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SELECTED BRITISH COLUMBIA MINERAL DEPOSIT PROFILES

Volume 3 - Industrial Minerals and Gemstones

Edited by George J. Simandl, Zdenek D. Hora,
and David V. Lefebure

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Introduction

The British Columbia Geological Survey (BCGS) started a mineral potential assessment project for the province in 1992 utilizing deposit models for defining and characterizing mineral and coal deposits. A fundamental part of this process was compilation of information about mineral deposits including descriptions, classification and resource data. The deposit models were used to classify known deposits and occurrences, to guide experts in their estimation of the number of possible undiscovered mineral deposits, and to group deposits to allow compilation of representative grade and tonnage data.

The BCGS initially relied largely on mineral deposit models published by the United States Geological Survey (USGS; Orris and Bliss, 1991, 1992; Cox and Singer, 1986 and Rytuba and Cox, 1991) and Geological Survey of Canada (GSC; Eckstrand, O.R., 1984 and Eckstrand *et al.*, 1996). A number of these models needed to be revised and changed to a standard, compact format. There was also a number of deposit models not published by USGS or GSC, that were needed to assess the mineral potential of British Columbia, particularly for industrial minerals. Therefore, the BCGS decided to use in-house expertise to produce an updated series of concise deposit models with assistance from economic geologists of the GSC, USGS, industry and academia. These deposit models are called 'deposit profiles' and are best described as 'deposit definitions'. They are essential to establish a common base for all experts cooperating in mineral potential estimations (Kilby *et al.*, 1998).

The BCGS is currently working towards publishing approximately 120 deposit profiles in Open File format. This document is the third volume in the series. The previous publications were entitled "Selected British Columbia Mineral Deposit Profiles, Volumes I and II" (Lefebure and Ray, 1995; Lefebure and Hoy, 1996). This is the first volume devoted entirely to industrial minerals and gemstones and includes 28 profiles. Fourteen of these profiles are for the same deposit types as models published by the USGS (Orris and Bliss, 1991, 1992; Cox and Singer, 1986). There is also some overlap with 21 industrial mineral and 2 gemstone deposit models published by the Ontario Geological Survey (Rogers *et al.*, 1995). The USGS has also published descriptive geoenvironmental mineral deposit models (du Bray, 1995).

During the early stages of the mineral potential assessment project, grade and tonnage data were also based solely on USGS data sets, such as those published by Singer *et al.* (1980, 1993). Later British Columbia data was utilized whenever possible and the methodology used for industrial mineral assessment was changed radically (Kilby *et al.*, 1998). Aggregate assessments of British Columbia have been done for several areas in the province using a different methodology (Massey *et al.*, 1998).

Mineral Deposit Profiles

British Columbia mineral deposit profiles are concise descriptions tied to a series of headings which will fit on several pages; a format similar to those of deposit models published by the GSC and the USGS (Eckstrand, 1984; Cox and Singer, 1986). They are primarily descriptive because the ore-forming processes are sometimes poorly understood. As with the USGS models, the profiles are intended to be global models with sufficient information to describe the deposit type anywhere in the world. However, they emphasize information specific to British Columbia with respect to tectonic setting, age of mineralization, examples, references, resource data and economic factors including market conditions. They are useful starting point for those unfamiliar with the subject.

These profiles are based on a combination of published information, the personal knowledge of the authors and, in many cases, information provided informally by industry geologists. Over 150 deposit models are thought to be relevant to British Columbia, including more than 70 industrial mineral profiles. The Survey is currently working towards completing descriptions for approximately 120 of these deposit models. Grade and tonnage data for selected metallic models has been published (Grunsky, 1995; Grunsky *et al* ., 1996).

Deposit model descriptions for industrial minerals have lagged behind those for metalliferous orebodies for a number of reasons, mainly because until recently fewer geologists were working in the sector and their involvement was mainly as short term consultants only. This also reflects the fact that most universities do not provide courses on industrial minerals or gemstones, but do study base and precious metal deposits. A list of the industrial mineral and gemstone deposit types covered by this and the next volume considered for publication is presented in Table 1.

Table 1. Mineral Deposit Profiles for Industrial Minerals and Gemstones

Code	Deposit Type	Publication
A01	Peat	not published
A02	Lignite (leonardite)	OF 1995-20
B05	Residual kaolin	not published
B11	Marl	not published
B12	Sand and Gravel	not published
C01	Surficial Placers	OF 1995-20
C02	Buried-channel Placers	OF 1995-20
C03	Marine Placers	OF 1995-20
C04	Paleoplacers	not published
D01	Open-system zeolites	OF 1999-10
D02	Closed-basin zeolites	OF 1999-10
D05	Sandstone U (vanadium)	not published
D07	Iron Oxide (apatite, magnetite)	OF 1995-20
E06	Bentonite	OF 1999-10
E07	Sedimentary kaolin	OF 1999-10
E08	Carbonate-hosted talc	OF 1999-10
E09	Sparry magnesite	OF 1999-10
E10	Carbonate-hosted barite	not published
E11	Carbonate-hosted fluorspar	not published
E17	Sediment-hosted, stratiform barite	OF 1999-10
F01	Sedimentary manganese	OF 1999-10
F02	Bedded gypsum	not published
F03	Gypsum-hosted sulphur	not published
F04	Bedded celestite	not published
F05	Palygorskite	not published
F06	Lacustrine diatomite	not published
F07	Upwelling-type phosphate	not published
F08	Warm current-type phosphate	not published
F09	Playa and Alkaline Lake Evaporites	not published
G03	Volcanogenic anhydrite / gypsum	not published
G06	Noranda/Kuroko massive sulphide	OF 1995-20
H01	Travertine	OF 1996-13
H03	Hot Spring (clays)	OF 1996-13
H04	High-sulphidation epithermal (alunite)	OF 1996-13
H05	Low-sulphidation epithermal (clays)	OF 1996-13
H06	Epithermal Mn	not published
H09	Hydrothermal alteration clays-Al-Si	not published
I07	Silica veins	not published
I10	Vein barite	OF 1996-13
I11	Barite-fluorite veins	OF 1996-13
I13	Sn veins (feldspar)	not published
I17	Cryptocrystalline magnesite veins	OF 1996-13
J01	Polymetallic manto	OF 1996-13
K08	Garnet skarns	OF 1999-10
K09	Wollastonite skarns	OF 1999-10

