals, mainly Pt–Fe alloys, form in the least evolved stages of magmatic evolution and are associated with crystallization of chromite. Ni and/or Cu mineralization can form if intrusive phases are contaminated by crustal C- or S-bearing fluids or graphitic sulphides, which reduce the magma fO_2 that is needed to promote sulfide saturation and stabilize sulfides. Palladium-rich minerals form in more evolved stages commonly associated with Cu mineralization.

5.2. Tectonic settings. Ural-Alaskan-type ultramafic-mafic intrusions are emplaced in convergent margin or supra-subduction zone settings (Nixon et al. 2015; Manor et al. 2016, 2017). These intrusions are typically formed by the emplacement and differentiation of hydrous mafic magmas generated in the mantle wedge above subduction zones (Himmelberg and Loney, 1995).

5.3. Associated deposit types. Pt and magnetite placers (C01, C02), magmatic Ti-Fe+/-V oxide deposits (M04), and potentially PGE and Ni laterites. Clinopyroxenite-hornbendite-gabbro Cu±PGE-Ag-Au mineralization overlaps with disseminated Ti-magnetite-apatite bodies (M04) at the Volkovosky deposit (also known as Volkovo and Volkovskoe) in the Urals (Laznicka, 1985, pages 245, 250); Anikina et al., 2014).

6. Mineral systems

The following mineral system description is derived primarily from Thakurta et al. (2008), Nixon et al. (2015), Barnes et al. (2016), Barnes and Robertson (2019), and Nixon et al. (2020a).

6.1. Source region. The metals in magmatic ores are sourced overwhelmingly from the transporting magmas themselves, which originate from a subduction-modified mantle source. The magma sources are derived from substantial (5-20%) partial melting of the mantle wedge overlying a subduction zone.

6.2. Source driver. Hot, hydrous magma is buoyant and will move upwards, possibly as a magma plume, to the base of the crust.

6.3. Source product. The parental magmas for the Ural-Alaskan-type complexes are considered to be unfractionated mantle-derived primary melts of hydrous, high-K ankaramites, which are alkaline basalts that consist of clinopyroxene with lesser highly magnesian olivine (up to Fo94) and plagioclase, with accessory biotite and apatite, but no orthopyroxene. With their moderate to high oxygen fugacities, Mg-rich (10–18 wt % MgO) magmas containing up to 7 wt % H_2O can liberate Ni, Cu, and PGEs from the upper mantle residue.

6.4. Transport driver. Magmas accumulated at the base of the lithospheric mantle ascend buoyantly to the middle to upper crust.

6.5. Transport path. Moho-penetrating faults are reactivated to provide a path for dense ultramafic-mafic magmas at the base of the crust. Ascent of large magma volumes through established crack networks requires a long-lived, continuous supply of magma and an established melt pathway that is amenable to reopening and exploitation by subsequent magma pulses, without substantial fractionation.

6.6. Transport termination. The mineral chemistry and phase equilibria of the ultramafic bodies suggest crystal fractionation and mineral concentration processes in magma chambers at depths of 3 to 9 km (Himmelberg and Loney, 1995). Intrusions form as a vertically migrating magma reaches a level of neutral buoyancy and then starts to spread laterally.

6.7. Deposit concentration. Chromitite layers result from magma mixing and subsequent settling of chromite grains with PGE. Sulfide saturation is usually triggered by the reduction of relatively oxidized parental arc magmas, the assimilation of S- and silica-bearing country rocks, and by the fractional crystallization of olivine and clinopyroxene causing precipitation of sulphides as intercumulus, net textured, disseminated aggregates, and/or massive accumulations.

6.8. Deposit controls. The type of mineralization reflects the metals in the particular magmatic phase and their incorporation into ore minerals from a cooling magma of an appropriate composition. Crustal contamination with sources of sulphur and carbon can play a key role in the formation of sulphides.

