List of Deposit Profiles in PDF File (November 2000)

BC Profile #	Deposit Type	Approximate Synonyms
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
B01*	Laterite Fe	Gossan Fe
B02*	Laterite Ni	- -
B03*	Laterite-Saprolite Au	Eluvial placers
B04*	Bauxite Al	Lateritic bauxite
B05	Residual kaolin	Primary kaolin
B07*	Bog Fe, Mn, U, Cu, Au	- -
B08	Surficial U	Calcrete U
B09*	Karst-hosted Fe, Al, Pb-Zn	- -
B10	Gossan Au-Ag	Residual Au; Precious metal gossans
B11*	Marl	- -
B12*	Sand and Gravel	- -
C01	Surficial placers	Placer Au-PGE-Sn-diamond-mag-gar-gems
C02	Buried-channel placers	Paleochannel placers
C03	Marine placers	Off-shore heavy mineral sediments
C04*	Paleoplacer U-Au-PGE-Sn-Ti-diam-mag-gar-zir	Quartz pebble conglomerate Au-U
D01	Open-system zeolites	- -
D02	Closed-basin zeolites	- -
D03	Volcanic redbed Cu	Basaltic Cu
D04	Basal U	- -
D05*	Sandstone U	Roll front U, Tabular U
D06	Volcanic-hosted U	Epithermal U, Volcanogenic U
D07	Iron oxide breccias & veins ±P±Cu±Au±Ag±U	Olympic Dam type, Kiruna type
E01*	Almaden Hg	Carbonate-hosted Au-Ag
E02	Carbonate-hosted Cu-Pb-Zn	Kipushi Cu-Pb-Zn
E03	Carbonate-hosted disseminated Au-Ag	Carlin-type Au, Sediment-hosted micron Au
E04	Sediment-hosted Cu	Sediment-hosted stratiform Cu
E05	Sandstone Pb	- -
E06	Bentonite	Volcanic clay, Soap clay
E07*	Sedimentary kaolin	Secondary kaolin
E08	Carbonate-hosted talc	Dolomite-hosted talc
E09	Sparry magnesite	Veitsch-type, carbonate-hosted magnesite
E10	Carbonate-hosted barite	Mississippi Valley-type barite
E11	Carbonate-hosted fluorspar	Mississippi Valley-type fluorite
E12	Mississippi Valley-type Pb-Zn	Carbonate-hosted Pb-Zn, Appalachian Zn
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
E15	Blackbird sediment-hosted Cu-Co	Sediment-hosted Cu-Co massive sulphide
E16	Shale-hosted Ni-Zn-Mo-PGE	Sediment-hosted Ni
E17	Sediment-hosted barite	Bedded barite
F01	Sedimentary Mn	- -
F02	Bedded gypsum	Marine evaporite gypsum
F03	Gypsum-hosted sulphur	Frasch sulphur
F04*	Bedded celestite	- -
F05*	Palygorskite	Attapulgite
F06	Lacustrine diatomite	Diatomaceous earth, Kieselguhr