L03	Alkalic porphyry (magnetite)	OF 1999-10
L04	Porphyry Cu (clay, corundum)	OF 1996-13
M04	Magmatic Ti-Fe±V oxide deposits (olivine)	OF 1999-10
M05	Alaskan-type (olivine)	OF 1996-13
M06	Ultramafic-hosted chrysotile asbestos	OF 1999-10
M07	Ultramafic-hosted talc-magnesite	OF 1999-10
M08	Vermiculite	OF 1999-10
N01	Carbonatite-hosted deposits	OF 1999-10
N02	Kimberlite-hosted diamonds	OF 1999-10
N03	Lamproite-hosted diamonds	OF 1999-10
O01	Rare element pegmatite - LCT family	not published
O02	Rare element pegmatite - NYF family	not published
O03	Muscovite pegmatite	not published
O04	Feldspar-quartz pegmatite	not published
P01	Andalusite hornfels	OF 1999-10
P02	Kyanite, muscovite, garnet in metasediments	OF 1999-10
P03	Microcrystalline graphite	OF 1999-10
P04	Crystalline flake graphite	OF 1999-10
P05	Vein graphite in metamorphic terrains	OF 1999-10
P06	Corundum in alumina-rich metasediments	OF 1999-10
Q01	Jade	not published
Q02	Rhodonite	not published
Q03	Agate	not published
Q04	Amethyst	not published
Q05	Jasper	not published
Q06	Columbia-type emeralds	OF 1999-10
Q07	Schist-hosted emeralds	OF 1999-10
Q08	Sediment-hosted precious opal	OF 1999-10
Q09	Ultramafic-related corundum	OF 1999-10
Q10	Alkali basalt and lamprophyre-hosted sapphire and ruby	OF 1999-10
Q11	Volcanic-hosted precious opal	OF 1999-10
R01	Cement shale	not published
R02	Expanding shale	not published
R03	Dimension stone - granite	not published
R04	Dimension stone - marble	not published
R05	Dimension stone - andesite	not published
R06	Dimension stone - sandstone	not published
R07	Silica sandstone	not published
R08	Flagstone	not published
R09	Limestone	not published
R10	Dolomite	not published
R11	Volcanic ash - pumice	not published
R12	Volcanic glass - perlite	not published
R13	Nepheline syenite	not published
S01	Broken Hill-type (barite)	OF 1996-13

We welcome comments and criticisms of the deposit profiles which will be used to improve future published versions. Editors of this volume can be contacted at the following addresses:

George Simandl - George.Simandl@gems2.gov.bc.ca; Tel: (250) 952-0413
David Lefebure - Dave.Lefebure@gems8.gov.bc.ca; Tel: (250) 952-0404

Mailing address:
British Columbia Geological Survey
Ministry of Energy and Mines
P.O. Box 9320, Stn Prov Govt
Victoria, British Columbia
V8V 1X4, CANADA
fax: (250) 952-0381
tel: (250) 952-0429

Industrial Minerals - Comments Related to the Use of these Models

Industrial mineral is defined as any rock, mineral, or other naturally occurring substant of economic value, exclusive of metallic ores, mineral fuels, and gemstones and commonly though of as one of the nonmetallics. For a more complete discussion of this definition and associated problems see Simandl (1998). Unlike metals, many industrial minerals such as salt, limestone and crushed stone have a low unit value, can incur significant transportation costs relative to mining and refining costs, and are often sold to specific markets.

In these circumstances the deposits have to be close to the market, or have access to inexpensive transportation, to become mines. For example, in some inland parts of British Columbia there is excellent potential to discover large, high quality limestone deposits, but transportation costs for the rock or possible products (e.g. cement, lime) currently prevents their development. On the other hand, deposits located on the coast are shipping products along entire coast of western North America. In other words, market conditions limit the value of the resource for the foreseeable future. In contrast many precious and base metal deposits with economic grades have relatively small resources, and their transportation costs are less important relative to production cost. Therefore, the geographic location of a market relative to the mine site is much less critical for base and precious metal mines and a larger number of parameters are used in the early stages of the economic evaluation of industrial mineral deposits. Many of the rules of thumb used in mining industry are not applicable to industrial minerals.

The following are some of the parameters used in evaluating industrial mineral deposits:

- technical specifications required by consumers;
- technical specifications of anticipated product;
- commodity unit-value under current and future market conditions;
- size and location of potential market;
- deposit grade and size;
- transportation costs;
- existing infrastructure; and
- extraction and processing costs.

The mining of industrial minerals does present some advantages over the metals. For example, industrial mineral mines generally have less impact on the environment in terms of potential acid drainage problems. In fact, many of the industrial minerals have environmental applications.

Gemstones -Comments Related to Use of these Models

Gemstone is defined as any mineral, rock, or other natural material (including organic materials, such as pearl, amber, jet, shell, ivory, and coral) that, when cut and polished, has sufficient beauty and durability for use as a personal adornment or other ornament.