6.9. Deposit accumulation. Larger intrusions and more voluminous amounts of the compositional phase related to a particular style of mineralization are required to accumulate larger zones and/or more attractive grades.

6.10. Post formation processes. Metamorphism is common and erpentization of the ultramafic rocks is widespread. Due to the convergent margin tectonic setting, there can be relatively rapid uplift of the region resulting in erosion of rocks overlying or containing the ore bodies. Weathering of mineralized rocks can produce Ni laterites in appropriate climates. In some cases, hydrothermal fluids may alter and/or remobilize mineralization.

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M09: Giant Mascot-type Ni-Cu±Co

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1. Identification

1.1. Synonyms. No synonym in English

1.2. Commodities and by-products. Ni, Cu, Co (Pt, Pd, Au, Ag).

1.3. Examples. In British Columbia: Millie (092GSE017), Giant Mascot (092HSW125), Pride of Emory (092HSW004), Star of Emory (092HSW093), Big Nic (092HSW168), and Anyox-Rodeo (104M 017). Elsewhere: Gordon Lake (Ontario); Americano do Brasil (Brazil); Tejadillas, (Spain); Gabbro Akarem and Genina Gharbia (Egypt); Hingquiling, Huangshandong, Huangshanxi, Hulu, and Heishan (China).

2. Geological characteristics

2.1. Capsule description. Giant Mascot deposits consist of pyrrhotite, pentlandite, and chalcopyrite mineralization occurring as pipes, lenses, or other discordant bodies within small, multiple-phase, ultramafic/mafic intrusions composed of dunite, peridotite, pyroxenite, hornblende pyroxenite, and hornblendite. Significant orthopyroxene along with olivine and clinopyroxene is a distinguishing characteristic. These intrusions are hosted by volcanic and sedimentary rocks or, more commonly, their metamorphic equivalents. Similar intrusions commonly occur in clusters or linear arrays not all of which will be mineralized.

2.2. Depositional environment and geological setting. The sulphides form in crustal magmatic bodies emplaced at moderate depths into sequences of metamorphosed sedimentary and volcanic rocks and associated intrusive rocks. It is common to have multiple ore bodies in the same deposit aligned along faults or a general structural trend.

2.3. Ages of mineralization. Most deposits formed during the Phanerozoic. The Giant Mascot deposit is Cretaceous and dated at 93 Ma (Manor et al., 2017). In China, the deposits of this type are Devonian (ca. 366 Ma), Permian (ca. 271-287 Ma), and Late Triassic (ca. 216 Ma; Han et al., 2019). The two deposits from Egypt are Neoproterozoic (ca. 963-973) and the Gordon Lake deposit in Canada is Neoarchean (2.7 Ga).

2.4. Associated rocks. Host rocks to the ultramafic-mafic complexes are generally medium- to high-grade metamorphic sedimentary and volcanic sequences cut by granitic intrusions. Dioritic and gabbroic rocks occur marginal to a number of intrusive complexes hosting Giant Mascot-type Ni-Cu deposits (e.g., Giant Mascot, Manor et al., 2016; Poyi, Xue et al., 2016; Gabbro Akarem, Helmy and El Mahallawi, 2003), in some cases largely or completely surrounding the complex. At Huangshandong, the first pulse of magma to arrive was the most fractionated and formed a barren, gabbroic layered sequence (Mao et al., 2015). At Giant Mascot, the Spuzzum diorite intrusion, which surrounds much of the ultramafic intrusive complex, is older by 2 million years (Manor et al., 2017).