F07	Upwelling-type phosphate	- -
F08	Warm current-type phosphate	- -
F09*	Playa and Alkaline Lake Evaporites	Hydromagnesite, Na carbonate lake brines
F10*	Lake Superior & Rapitan types iron-formation	- -
F11*	Ironstone	Minette ores
G01	Algoma-type iron-formation	- -
G02	Volcanogenic Mn	- -
G03*	Volcanogenic anhydrite / gypsum	- -
G04	Besshi massive sulphide Cu-Zn	Kieslager
G05	Cyprus massive sulphide Cu (Zn)	- -
G06	Noranda / Kuroko massive sulphide Cu-Pb-Zn	- -
G07	Subaqueous hot spring Ag-Au	- -
H01	Travertine	Tufa
H02	Hot spring Hg	- -
H03	Hot spring Au-Ag	- -
H04	Epithermal Au-Ag-Cu; high sulphidation	Acid-sulphate, qtz-alunite Au, Nansatsu-type
H05	Epithermal Au-Ag; low sulphidation	Adularia-sericite epithermal
H06*	Epithermal Mn	- -
H07	Sn-Ag veins	Polymetallic Sn veins
H08	Alkalic intrusion-associated Au	Alkalic intrusion-related Au, Au-Ag-Te veins
H09*	Hydrothermal alteration clays-Al-Si	Kaolin, Alunite, Siliceous cap, Pyrophyllite
I01	Au-quartz veins	Mesothermal, Motherlode, saddle reefs
I02	Intrusion-related Au pyrrhotite veins	Subvolcanic shear-hosted gold
I03	Turbidite-hosted Au veins	Meguma type
I04	Iron formation-hosted Au	Iron formation-hosted gold
I05	Polymetallic veins Ag-Pb-Zn±Au	Felsic intrusionassociated Ag-Pb-Zb veins
I06	Cu±Ag quartz veins	Churchill-type vein Cu
I07*	Silica veins	- -
I08	Silica-Hg carbonate	- -
I09	Stibnite veins and disseminations	Simple and disseminated Sb deposits
I10	Vein barite	- -
I11	Barite-fluorite veins	- -
I12*	W veins	Quartz-wolframite veins
I13*	Sn veins and greisens	- -
I14	Five-element veins Ni-Co-As-Ag±(Bi, U)	Ni-Co-native Ag veins, cobalt-type veins
I15	Classical U veins	Pitchblende veins, vein uranium
I16	Unconformity-associated U	Unconformity-veins, Unconformity U
I17	Cryptocrystalline magnesite veins	Bone magnesite, Kraubath-type magnesite
J01	Polymetallic manto Ag-Pb-Zn	Polymetallic replacement deposits
J02	Manto and stockwork Sn	Replacement Sn, Renison-type
J03*	Mn veins and replacements	covered by I05 and J01
J04	Sulphide manto Au	Au-Ag sulphide mantos
K01	Cu skarns	- -
K02	Pb-Zn skarns	- -
K03	Fe skarns	- -
K04	Au skarns	- -
K05	W skarns	- -
K06	Sn skarns	- -
K07	Mo skarns	- -
K08	Garnet skarns	- -
K09	Wollastonite skarns	- -
L01	Subvolcanic Cu-Ag-Au (As-Sb)	Enargite Au, Transitional Au-Ag
L02*	Porphyry-related Au	Granitoid Au, Porphyry Au
L03	Alkalic porphyry Cu-Au	Diorite porphyry copper