Gemstones are similar to metallics in terms of high value per weight unit. A single large, high quality stone may double the cash flow of a mid-size gemstone mining operation. The grades and tonnages of these deposits are highly variable and unpredictable. This is especially true for hardrock operations that produce highly priced gemstones, such as rubies, emeralds and top quality precious opal. Producers can not rely on daily price quotations for their products because its varies in quality from one stone to the next. It is possible to dramatically enhance the value of a gem by intensive marketing techniques. For example, the single channel marketing system for diamonds promoted by De Beers since 1930's has resulted in these stones being very highly valued, although the situation is now changing (Sevdermsh *et al*. 1998). The prices of most of the other gemstones are more directly controlled by supply and demand. Unlike minerals that are marketed to industrial users, the output of relatively small gemstone deposits may be sold over the Internet, by telemarketing, trough wholesalers and distributors, or directly to the general public. As in the case of industrial minerals, value-adding (processing the raw gems by cutting and polishing, and in some cases heat treatment, where the latter is an accepted industry standard) may enhance the value of the stones an order of magnitude or more. Marketing and selling of precious opal from Spencer, Idaho and Vernon, British Columbia, nephrite from British Columbia, amolite from Alberta (Vandervelde, 1991) and red beryl from Utah are excellent examples of small, successful operations.

Deposit Classification

Methods for grouping deposit types have generated considerable discussion (Jensen and Bateman, 1979; Peters, 1978). This reflects the difficulties in any subdivision of complex natural phenomena, particularly when some deposit types are end members of a continuum. The many classification systems developed since Agricola are testimony to the elusive nature of a satisfactory classification scheme for mineral deposits. This is not particularly surprising given the ongoing advances in our understanding of ore-forming processes. With British Columbia mineral deposit profiles, the approach has been to regard the deposit models as the key element and any classification system as merely an index for placing the models into a useful context for the user. An admirable example of providing multiple indexes to mineral deposit types is presented by Laznicka (1985).

The deposit profiles included in this Open File are organized by deposit group. This classification system uses a combination of characteristics to separate deposits into groupings which relate well to areas of expertise of economic geologists (Table 2). This is a single entry listing with headings, such as industrial rocks, gemstones, and pegmatites (Lefebure *et al.*, 1995a). Two other classification systems have been published, one according to the most commonly associated host lithologies (Lefebure *et al.*,1995; Lefebure and Ray, 1995) and the other by commodities (Lefebure and Höy, 1996). Both these tables are multiple entry indexes. The former is particularly useful for mineral potential assessments when the bedrock geology is the most important criterion for estimating the number of undiscovered deposits.

The BCGS alphanumeric reference code for the deposit profiles is recorded in all tables. This is a single letter followed by a two digit number. If the BCGS does not yet have an existing draft profile for a deposit type, this is indicated by an asterisk after the code (e.g. B01*). For the convenience of readers familiar with the USGS models published by Cox and Singer (1986), Orris and Bliss (1991, 1992) and in a few scattered articles (for example, Rytuba, J. J. and Cox, D. P. , 1991), the relevant codes of USGS models are listed in the deposit groups index of Table 2. Note that there are codes for deposit types listed by Orris and Bliss (1991, page 66) that have not yet been published. As with the BCGS profiles, these codes are marked by an asterisk (39f*) to show that they are not published. 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 deposit; therefore, references to these three industrial mineral models of Orris and Bliss are prefixed with IM.

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Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC PROFILE #	DEPOSIT TYPE	APPROXIMATE SYNONYMS	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	--
A06	Oil Shale	Kerogen shale	--
B - RESIDUAL/SURFICIAL			
B01*	Laterite Fe	Gossan Fe	--
B02*	Laterite Ni		38a
B03*	Laterite-Saprolite Au	Eluvial placers	38g
B04*	Bauxite Al	Lateritic bauxite	38b
B05	Residual minerals (kaolin, barite, fluorite, vermiculite)	Primary kaolin	38h*
B07*	Bog Fe, Mn, U, Cu, Au		--
B08	Surficial U	Calcrete U, Supergene U	--
B09*	Karst-hosted Fe, Al, Pb-Zn		--
B10	Supergene base and precious metals	Residual Au; Precious metal gossans	--
B11*	Marl		--
B12*	Sand and Gravel	Aggregate	--
C - PLACER			
C01	Surficial placers	Placer Au-PGE-Sn-diamond-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 SEDIMENTS AND VOLCANICS			
D01	Open-system zeolites		25oa
D02	Closed-basin zeolites		25ob
D03	Volcanic redbed Cu	Basaltic Cu	23
D04	combined with D05		
D05	Sandstone U	Roll front U, Tabular U, Basal U	30c
D06	Volcanic-hosted U	Epithermal U, Volcanogenic U	25f
D07	Iron oxide breccias & veins ±P±Cu±Au±Ag±U	Olympic Dam type, Kiruna type	29b,25i

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

Version 2.2

BC	EXAMPLES	
PROFILE #	GLOBAL	B.C.
	A - ORGANIC	
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
A06	Fort McMurray (Alberta)	Hc, Frederick Island
	B - RESIDUAL/SURFICIAL	
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
B07*	Trois Riviéres (Québec)	Whipsaw Creek, Limonite Creek, Kaslo Creek
B08	Flodelle Creek (Washington)	Prairie Flats
B09*	Transvaal (Pb-Zn, South Africa), Sardinia (Pb-Zn), Jamaica (Al)	Villalta (Fe)
B10	Rio Tinto (Spain)	Villalta
B11*		Cheam Lake (Chiliwack)
B12*		Sechelt
	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 (off north end of Vancouver Island)
C04*	Elliot Lake & Blind River (Ontario), Witwatersrand (South Africa)	Mulvehill
	D- CONTINENTAL SEDIMENTS AND VOLCANICS	
D01	Death Valley Junction (California), John Day Formation (Oregon)	Asp Creek, Bromley Vale, Sunday Creek
D02	Bowie (Arizona), Lake Tecopa (California), Lake Magadi (Kenya)	
D03	Keewenaw (Michigan), Coppermine (Northwest Territories)	Sustut Copper, Shamrock, NH
D04		
D05	Colorado Plateau, Grants (New Mexico), Sherwood (Washington)	Blizzard, Tyee
D06	Marysvale (Utah), Aurora (Oregon)	Rexspar, Bullion (Birch Island)
D07	El Romeral (Chile), Sue-Dianne (Northwest Territories)	Iron Range