2.5. Host rocks. The Ni-Cu mineralization is primarily hosted by ultramafic rocks, including hornblende harzburgite, hornblende websterite, two-pyroxene hornblendite, and hornblendite. Hornblende dunite, olivine-hornblende pyroxenite, and hornblende orthopyroxenite can also host mineralization. For some Chinese deposits the primary ore host is wehrlite, a peridotite with up to a few % orthopyroxene. At Gabbro Akarem, there are also outer zones of weakly mineralized (<0.3 modal % sulphides) olivine-plagioclase hornblendite, hornblende-plagioclase pyroxenite and plagioclase hornblendite rock (Helmy and El Mahallawi, 2003). The absence of sharp lithologic contacts and presence of crosscutting ultramafic rocks is common for this type of deposit. The magmatic minerals are olivine, orthopyroxene, clinopyroxene, and hornblende, with minor biotite and plagioclase, and accessory rutile, apatite, and zircon. Some mafic complexes host a variety of late leucocratic intrusions that may represent residual liquid segregations or have been derived from partially melted wallrock. These intrusions commonly contain magmatic 'hornblende' (typically tschermakite, pargasite, magnesio-hornblende, magnesio-hastingsite, and edenite), compositionally similar to Ural-Alaskan-type intrusions (Nixon et al., 2015). Xenoliths of wall rocks and mafic intrusive rocks exhibit various stages of penetration and absorption by the enclosing intrusive phase, such as a pyroxenite. Sulphide mineralization may be well developed at the margins of xenoliths. Olivine- and pyroxene-rich cumulates form the core of the zoned ultramafic suite at the Giant Mascot deposit, with the magmatic sulfide ores mostly restricted to the dunite, peridotite, and pyroxenite (Pinsent, 2002; Manor et al., 2017). Discrete dunite pods form relatively rare inclusions in peridotite, and pyroxenites commonly enclose subrounded peridotite and cognate pyroxenite xenoliths. The most extensive map unit in the Giant Mascot ultramafic suite is hornblende pyroxenite, which also forms cm-scale veins with sharp contacts in pyroxenite. Small-scale veins and dikes of hornblendite cut all rock units in the intrusion. Pegmatitic hornblendite forms a discontinuous rim against dioritic wall rocks. The youngest phases are felsic pegmatite and aplite dikes and veins that cut hornblende pyroxenite, hornblendite, and hornblende gabbro. U-Pb geochronology at Giant Mascot indicates that the zonal structure of the intrusion was constructed in less than a million years (Manor et al., 2017).

2.6. Deposit form. The intrusions are small (typically <4 km2) and commonly elongate, forming subvertical, composite or simple dikes, plugs, and sill-like bodies that can be followed for hundreds of m beneath the surface (>2 km at Poyi, China; Xue et al., 2016). They may lack a discernible internal structure or exhibit a concentric, bilateral, or unilateral arrangement of rock units separated by sharp to gradational contacts, and have layering on scales of 100 m or, rarely, cm (Nixon et al., 2015). The ores form pipe-like, lensoid, tabular and pod-like bodies that can be generally aligned along a fault. Some intrusions are rhomboid in plan due to transtension along strike-slip faults (Lightfoot and Evans-Lamswood, 2015). Intrusion keels commonly connect to a dike.

2.7. Ore controls. The ore deposits occur in ultramafic-mafic magmatic intrusives of high MgO basaltic composition with olivine-clinopyroxene-orthopyroxene minerals. The mineralization is largely associated with cumulate and least differentiated phases. The massive sulphide ore bodies typically form adjacent to contacts with the country rock. The network and disseminated mineralization form zones associated with dunite or clinopyroxenite host rocks.

2.8. Ore texture and structure. Ore textures are diverse and include: net textured sulphides; brecciated sulphide aggregates; intercumulus disseminated sulphide minerals; massive sulphides; and sulphides supporting fragments of different intrusive phases. Some deposits consist almost entirely of disseminated and net-textured ores (e.g., Haungshandong) with little or no semi-massive sulphide ores. Massive sulphide veins occur in some deposits but are volumetrically insignificant. Ore minerals display poikilitic, reaction rim, sideronitic, interstitial, and corrosion textures (Han et al., 2019). Flame structure of pentlandite in pyrrhotite and chain-like aggregates of pentlandite in pyrrhotite are evidence of exsolution/peritectic reaction from the primary sulphide phase(s). Sulphides can occur as irregular grains or aggregations of grains around crystals of olivine and pyroxene. The boundaries between pyrrhotite and pentlandite may be sharp, jagged, or corroded.