L04	Porphyry Cu ± Mo ± Au	Calcalkaline porphyry
L05	Porphyry Mo (Low F- type)	Calcalkaline Mo stockwork
L06	Porphyry Sn	Subvolcanic tin
L07	Porphyry W	Stockwork W-Mo
L08	Porphyry Mo (Climax-type)	Granite molybdenite
M01*	Flood Basalt-Associated Ni-Cu	Basaltic subvolcanic Cu-Ni-PGE
M02	Tholeiitic intrusion-hosted Ni-Cu	Gabbroid-associated Ni-Cu
M03	Podiform chromite	- -
M04	Magmatic Fe-Ti±V oxide deposits	Mafic intrusion-hosted Ti-Fe deposits
M05	Alaskan-type Pt±Os±Rh±Ir	Zoned ultramafic, Uralian-type
M06	Ultramafic-hosted asbestos	Serpentinite-hosted asbestos
M07	Ultramafic-hosted talc-magnesite	- -
M08	Vermiculite deposits	- -
N01	Carbonatite-hosted deposits	- -
N02*	Kimberlite-hosted diamonds	Diamond pipes
N03*	Lamproite-hosted diamonds	- -
O01	Rare element pegmatite - LCT family	Zoned pegmatite (Lithium-Cesium-Tantalum)
O02	Rare element pegmatite - NYF family	Niobium-Yttrium-Fluorine pegmatite
O03	Muscovite pegmatite	Mica-bearing pegmatite
O04*	Feldspar-quartz pegmatite	Barren pegmatite
P01	Andalusite hornfels	- -
P02	Kyanite-sillimanite schists	- -
P03	Microcrystalline graphite	Amorphous graphite
P04	Crystalline flake graphite	- -
P05	Vein graphite	Lump and chip graphite
P06	Corundum in aluminous metasediments	- -
Q01	Jade	- -
Q02	Rhodonite	- -
Q03*	Agate	- -
Q04*	Amethyst	- -
Q05*	Jasper	- -
Q06	Columbia-type emerald	- -
Q07	Schist-hosted emerald	Exometamorphic emerald deposit
Q08	Sediment-hosted opal	Australian-type opal
Q09	Gem corundum in contact zones	- -
Q10	Gem corundum hosted by alkalic rocks	- -
Q11	Volcanic-hosted opal	- -
R01	Cement shale	- -
R02	Expanding shale	- -
R03	Dimension stone - granite	- -
R04	Dimension stone - marble	- -
R05	Dimension stone - andesite	- -
R06*	Dimension stone - sandstone	- -
R07	Silica sandstone	High-silica quartzite
R08*	Flagstone	- -
R09	Limestone	- -
R10*	Dolomite	- -
R11*	Volcanic ash - pumice	- -
R12*	Volcanic glass - perlite	- -
R13*	Nepheline syenite	- -
R14*	Alaskite	- -
R15*	Crushed rock	Road metal, Riprap, Railroad ballast
S01	Broken Hill type Pb-Zn-Ag±Cu	Shuswap-type, Ammeburg-type Pb-Zn

LIGNITE A02

by Barry Ryan[1]

IDENTIFICATION

SYNONYM: Brown coal.

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

AGE OF MINERALIZATION: Quaternary; Tertiary; occasionally older.

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

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

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

LIGNITE A02

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

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

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

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

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

COMMENTS: Lignite has the lowest rank of all classes of coal (R_{max} less than 0.4 %).

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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

REFERENCES

Armstrong, W.M., Fyles, J.T., Guelke, C.B., Macgregor, E.R., Peel, A.L., Tompson, A.R. and Warren, I.H. (1976): Coal in British Columbia, A Technical Appraisal*; B.C. Ministry of Energy, Mines and Petroleum Resources*, Coal Task Force, 241 pages.

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Matheson, A. (1986): Coal in British Columbia; *; B.C. Ministry of Energy, Mines and Petroleum Resources*, Paper 1986-3, 169 pages.

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

SUB-BITUMINOUS COAL A03

by Barry Ryan[1]

IDENTIFICATION

SYNONYMS: Steam coal, thermal coal, black lignite.

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

AGE OF MINERALIZATION: Often Tertiary but can be older.

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

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

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

Ryan, B.D. (1995): Sub-bituminous coal; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 9-11.

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

SUB-BITUMINOUS COAL A03

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

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

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

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

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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

REFERENCES

Armstrong, W.M., Fyles, J.T., Guelke, C.B., Macgregor, E.R., Peel, A.L., Tompson, A.R. and Warren, I.H. (1976): Coal in British Columbia, A Technical Appraisal*; B.C. Ministry of Energy, Mines and Petroleum Resources*, Coal Task Force, 241 pages.

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

BITUMINOUS COAL A04

by Barry Ryan[1]

IDENTIFICATION

SYNONYMS: Metallurgical coal, coking coal, humic coal.

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

EXAMPLES (British Columbia - *Canada/International*): Line Creek (082GNE020), Quintette (093I010, 011, 019, 020); *Sydney coalfield (Nova Scotia, Canada), Sydney coalfield (Australia).*

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

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

Ryan, B.D. (1995): Bituminous coal; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 13-15.