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC PROFILE #	DEPOSIT TYPE	APPROXIMATE SYNONYMS	USGS MODEL #
E - SEDIMENT-HOSTED			
E01*	Almaden Hg		27b
E02	Kipushi Cu-Pb-Zn	Carbonate-hosted Cu-Pb-Zn	32c
E03	Carbonate-hosted disseminated Au-Ag	Carlin-type Au, Sediment-hosted micron Au	26a,19c
E04	Sediment-hosted Cu	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	Carbonate-hosted barite	Mississippi Valley-type barite	- -
E11	Carbonate-hosted fluorspar	Mississippi Valley-type fluorite	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	Sedimentary-hosted, stratiform barite	Bedded barite	31b
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	Upwelling-type phosphate		34c
F08	Warm current-type phosphate		34d
F09*	Playa and alkaline lake evaporites	Hydromagnesite, lake brines	35ba,bm(T)
F10	Iron Formation - Lake Superior & Rapitan Types		34a
F11	Ironstone	Minette and Clinton subtypes	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	Eskay Creek-type	- -

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

Version 2.2

BC PROFILE #	EXAMPLES	
	GLOBAL	B.C.
	E - SEDIMENT-HOSTED	
E01*	Almaden (Spain), Santa Barbara (Peru)	
E02	Tsumeb (Namibia), Kipushi (Zaire), Ruby Creek (Alaska)	
E03	Carlin, Getchell & Cortez (Nevada), Mesel (Indonesia)	Golden Bear, Slam
E04	Kupferschiefer (Germany & Poland), White Pine (Michigan)	Roo, Commerce, Chal 4
E05	Laisvall (Sweden), George Lake (Saskatchewan)	
E06	Black Hills (Wyoming), Milos (Greece), Landshut (Germany)	Hat Creek, Princeton, Quilchena, French Bar
E07	Wrens, Sandersville (Georgia), Aiken (South Carolina)	Sumas Mountain, Blue Mountain, Lang Bay
E08	Treasure Mtn (Montana), Trimouns (France), Henderson (Ontario)	Red Mountain, Gold Dollar, Saddle occurrences
E09	Eugui (Spain), Veitsch, Entachen Alm (Austria), Satka (Russia)	Mt. Brussilof, Driftwood Creek, Marysville
E10	Illinois - Kentucky, Italian Alps	Muncho Lake
E11	Illinois - Kentucky, Italian Alps	Liard Fluorite
E12	Viburnum Trend (Missouri), Pine Point (Northwest Territories)	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), Mountain Springs (Nevada), Fig Tree (South Africa)	Kwadacha, Gin, Gnome
	F - CHEMICAL SEDIMENT	
F01	Molongo (Mexico), Urcut (Hungary), Groote Eylandt (Australia)	
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 & Trout Ck Formations (Oregon), Lake Myvatn (Iceland)	Crownite Formation (Quesnel)
F07	Phosphoria Formation (Idaho), Meskala (Morocco)	Fernie synclinorium
F08	Athabaska Basin (Saskatchewan), Florida	
F09*		Milk River
F10	Crest (Yukon), Mesabi Ranges (Minnesota), Jacadigo (Brazil)	
F11	Clear Hills (Alberta), Clinton Formation (Alabama), France	Moberly?
	G - MARINE VOLCANIC ASSOCIATION	
G01	Vermillion iron formation (Minnesota), Helen mine (Ontario)	Falcon, Lady A
G02	Olympic Mountains (Washington), Nicoya (Costa Rica)	
G03*		Britannia, Falkland
G04	Besshi (Japan), Greens Creek (Alaska)	Goldstream, Windy Craggy, Standard, True Blue
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. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC PROFILE #	DEPOSIT TYPE	APPROXIMATE SYNONYMS	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, Nansatsu-type**	**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**	**Alkalic intrusion-related Au, Au-Ag-Te veins**	**22b**
H09*	**Hydrothermal alteration clays-Al-Si**	**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, Saddle Reefs**	**36a**
I04	**Iron formation-hosted Au**		**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**	**Cornish-type lodes**	**15b, 15c**
I14	**Five-element veins Ni-Co-As-Ag±(Bi, U)**	**Ni-Co-native Ag or cobalt-type veins**	**- -**
I15	**Classical U veins**	**Pitchblende veins, vein uranium**	**- -**
I16	**Unconformity-associated U**	**Unconformity-veins, Unconformity U**	**37a**
I17	**Cryptocrystalline magnesite veins**	**Bone magnesite, Kraubath-type magnesite**	**- -**
I18	**Plutonic-related Au-quartz veins and veinlets**	**Fort Knox-type, intrusion-related Au**	**- -**
J - MANTO			
J01	**Polymetallic manto Ag-Pb-Zn**	**Polymetallic replacement deposits**	**19a**
J02	**Manto and stockwork Sn**	**Replacement Sn, Renison-type**	**14c**
J03*	**Mn veins and replacements**		**19b**
J04	**Sulphide manto Au**	**Au-Ag sulphide mantos**	**- -**

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC	EXAMPLES	
PROFILE #	GLOBAL	B.C. Version 2.2
	H - EPITHERMAL	
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)	Cinola, Clisbako, Wolf?, 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)	Shag Rock
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	Copper Rand & Portage (Quebec)	Scottie, Snip, Johnny Mountain, Iron Colt
I03	Ballarat (Australia), Meguma (Nova Scotia)	Frasergold, Reno, Queen, Island Mountain
I04	Geraldton (Ontario), Homestake (South Dakota)	
I05	Elsa (Yukon), Coeur d'Alene (Idaho), Creede (Colorado)	Silver Queen, Beaverdell, Silvana, Lucky Jim
I06	Nikolai (Alaska), Bruce Mines (Ontario), Butte (Montana)	Davis-Keays, Churchill Copper, Bull River
I07*		Granby Point
I08	Red Devil? (Alaska), New Almaden, New Idria (California)	Pinchi, Bralorne Takla, Silverquick
I09	Becker-Cochran (Yukon), Lake George (New Brunswick), Bolivia	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, Kraus 14
I14	Cobalt camp (Ontario), Erzgebirge district (Germany)	
I15	Beaverlodge area (Saskatchewan), Schwartzwalder (Colorado)	Purple Rose, Fisher, Dixie
I16	Rabbit lake, Key Lake (Saskatchewan), Jabiluka (Australia)	
I17	Chalkidiky area (Greece), Kraubath (Austria)	Sunny, Pinchi Lake
I18	Fort Knox, Pogo (Alaska), Mokrsko (Czech Republic)	Rozan, Cam Gloria?
	J - MANTO	
J01	East Tintic district (Utah), Naica (Mexico), Sa Dena Hess (Yukon)	Bluebell, Midway
J02	Renison Bell & Cleveland (Australia), Dachang district (China)	
J03*	Lake Valley (New Mexico), Phillipsburg (Montana)	
J04	Ketza River (Yukon)	Mosquito Creek , Island Mountain