2.9. Ore mineralogy. Predominately pyrrhotite (locally nickeliferous), pentlandite, chalcopyrite, pyrite, cubanite, marcasite, sphalerite and magnetite. Accessory minerals may include chromite, linnaeite, siegenite, violarite, valleriite, millerite, nickeline, bismuthotellurides, ilmenite and magnetite. Rarely present mineral are melonite ($NiTe_2$), hessite ($AgTe_2$), volinskyite ($AgBiTe_2$), tellurobismuthite (Bi_2Te_3), mackinawite and bravoite. At Giant Mascot, violarite, polydymite, and symplectic intergrowths of pyrrhotite-orthopyroxene, chalcopyrite-chlorite + actinolite, and pyrite-chalcopyrite are interpreted as low-temperature or late metamorphic reactions involving pentlandite (Manor et al., 2016). Sulfarsenide minerals, such as gersdorffite (NiAsS), cobaltite (CoAsS), and nickeline (NiAs) are typically associated with platinum group minerals (PGM).

2.10. Gangue mineralogy. Gangue mineralogy can include magmatic silicates and oxide minerals of the intrusion; minerals resulting from contact and regional metamorphism, and minerals in partially ingested xenoliths and hornfelsed country rock (Schulz et al., 2010). Gangue minerals in the intrusive phases comprise olivine, orthopyroxene, clinopyroxene, hornblende, and plagioclase, generally with minor Cr spinel and phlogopite. In these deposits there is a sequence of crystallization of first-formed olivine and clinopyroxene and later formed orthopyroxene. Silicate minerals may be rounded and corroded. Olivine commonly exhibits corrosion textures. Orthopyroxene and clinopyroxene oikocrysts may have abraded and jagged textures. Co-precipitated clinopyroxene and orthopyroxene may show interpenetrating textures. Plagioclase is an interstitial phase in the ultramafic rocks with generally limited abundances, rarely occurring as phenocrysts. In some instances, there are orbicular textures of olivine, pyroxene and plagioclase.

2.11. Alteration mineralogy. Alteration is variable and generally late stage, with little connection to the ore bodies. Characteristic minerals in the alteration zones are talc, chlorite, serpentine, sericite, and carbonate (Han et al., 2019).

2.12. Weathering. Black to dark brown limonite forms as an oxidation product of sulphide minerals, specifically pyrrhotite. Nickeliferous zones commonly exhibit pinkish or emerald-green iridescence. Secondary minerals include chalcocite, covellite, violarite, melanterite (FeSO4 SO4 7H2O), and morenosite (NiSO4•7(H2O). In many cases analysis for Ni, Cu, Zn, Co, Cr, Mn and Pb will distinguish Ni–Cu gossans from other oxidized sulphide assemblages and pseudo-gossans. Analysis for Pd and Ir may resolve ambiguous cases (Roberts and Travis, 1986). The use of reflected light microscopy to examine microtextures preserved in the surface gossans from a supergene pyrite-violarite-marcasite sulphide assemblage has allowed geochemical classification schemes to be refined (Roberts and Travis, 1986). The preservation of supergene zone textures by pseudomorphous Si–Fe replacement may permit determining the original sulphide proportions and Ni–Cu grade. Relict microtextures can be preserved, even in pale, highly siliceous gossans containing less than 0.01% Ni.