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

BITUMINOUS COAL A04

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

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

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

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

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

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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

REFERENCES

Armstrong, W.M., Fyles, J.T., Guelke, C.B., Macgregor, E.R., Peel, A.L., Tompson, A.R. and Warren, I.H. (1976): Coal in British Columbia, A Technical Appraisal*; B.C. Ministry of Energy, Mines and Petroleum Resources*, Coal Task Force, 241 pages.

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

ANTHRACITE A05

by Barry Ryan[1]

IDENTIFICATION

SYNONYMS: Hard coal, stone coal, smokeless fuel.

COMMODITIES: Coal, carbon.

EXAMPLES (British Columbia - *International/Canada*): Klappan (104H020,021,022), Panorama South (104A082)*; Canmore (Alberta, Canada), Pennsylvania coalfields (USA).*

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

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

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

Ryan, B.D. (1995): Sub-bituminous coal; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 9-11.

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

ANTHRACITE A05

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

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

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

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

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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

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SURFICIAL PLACERS C01

by Victor M. Levson[1]

IDENTIFICATION

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

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

Levson, V.M. (1995): Surficial placers; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 21-23.

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

SURFICIAL PLACERS C01

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

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

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

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

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

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

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

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

EXPLORATION GUIDES

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

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

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

SURFICIAL PLACERS C01

ECONOMIC FACTORS

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

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

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

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BURIED-CHANNEL PLACERS C02

by Victor M. Levson[1] and Timothy R. Giles[2]

IDENTIFICATION

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

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

Levson, V.M. and Giles, T.R. (1995): Buried-channel placers; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 25-28.

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] British Columbia Ministry of Forests, Kamloops, B.C., Canada

BURIED-CHANNEL PLACERS C02

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

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

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

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

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

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

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

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

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

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

EXPLORATION GUIDES

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

BURIED-CHANNEL PLACERS C02

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

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

ECONOMIC FACTORS

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

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

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

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MARINE PLACERS C03

by Victor M. Levson[1]

IDENTIFICATION

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

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

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

Levson, V.M. (1995): Marine placers; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 29-31.

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

MARINE PLACERS C03

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

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

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

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

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

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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OPEN-SYSTEM ZEOLITES D01

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

IDENTIFICATION

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

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

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

GEOLOGICAL CHARACTERISTICS

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

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

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Non-marine and shallow marine basins in volcanic terrains. Depositional basins may be fault 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 hosted by volcanic ash and tuff beds with minor intercalated flows. Silicic tuffs commonly were deposited as non-welded ash flows. Other rock types include fluviatile mudstone, sandstone, conglomerate and diatomite.

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

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

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

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

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

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

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

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

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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.

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

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

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The value of zeolite deposits varies depending on the end product use and zeolite species present. Properties, such as cation exchange capacity for radionuclides, heavy metals or NH^{+}_{4}, are more meaningful than grade. This is because these properties are commonly different for the same zeolite species originating from two distinct deposits. The zeolite content of better deposits currently mined is estimated to have zeolite content above 60 %, but may reach over 80%. Deposits supplying materials to control the odor to local farms may have zeolite content well below 50%, but must be close to the market.

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

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

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

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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.

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CLOSED-BASIN ZEOLITES D02

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

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

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

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

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

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

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

EXPLORATION GUIDES

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

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

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

CLOSED-BASIN ZEOLITES D02

ECONOMIC FACTORS

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

ECONOMIC LIMITATIONS: Distance to the market is an important limitation for materials used in agricultural and construction applications. High-value specialty zeolites are international travelers. Production is typically from open pits with as much as 30 m of overburden. Mining costs reported by Holmes (1994) vary from US$ 3 to 6 per ton. Ground natural zeolites are selling for US$30 to 120 for low-value industrial use, but small tonnages of specialty products for the radioactive waste market can sell for more than $US 1000.00 per ton. Environmental regulations vary from one jurisdiction to 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.