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC PROFILE #	DEPOSIT TYPE	APPROXIMATE SYNONYMS	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
M - ULTRAMAFIC / MAFIC ASSOCIATION			
M01*	Flood Basalt-Associated Ni-Cu	Basaltic subvolcanic Cu-Ni-PGE	5a/5b
M02	Tholeiitic intrusion-hosted Ni-Cu	Gabbroid-associated 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 asbestos	Serpentinite-hosted asbestos	8d
M07	Ultramafic-hosted talc-magnesite		8f*
M08	Vermiculite deposits		- -
N - CARBONATITES, KIMBERLITES & LAMPROITES			
N01	Carbonatite-hosted 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*

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC	EXAMPLES	
PROFILE #	GLOBAL	B.C.
		Version 2.2
	K - SKARN	
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 & McCoy (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	San Pedro (New Mexico)	Mount Riordan (Crystal Peak)
K09	Fox Knoll (New York), Lappeenranta (Finland), Khila (India)	Mineral Hill, Zippa Mountain, Rossland
	L - PORPHYRY	
L01	Lepanto (Philippines), Resck (Hungary), 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)	
	M - ULTRAMAFIC / MAFIC ASSOCIATION	
M01*	Noril'sk (Russia), Duluth (Minnesota)	
M02	Lynn Lake (Manitoba), Kluane (Yukon)	Giant Mascot, Nickel Mountain
M03	Josephine ophiolite (Oregon), Coto (Philippines), Elazig (Turkey)	Castle Mountain, Scottie Creek
M04	Methuen (Ontario) Lac Tio (Québec), Tellnes (Norway)	Bearpaw Ridge?
M05	Red Mountain, Goodnews Bay (Alaska), Tin Cup Peak (Oregon)	Tulameen Complex
M06	Thetford & Black Lake (Québec), Barberton (South Africa)	Cassiar, McDame, Letain, Ace
M07	Luzcan (Québec), Deloro (Ontario), Lahnaslampi (Finland)	Rawhide, South Talc Lake, Gisby, J&J
M08	Libby (Montana). Waldrop Pit (South Carolina)	Joseph Lake, Sowchea Creek
	N - CARBONATITES, KIMBERLITES & LAMPROITES	
N01	Oka (Québec), Mountain Pass (California), Palabora (S. Africa)	Aley, Rock Canyon Creek?
N02	Ekati (Northwest Territories), Kimberley (South Africa)	
N03	Prairie Creek (Arkansas), Argyle (Australia), Kapamba (Zambia)	
	O - PEGMATITE	
O01	Tanco (Manitoba), Greenbushes (Australia)	Hellroaring Creek, McConnell
O02	South Platte district (Colorado), Bancroft (Ontario)	Lumby, Crescent, Will
O03	Bihar Belt (India), Spruce Pine District (North Carolina)	Family Farm, Baker Inlet
O04*	Buckingham (Québec)	

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC PROFILE #	DEPOSIT TYPE	APPROXIMATE SYNONYMS	USGS MODEL #
	P - METAMORPHIC-HOSTED		
P01	Andalusite hornfels		--
P02	Kyanite,muscovite, garnet in metasediments	Sillimanite and kyanite deposits	--
P03	Microcrystalline graphite	Amorphous graphite	18k
P04	Crystalline flake graphite	Disseminated flake graphite	37f
P05	Vein graphite in metamorphic terrains	Lump and chip graphite	37g
P06	Corundum in alumina-rich metasediments	Corundum-bearing schists	--
	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	"Volcanic opal"	--
	R - INDUSTRIAL ROCKS		
R01	Cement shale		--
R02	Expanding shale		--
R03	Dimension stone - granite		--
R04	Dimension stone - marble		--
R05	Dimension stone - andesite		--
R06*	Dimension stone - sandstone		30d*
R07	Silica sandstone	High-silica quartzite	30e*
R08*	Flagstone		--
R09	Limestone		--
R10*	Dolomite		--
R11*	Volcanic ash - pumice		--
R12*	Volcanic glass - 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	--

Table 2. Listing of British Columbia Mineral Deposit Profiles by Deposit Group

BC	EXAMPLES	
PROFILE #	GLOBAL	B.C. Version 2.2
	P - METAMORPHIC-HOSTED	
P01	Groot Marico-Zeerust (South Africa), Glomel (France)	Kootenay, Kwoiek Needle, Atna Peak
P02	NARCO (Québec), Willis Mountain (Virginia), Sonapahar (India)	Trail Bay, Yelow Creek, Hawkesbury Island
P03	Kellog (Mexico), Keiserberg (Austria)	
P04	Graphite Lake & Black Donald (Ontario), Peerless (Québec)	Black Crystal, Mon, AA
P05	Calumet & Clot (Québec), Dillon (Montana), Bogala (Sri Lanka)	
P06	Elk Creek & Bozeman (Montana), Gangoda (Sri Lanka)	Blu Starr
	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, Las Cruces, El Diamante & Muzo (Columbia)	
Q07	Habachtal (Austria), Gravelotte (South Africa), Socoto (Brazil)	
Q08	Coober Pedy, Mintabie, Lightning Ridge (Australia)	
Q09	Umba (Tanzania), Kinyki Hill (Kenya)	
Q10	Yogo Gulch (Montana), Breamar & Stratmore (Australia)	Mark Diatreme
Q11	Virgin Valley (Nevada), Tepe Blue Fire (Idaho), Queretaro (Mexico)	Klinker, Northern Lights, Eagle Creek
	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	10/14/1999
S01	Broken Hill (Australia), Aggeneys district (South Africa)	Cottonbelt, River Jordan, Ruddock Creek

OPEN-SYSTEM ZEOLITES D01

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

IDENTIFICATION

SYNONYM: Open-system zeolites. In many cases it may be practically impossible to distinguish these deposits from burial metamorphic zeolites. Therefore, at least from the explorationists point of view, they may be equivalent.