2.13. Comments. At least three types of nickel deposits are found in convergent margin settings: 1) Giant Mascot Ni-Cu-Co-(PGEs); 2) Ural-Alaskan PGEs/Ni-Cu-Co; and 3) gabbroic-associated Cu-Ni±PGE (Eckstrand, 1984; Nixon et al., 2015). Giant Mascot Ni-Cu deposits have recently been categorized as a distinct type (Nixon et al., 2015) that differ from Ural-Alaskan complexes because they include significant orthopyroxene-bearing intrusive phases. However, both types can be zoned, contain magnesium-rich olivines, and form from primitive hydrous arc parental magmas. The Giant Mascot and Ural Alaskan deposits have significant mineralized ultramafic intrusive phases whereas the gabbroic deposits generally do not.

3. Exploration and resource assessment guides

3.1. Geochemical signatures. Sampling rocks, soils, stream sediments, and tills is effective at leading to mineralization using elevated values of the elements Ni, Cu, Co and in some cases Pt and Pd. Olivine can sequester nickel within its crystal structure. For example, the nickel concentrations in olivine in mineralized peridotite, pyroxenite and dunite at Giant Mascot vary from 336 to 3,859 ppm (Manor et al., 2016). Anomalously high nickel contents (>2,000 ppm) occur in olivine with forsterite contents ranging from Fo80.6 to Fo87.4. Barren peridotite (576–1,797 ppm Ni) and pyroxenite (666–1018 ppm Ni) can also return anomalous nickel values at Giant Mascot, indicative of the favourable magmatic environment for nickel mineralization. The nickel held in olivine is not recovered by mines but does affect whole rock and assay analyses (see section titled economic limitations). Lithogeochemistry can be used in conjunction with geological mapping to identify favourable host rocks. For example, the Huangshandong mafic–ultramafic intrusive rocks display arc-like geochemical signatures, such as a low Ca in olivine and negative Nb–Ta anomalies in whole rocks (Mao et al., 2015).

3.2. Geophysical signatures. Airborne, ground, and drill-hole surveys can be useful. The following information is based largely on a presentation by Peters (2017). Electromagnetic (EM) surveys are the most widely used and successful geophysical method to identify massive sulphide with pyrrhotite, chalcopyrite, and pentlandite. Downhole EM works to depths of 3 km or more and can be used for down-dip testing of prospective contacts. Induced polarization (IP) surveys are effective at identifying disseminated sulphides, but the high chargeability of disseminated magnetite may generate similar anomalies. Magnetic surveys are important for interpreting the geology and a useful addition to geophysical logging of drill holes, but they rarely lead to direct detection of massive sulphides. Gravity surveys are used primarily for mapping to locate dense host rocks, regional margins, sutures, feeder zones, and magma chambers. They are most effective as ground-based surveys. Seismic surveys are used as a tool for mapping lithology, structure, and may detect larger sulphide bodies. Passive seismic survey methods are improving and cheaper than conventional seismic methods but deliver lower resolution results. Refraction tomography enables regional mapping of deep structure, crustal thickness and prospective mantle-tapping zones. Magnetotellurics (MT) uses natural magnetic and electric fields to identify weak resistivity contrasts at significant depths. Audio magnetotellurics (AMT) is faster but can only test shallower depths. Controlled Source Audio Magnetoltellurics uses an active transmitter so it is superior at shallow depths and can also identify deep regional subsurface structures. Airborne magnetotellurics provide rapid coverage but can only measure the vertical field.

3.3. Other guides. Geological mapping can identify multiple-phase, ultramafic to mafic intrusions composed of dunite, peridotite, pyroxenite, hornblende pyroxenite and hornblendite that may host nickel mineralization.

4. Economic factors

4.1. Typical grade and tonnage. The Giant Mascot nickel mine in British Columbia operated from 1936 to 1974 producing 4,319,976 tonnes of ore that yielded 16,516 grams of Ag, 1,026 grams Au, 140,700 kilograms Co, 13,212,770 kilograms Cu and 26,573,090 kilograms of Ni (092HSSW004, MINFILE record). Aho (1956) provided average ore grades for Giant Mascot of 1.4% Ni, 0.5% Cu with about 1% Cr, 0.10% Co, 0.02 oz/ton Au and 0.01 oz/ton platinum metals (Table 1).