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

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

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VOLCANIC REDBED CU D03

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

IDENTIFICATION

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

COMMODITIES (BYPRODUCTS): Cu (Ag)

EXAMPLES (British Columbia - *Canada/International*): Sustut Copper (094D063), Shamrock (092HNE092), NH (093L082), North Star (094D032); *White River (Yukon, Canada), 47 Zone and June, Coppermine River area (Northwest Territories, Canada) Mountain Grill and Radovan (Alaska, USA), Calumet-Hecla and Kearsarga, Keweenaw Peninsula (Michigan, USA), Mantos Blancos, Ivan and Altamira (Chile).*

GEOLOGICAL CHARACTERISTICS

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

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

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

AGE OF MINERALIZATION: Proterozoic to Tertiary.

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

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

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

Lefebure, D.V. and Church, B.N. (1996): Volcanic redbed Cu; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 5-7.

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

VOLCANIC REDBED CU D03

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

GANGUE MINERALOGY [Principal and *subordinate*]: Typically minor gangue; *hematite, magnetite, calcite, quartz, epidote, chlorite and zeolite minerals.*

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

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

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

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

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

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

VOLCANIC REDBED CU D03

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

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IRON OXIDE BRECCIAS AND VEINS P-Cu-Au-Ag-U D07

By David V. Lefebure[1]

IDENTIFICATION

SYNONYMS: Olympic Dam type, Kiruna type, apatite iron ore, porphyrite iron (Yangtze Valley), iron oxide rich deposits, Proterozoic iron oxide (Cu-U-Au-REE), volcanic-hosted magnetite.

COMMODITIES (*BYPRODUCTS*): Fe, P, Cu, Au, Ag, U (*potential for REE, Ba, F*).

EXAMPLES (British Columbia - *Canada/International*): Iron Range (082FSE014 - 028) - *Sue-Dianne (Northwest Territories, Canada); Wernecke breccias (Yukon, Canada), Kiruna district(Sweden), Olympic Dam (Australia), Pea Ridge and Boss-Bixby (Missouri, USA), El Romeral (Chile).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Magnetite and/or hematite breccia zones and veins which form pipes and tabular bodies hosted by continental volcanics and sediments and intrusive rocks. The deposits exhibit a wide range in their nonferrous metal contents. They vary from Kiruna type monometallic (Fe ± P) to Olympic Dam type polymetallic (Fe ± Cu ± U ± Au ± REE).

TECTONIC SETTING: Associated with stable cratons, typically associated with grabens related to rifting. Intracratonic extensional tectonics coeval with hostrock deposition. Upper crustal igneous or sedimentary rocks.

DEPOSITIONAL ENVIRONMENT/ GEOLOGICAL SETTING: Found crosscutting a wide variety of sedimentary and igneous rocks; magnetite-apatite deposits show an affinity for volcanics and associated hypabyssal rocks.

AGE OF MINERALIZATION: Proterozoic to Tertiary and believed to be virtually contemporaneous with associated suite of intrusive and/or volcanic rocks. Polymetallic Fe oxide deposits are commonly mid-Proterozoic age varying from 1.2 to 1.9 Ga.

HOST/ASSOCIATED ROCK TYPES: Veins and breccias crosscut, or are conformable with, a wide variety of continental sedimentary and volcanic rocks and intrusive stocks, including felsic volcanic breccia, tuff, clastic sedimentary rocks and granites. There may be a special association with a felsic alkalic rock suite ranging from “red” granite, and rapakivi granite to mangerite and charnockite and various volcanic equivalents. Fe oxides have been reported as common accessories in the associated igneous rocks. In some deposits the Fe oxide forms the matrix to heterolithic breccias which are composed of lithic and oxide clasts (usually hematite fragments), hematite-quartz microbreccia and fine-grained massive breccia. Some deposits have associated hematite-rich breccias, bedded Fe oxides and Fe oxide-bearing volcanic rocks which are conformable with associated volcanic rocks. Magnetite lavas and feeder dikes exist on the El Laco volcano in Chile.

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DEPOSIT FORM: Discordant pod-like zones, veins (dike-like), tabular bodies and stockworks; in some deposits dikes are overlain by Fe oxide tuffs and flows. The veins and tabular zones extend horizontally and vertically for kilometres with widths of metres to hundreds of metres.