COMMODITIES (BYPRODUCTS): 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), clinoptilolite, Death Valley Junction, (California, USA), phillipsite and chabazite, Yellow tuffs near Naples (Italy).*

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 bound. 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 parts of volcanic ash and tuff beds with minor intercalated flows. The 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.

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.*

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[1] United States Geological Survey, Federal Center, Denver, Colorado, USA

[2] British Columbia Geological Survey, Victoria, B.C., Canada

OPEN-SYSTEM ZEOLITES - D01

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. Chabazite forms within the systems characterized by low Na/K ratio, whereas phillipsite dominates where solutions have 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 100C, 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 an other. 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.

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. 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.

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 (100's to 1000's 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.

OPEN-SYSTEM ZEOLITES - D01

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 the above listed parameters 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 < 2m to 30 m 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 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.

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CLOSED-BASIN ZEOLITES D02

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

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.

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.

[1] United States Geological Survey, Denver, Colorado, USA
[2] British Columbia Geological Survey, Victoria, B.C., Canada

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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.

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 90% 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 80% 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 an other. 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.

CLOSED-BASIN ZEOLITES - D02

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 m to 30 m 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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CLOSED-BASIN ZEOLITES - D02

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BENTONITE E06

by Z.D. Hora[1]

IDENTIFICATION

SYNONYMS: Sodium and calcium, 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 (0920099); *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.*

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.

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[1] British Columbia Geological Survey, Victoria, B.C., Canada

BENTONITE - E06

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, (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 from US$25 to 40 a short ton.

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.)

BENTONITE - E06

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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SEDIMENTARY KAOLIN E07

by Z.D. Hora[1]

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 (92F137), Quinsam (92F319), Giscome Rapids (93J020); *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".

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.*

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[1] British Columbia Geological Survey, Victoria, B.C., Canada

SEDIMNTARY KAOLIN - E07

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.

SEDIMENTARY KAOLIN - E07

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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CARBONATE-HOSTED TALC

E08

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

MINERAL DEPOSIT B.C. PROFILES

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 (082O001), Red Mountain (082O002), Saddle Occurrences (082O003); *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 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.

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

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.

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[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Geological Survey of Canada, Sydney, B.C., Canada

CARBONATE-HOSTED TALC - E08

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 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:

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

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:

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

In this second reaction calcite precipitation is not expected. This reaction takes place at lower temperature (given identical pressure and X_{CO2} 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).

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.

CARBONATE-HOSTED TALC - E08

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 pyrophllite 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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SPARRY MAGNESITE E09

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

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, shales, chert. Associated with sandstone, conglomerate and volcanics 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.

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.

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.

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[1] British Columbia Geological Survey, Vicotira, B.C., Canada
[2] Spokane Resources Ltd., Vancouver, B.C., Canada

SPARRY MAGNESITE - E09

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 240°C. 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, highs within particular stratigraphic horizons.

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.

SPARRY MAGNESITE - E09

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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SEDIMENTARY-HOSTED, STRATIFORM BARITE E17

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

IDENTIFICATION

SYNONYM: Bedded barite.

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

EXAMPLES (British Columbia (MINFILE #)- *Canada/International*): Kwadacha (094F020), Gin (094F017), 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 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.

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.*

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[1] Geological Survey of Canada, Sidney, B.C., Canada
[2] British Columbia Geological Survey, Victoria, B.C., Canada
[3] United States Geological Survey, Tuscon, Arizona, USA

SEDIMENTARY-HOSTED, STRATIFORM BARITE - E17

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).

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.

SEDIMENTARY-HOSTED, STRATIFORM BARITE - E17

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. 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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SEDIMENTARY MANGANESE F01

by E. R. Force[1], S. Paradis[2] and G.J. Simandl[3]

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 a few to over 50 metres in thickness and extend from a 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.

TEXTURE/STRUCTURE: Oolites and sedimentary pisolites, rhythmic laminations, slumped bedding, hard-ground fragments, abundant fossils, fossil replacements and siliceous microfossils are some 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.*

[1] United States Geological Survey, Tuscon, Arizona, USA
[2] Geological Survey of Canada, Sidney, B.C., Canada
[3] British Columbia Geological Survey, Victoria, B.C., Canada

SEDIMENTARY MANGANESE - F01

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 a high accumulation rate of organic matter in sediments will promote the development of anoxic conditions below the surface causing surface layers 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. Sedimentary manganese deposits may be transformed into Mn-silicates during metamorphism. The metamorphic process could be schematically represented by the reaction:

$$\text{Rhodochrosite} + SiO_2 = \text{Rhodonite} + CO_2$$

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.

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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GARNET SKARNS

K08

by Gerald E. Ray[1]

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).

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).

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[1] British Columbia Geological Survey, Victoria, B.C., Canada

GARNET SKARNS - K08

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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WOLLASTONITE SKARNS K09

by G.J. Simandl[1], S. Paradis[2], G.J Orris[3] and G. E. Ray[1]

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 (104B384), 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.

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.