4.2. Economic limitations. Some of the individual mineralized zones associated with Giant Mascot-type deposits may be too small to mine economically on their own. These limitations could change with increased demand for Co or PGEs. The nickel contents of the silicate minerals are not recoverable economically so it is important to correct analyses of mineralized samples, particularly those with considerable olivine, to reflect only the sulphide-hosted nickel. For example, the Poyi deposit in China contains 1.3 Mt Ni, 0.220 mt Cu and 60,000 Mt Co based on a cutoff grade of 0.2 wt % Ni. However, the size of the deposit is reduced to only 0.2 Mt Ni if a higher cutoff grade of 0.3 wt % Ni is used to eliminate rocks that contain no significant sulphides (Xue et al., 2016). Surficial weathering of olivine-rich rocks in a tropical climate can produce nickel laterites that incorporate some of the ~0.3% Ni contained in the olivine.

4.3. End uses. Nickel and copper are two of the most valuable metals for a modern industrial society and cobalt is increasingly attractive for a variety of developing applications, such as batteries.

4.4. Importance. Giant Mascot-type deposits have been a relatively minor source of nickel and copper with cobalt and platinum

Table 1. Grade and tonnages for selected Giant Mascot-type deposits.

	Mt	Ni %	Cu %	Co %	Pt g/t	Pd g/t	Reference
Canada							
Giant Mascot (British Columbia)	4.2	0.77	0.34	0.03			Nixon et al., 2015
Gordon Lake (Ontario)	1.5	0.92	0.47		0.9 Pt+Pd		Nixon et al., 2015
International							Nixon et al., 2015
Americano do Brasil	3.1	1.12	1.02				Nixon et al., 2015
Gabbro Akarem (Eygpt)	0.7	0.95 % Ni+Cu					Nixon et al., 2015
Hongqiling No.7 (China)		2.31	0.63	0.05			Han et al., 2019
Huangshanxi (China)	80	0.54	0.29				Han et al., 2019
Heishan (China)	35	0.6	0.3				Nixon et al., 2015
Erbutu (China)	1	0.3-2.0					Nixon et al., 2015
Tulaergen (China)	~37	0.24-0.42	0.27	0.024			Yujian et al., 2018

group elements as by-products, except in China. For more than 70 years however, systematic exploration for this type of deposit outside of China has been limited and thus considerable exploration potential remains. In the early 2000s ultramafic rocks in southwestern British Columbia similar to those at Giant Mascot were drilled by Leader Mining International Incorporated in an attempt to define an economic resource for magnesium extracted from olivine-rich rocks with high MgO (Canadian Stockwatch, January 7, 2002). This source of magnesium is not yet economically viable.

5. Genesis

5.1. Genetic model. Current models consider that sulfide saturation was triggered by the reduction of relatively oxidized parental arc magmas, the assimilation of sulphur and silica-bearing country rocks, and by the fractional crystallization of olivine and orthopyroxene producing Cu- and Ni-bearing sulphide droplets that collect in the root zone of a large magma chamber or underlying mineralized conduits and feeders. A larger than expected deposit can form in a small intrusion if there are multiple pulses of primitive parent magma that flow through the same dike or sill and interact with wall rock bearing sulphide, sulphate, or carbonate causing the formation of liquid sulphide droplets. The dense droplets will settle and accumulate in favourable parts of the conduits but can be upgraded by the addition of more sulphide droplets or incorporation of more nickel and copper into existing droplets (Barnes et al., 2016; Manor et al., 2016). Subsequent erosion can remove much of the overlying mafic and ultramafic volcanic and intrusive rocks and leave behind the root or feeder zone.