[1] British Columbia Geological Survey, Victoria, British Columbia, Canada
[2] Geological Survey of Canada, Pacific Geoscience Centre, Sidney, British Columbia
[3] United States Geological Survey, Tuscon, Arizona, United States

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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.

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).

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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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WOLLASTONITE SKARNS - K09

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MAGMATIC Ti-Fe±V OXIDE DEPOSITS

MO4

By G.A. Gross[1], C. F. Gower[2] and D.V. Lefebure[3]

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, Egersund (Norway), Smaalands-Taberg, Ulvno (*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.

[1] Geological Survey of Canada, Ottawa, Ontario, Canada
[2] Newfoundland Department of Mines and Energy, St. John's, Nfld, Canada
[3] British Columbia Geological Survey, Victoria, B.C., Canada

MAGMATIC Ti-Fe±V OXIDE DEPOSITS - MO4

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-TiV 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.

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.

MAGMATIC Ti-Fe±V OXIDE DEPOSITS - MO4

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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MAGMATIC Ti-Fe±V OXIDE DEPOSITS - MO4

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ULTRAMAFIC-HOSTED CHRYSOTILE ASBESTOS M06

by Z.D. Hora[1]

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 non-foliated 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.

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 center 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.

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[1] British Columbia Geological Survey, Victoria, B.C., Canada

ULTRAMAFIC-HOSTED CHRYSOTILE ASBESTOS - M06

ORE MINERALOGY [Principal and *subordinate*]: Chrysotile.

GANGUE MINERALOGY [Principal and *subordinate*]: 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 non-foliated, 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.

ULTRAMAFIC-HOSTED CHRYSOTILE ASBESTOS - M06

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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ULTRAMAFIC-HOSTED CHRYSOTILE ASBESTOS - M06

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ULTRAMAFIC-HOSTED TALC-MAGNESITE M07

by G. J. Simandl[1] and D. Ogden[2]

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.

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.*

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[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Omaya Inc., Proctor, Vermont, USA

ULTRAMAFIC-HOSTED TALC-MAGNESITE - M07

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.

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.

ULTRAMAFIC-HOSTED TALC-MAGNESITE - M07

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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ULTRAMAFIC-HOSTED TALC-MAGNESITE - M07

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VERMICULITE

M08

by G.J. Simandl[1], T. Birkett[2] and S. Paradis[3]

IDENTIFICATION

COMMODITY (BYPRODUCT): Vermiculite (± apatite).

EXAMPLES (British Columbia - *Canadian/International*): Joseph Lake (093K100), Sowchea Creek vermiculite (093K101); *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.

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.*

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] SOQUEM, Québec, Québec, Canada
[3] Geological Survey of Canada, Sidney,B.C., Canada

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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.

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.

VERMICULITE - M08

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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VERMICULITE - M08

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CARBONATITE-ASSOCIATED DEPOSITS (MAGMATIC, REPLACEMENT AND RESIDUAL)

N01

by T.C. Birkett[1] and G.J. Simandl[2]

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.

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.

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[1] SOQUEM, Sainte-Foy, Quêbec, Canada
[2] British Columbia Geological Survey, Victoria, B.C., Canada

CARBONATITE-ASSOCIATED DEPOSITS - N01

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.

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.

CARBONATITE-ASSOCIATED DEPOSITS - N01

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.

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.

CARBONATITE-ASSOCIATED DEPOSITS - N01

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KIMBERLITE-HOSTED DIAMONDS N02

by Jennifer Pell[1]

IDENTIFICATION

SYNONYMS: Diamond-bearing 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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[1] Consulting Geologist, Vancouver, British Columbia, Canada

KIMBERLITE-HOSTED DIAMONDS - N02

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 daimond fragments and one diamond are reported from the Ram pipes.

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.

KIMBERLITE-HOSTED DIAMONDS - N02

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.

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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LAMPROITE-HOSTED DIAMONDS

N03

by Jennifer Pell[1]

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.

ORE MINERALOGY: Diamond.

GANGUE MINERALOGY (Principal and *subordinate*): Olivine, phlogopite, richterite, diopside, sanidine; *priderite, wadeite, ilmenite, chromite, perovskite, spinel, apatite, pyrope garnet.*

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[1] Consulting Geologist, Vancouver, British Columbia, Canada

LAMPROITE-HOSTED DIAMONDS - N03

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.

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.

LAMPROITE-HOSTED DIAMONDS - N03

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 .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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ANDALUSITE HORNFELS

PO1

By Z.D. Hora[1]

IDENTIFICATION

SYNONYM: Chiastolite hornfels.

COMMODITIES (BYPRODUCTS): Andalusite (staurolite, garnet).

EXAMPLES [BRITISH COLUMBIA (MINFILE #) - *Canada/International*]: Kootenay (082FSE099), Kwoiek Needle (092ISW052), Atna Peak (103H040); *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, B.C., Canada

ANDALUSITE HORNFELS - PO1

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 *subordinate*): 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.

ANDALUSITE HORNFELS - PO1

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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KYANITE, MUSCOVITE, GARNET IN METASEDIMENTS

P02

By G.J. Simandl[1], S. Paradis2, W.H. McCracken[3] and K.D. Hancock[4]

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 (103J024), Yellow Creek (083D007), Hawkesbury Island kyanite (103H058); *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.

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.

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Geological Survey of Canada, Sidney, B.C., Canada
[3] F.S. Alloys and Minerals Corporation, Pittsburgh, Pennsylvania, United States
[4] Spokane Resources Ltd., Vancouver, B.C., Canada

KYANITE, MUSCOVITE, GARNET IN METASEDIMENTS - P02

ORE MINERALOGY [Principal and *subordinate*]: Kyanite/ ± *muscovite,* ± *garnet,* ± *staurolite* or sillimanite/± *corundum.*

GANGUE MINERALOGY [Principal and *subordinate*]: Q*uartz, biotite,* ± *muscovite,* ± *garnet, feldspar,* ± *staurolite,* ± *corundum,* ± *graphite,* ± *sulphides,* ± *oxides,* ± *amphiboles,* ± *sapphire,* ± *cordierite,* ± *andalusite,* ± *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 (P06) 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.

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.

KYANITE, MUSCOVITE, GARNET IN METASEDIMENTS - P02

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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KYANITE, MUSCOVITE, GARNET IN METASEDIMENTS - P02

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MICROCRYSTALLINE GRAPHITE

P03

G.J. Simandl[1] and W.M. Kenan[2]

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.*

ALTERATION MINERALOGY: N/A.

WEATHERING: Weathered outcrops of microcrystalline graphite are typically dull, porous and dark-gray to black.

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[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Ashbury Graphite Mills, Ashbury, New Jersey, United States

MICROCRYSTALLINE GRAPHITE - P03

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.

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.

MICROCRYSTALLINE GRAPHITE - P03

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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CRYSTALLINE FLAKE GRAPHITE P04

by G.J. Simandl[1] and W.M. Kenan[2]

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.*

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.

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[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Ashbury Graphite Mills Inc., Ashbury, New Jersey, United States

CRYSTALLINE FLAKE GRAPHITE - P04

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.

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.

CRYSTALLINE FLAKE GRAPHITE - P04

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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VEIN GRAPHITE IN METAMORPHIC TERRAINS P05

by G.J. Simandl[1] and W.M. Kenan[2]

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.*

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.

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Ashbury Graphite Mills Inc., Ashbury, New Jersey, United States

VEIN GRAPHITE IN METAMORPHIC TERRAINS - P05

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.

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.

VEIN GRAPHITE IN METAMORPHIC TERRAINS - P05

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CORUNDUM IN ALUMINA-RICH METASEDIMENTS P06

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

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 Starr (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.

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.

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[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Geological Survey of Canada, Sidney, B.C., Canada

CORUNDUM IN ALUMINA-RICH METASEDIMENTS - P06

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.

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).

CORUNDUM IN ALUMINA-RICH METASEDIMENTS - P06

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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COLOMBIA-TYPE EMERALDS Q06

G.J. Simandl[1], S. Paradis[2] and T. Birkett[3]

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.

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 is fibrous or rhombohedral. In some cases, emerald may be found in black shale adjacent to the veinlets or cenicero.

ORE MINERALOGY [Principal and *subordinate*]: Emerald; *beryl specimens and common beryl.*

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[1] British Columbia Geological Survey, Victoria, B.C, Canada
[2] Geological Survey of Canada, Sidney, B.C., Canada
[3] SOQUEM, Quebec City, Quebec, Canada

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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.

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.

COLOMBIA-TYPE EMERALDS - Q06

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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SCHIST-HOSTED EMERALDS Q07

G.J. Simandl[1], S. Paradis[2] and T.Birkett[3]

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.

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.

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Geological Survey of Canada, Sidney, B.C., Canada
[3] SOQUEM, Quebec City, Quebec, Canada

SCHIST-HOSTED EMERALDS - Q07

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.

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).

SCHIST-HOSTED EMERALDS - Q07

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.

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.

SCHIST-HOSTED EMERALDS - Q07

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 berylium-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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SEDIMENT-HOSTED PRECIOUS OPAL Q08

by: S. Paradis[1], J. Townsend[2] and G J. Simandl[3]

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.

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.

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[1] Geological Survey of Canada, Sidney, British Columbia, Canada - GSC contribution number 199015
[2] Minerals Group, Department of Primary Industries and Resources, Adelaide, South Australia
[3] British Columbia Geological Survey, Victoria, British Columbia, Canada

SEDIMENT-HOSTED PRECIOUS OPAL - Q08

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. 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.

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.

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.

SEDIMENT-HOSTED PRECIOUS OPAL - Q08

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 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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SEDIMENT-HOSTED PRECIOUS OPAL - Q08

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ULTRAMAFIC-RELATED CORUNDUM (CONTACT METAMORPHIC/METASOMATIC) Q09

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

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 (coarsegrained rock consisting of anhedral corundum crystals in an oligoclase 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.

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).

[1] British Columbia geological Survey, Victoria, B.C., Canada
[2] Geological Survey of Canada, Sidney, B.C., Canada

ULTRAMFIC-RELATED CORUNDUM - Q09

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,* ± *kyanite,* ± *talcose material and possibly anthopyllite.*
In metasomatic zones cross-cutting ultramafic rocks without plumasite core: vermiculite,chlorite. The main inclusion in gem corundum is vermiculite.
In contact metamorphic deposits: a) In emery ores: hercinite, pleonaste, magnetite, hematite,/*ilmenite, ilmenohematite, hypersthene, spaphirine, sillimanite, corderite, garnet, biotite, feldspar, staurolite, gahnite*. Some of the minor constituents in emery ore may be due to host rock 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.

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.

ULTRAMFIC-RELATED CORUNDUM - Q09

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.

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.

ULTRAMFIC-RELATED CORUNDUM - Q09

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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ALKALI BASALT AND LAMPROPHYRE- HOSTED SAPPHIRE and RUBY

Q10

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

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 (082N089); *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 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.

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[1] British Columbia geological Survey, Victoria, B.C., Canada

[2] Geological Survey of Canada, Sidney, B.C., Canada

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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 is 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 errosional 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.

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.

ALKALI BASALT AND LAMPROPHYRE- HOSTED SAPPHIRE and RUBY - Q10

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).

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VOLCANIC-HOSTED PRECIOUS OPAL Q11

S. Paradis[1], G.J. Simandl[2] and A. Sabina[3]

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.

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.*

[1] Geological Survey of Canada, Sidney, B.C., Canada
GSC contribution number 199015
[2] British Columbia Geological Survey, Victoria, B.C., Canada
[3] Geological Survey of Canada, Ottawa, Ontario, Canada

VOLCANIC-HOSTED PRECIOUS OPAL - Q11

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.

VOLCANIC-HOSTED PRECIOUS OPAL - Q11

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 are not suitable for gems because they crack too easily; however, the opal from many 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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