5.2. Tectonic settings. These Ni-Cu deposits are found in Phanerozoic cratonic margins and Precambrian greenstone belts. They form at convergent plate boundaries that are associated with a continental or island arc. The development of crustal-scale structures through oblique convergence of a subducting plate enables the generation and emplacement of partial melts from a mantle source. Continued convergence during cooling of a complex creates conduits where conditions are optimal for wallrock contamination and where sulphide mineral segregations may be generated and mobilized.

5.3. Associated deposit types. Gabbroic-hosted Ni-Cu±PGE (M02); lateritic Ni 38a (Singer, 1986).

6. Mineral systems

The following mineral system description is derived from Nixon et al. (2015), Manor et al. (2016), Barnes et al. (2016), Manor et al. (2017), Barnes and Mungall (2018), and Barnes and Robertson (2019). More research is needed to properly describe the source region, source driver and source product for Giant Mascot deposits. The source magmas are Mg-rich, with moderate to high oxygen fugacities that can transport Ni, Cu and PGEs. The magma sources are sub-lithospheric and derived from the mantle wedge. The metals in Giant Mascot deposits are sourced overwhelmingly from the transporting magmas.

6.1. Source region. Magmas derived from the mantle wedge overlying a subduction zone.

6.2. Source driver. Hydrated mantle melts to produce magmas.

6.3. Source product. Mg-rich (10-18 wt % MgO) magmas with up to 7 wt % H_2O.

6.4. Transport driver. Buoyancy transports the melts upwards by following crustal faults and by vertical and lateral dike propagation.

6.5. Transport path. Ascent of large magma volumes through established crack networks requires a long-lived, continuous supply of magma and pathways that are amenable to reopening and exploitation by repeated magma pulses. Melts need to rise without substantial fractionation to a trap in the continental crust. Flow of relatively undifferentiated mafic melts and crystal mush to high-level magma chambers may therefore be directly from the asthenospheric source or indirectly, through a mid-crustal reservoir. During its ascent to the highest level chamber, the magma crystallizes the liquidus phases olivine, orthopyroxene, and clinopyroxene. Should the magma develop high sulphur contents at any stage before entrapment, it will cause premature segregation of a dense sulphide liquid and, with it, the highly chalcophile Ni, Cu, and PGEs.

6.6. Transport termination. Intrusions form as a vertically migrating magma reaches a level of neutral buoyancy and then starts to spread laterally due to a minimum compressive stress that is horizontal.

6.7. Deposit concentration.. Sulfide saturation is usually triggered by the reduction of relatively oxidized parental arc magmas, the assimilation of S- and silica-bearing country rocks, and by the fractional crystallization of olivine and orthopyroxene causing precipitation as intercumulus sulphides, net-textured sulphides, disseminated aggregates, and/or massive accumulations. In some cases, magmas moved laterally through dikes, promoting melt contamination, formation of sulphide droplets and crystallization of olivine and orthpyroxene that collect at the base of the dike in a dense slurry. The eventual dike form may be dramatically affected by expansion into favorable host rocks, locally taking the form of a chonolith body.

6.8. Deposit controls. These crystal-rich magmas ascend into primary mineralized channels for the massive, unzoned orebodies, whereas the zoned orebodies involved successive injections through the similar channel ways. The incorporation of crustal-derived components, such as sulfides, felsic rocks, carbonate, graphite, or organic materials, from country rock is an important control on the formation of sulphides.

6.9. Deposit accumulation. These crystal-rich magmas ascend into primary mineralized channels for the massive, unzoned orebodies, whereas the zoned orebodies involved successive injections through the similar channel ways. The incorporation of crustal-derived components, such as sulfides, felsic rocks, carbonate, graphite, or organic materials, from country rock is an important control on the formation of sulphides.

6.10. Post formation processes. Late-stage hydrous fluids may develop and alter preformed mineral assemblages. Deuteric alteration minerals include uralitic hornblende, chlorite, amphibole, biotite, carbonate, epidote, and prehnite. Due to the tectonic setting, there can be relatively rapid uplift resulting in erosion of rocks overlying the ore bodies.

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