Lefebure, D.V. (1995): Iron Oxide Breccias and Veins P-Cu-Au-Ag-U; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 33-36.

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

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TEXTURE/STRUCTURE: Cu-U-Au mineralization is typically hosted in the Fe oxide matrix as disseminations with associated microveinlets and sometimes rare mineralized clasts. Textures indicating replacement and microcavity filling are common. Intergrowths between minerals are common. Hematite and magnetite may display well developed crystal forms, such as interlocking mosaic, tabular or bladed textures. Some of the deposits (typically hematite rich) are characterized by breccias at all scales with Fe oxide and hostrock fragments which grade from weakly fractured hostrock on the outside to matrix-supported breccia (sometimes heterolithic) with zones of 100% Fe oxide in the core. Breccias may be subtle in hand sample as the same Fe oxide phase may comprise both the fragments and matrix. Breccia fragments are generally angular and have been reported to range up to more than 10 m in size, although they arefrequently measured in centimetres. Contacts with hostrocks are frequently gradational over scale of centimetres to metres. Hematite breccias may display a diffuse wavy to streaky layered texture of red and black hematite.

ORE MINERALOGY (Principal and *subordinate*): The deposits vary between magnetite-apatite deposits with actinolite or pyroxene (Kiruna type) and hematite-magnetite deposits with varying amounts of Cu sulphides, Au, Ag, uranium minerals and REE (Olympic Dam type). Hematite (variety of forms), specularite, magnetite, bornite, chalcopyrite, chalcocite, pyrite; *digenite, covellite, native copper, carrolite, cobaltite, Cu-Ni-Co arsenates, pitchblende, coffinite, brannerite, bastnaesite, monazite, xenotime, florencite, native silver and gold and silver tellurides*. At Olympic Dam, Cu is zoned from a predominantly hematite core (minor chalcocite-bornite) to chalcocite-bornite zone then bornite-chalcopyrite to chalcopyrite-pyrite in the outermost breccia. Uraninite and coffinite occur as fine-grained disseminations with sulphides; native gold forms fine grains disseminated in matrix and inclusions in sulphides. Bastnaesite and florencite are very fine grained and occur in matrix as grains, crystals and crystal aggregates.

GANGUE MINERALOGY (Principal and *subordinate*): Gangue occurs intergrown with ore minerals, as veins or as clasts in breccias. Sericite, carbonate, chlorite, quartz, fluorite, barite, and sometimes minor *rutile and epidote*. Apatite and actinolite or pyroxene with magnetite ores (Kiruna type). Hematite breccias are frequently cut by 1 to 10 cm veins with fluorite, barite, siderite, hematite and sulphides.

ALTERATION MINERALOGY (Principal and *subordinate*): A variety of alteration assemblages with differing levels of intensity are associated with these deposits, often with broad lateral extent. <u>Olympic Dam type:</u> Intense sericite and hematite alteration with increasing hematite towards the centre of the breccia bodies at higher levels. Close to the deposit the sericitized feldspars are rimmed by hematite and cut by hematite veinlets. Adjacent to hematite breccias the feldspar, rock flour and sericite are totally replaced by hematite. Chlorite or k-feldspar alteration predominates at depth. <u>Kiruna type:</u> Scapolite and albite?; there may also be actinolite-epidote alteration in mafic wallrocks. With both types of deposits quartz, fluorite, barite, carbonate, rutile, orthoclase ± epidote and garnet alteration are also reported.

WEATHERING: Supergene enrichment of Cu and U, for example, the pitchblende veins in the Great Bear magmatic zone.

ORE CONTROLS : Strong structural control with emplacement along faults or contacts, particularly narrow grabens. Mid-Proterozoic rocks particularly favourable hosts. Hydrothermal activity on faults with extensive brecciation. May be associated with felsic volcanic and alkalic igneous rocks. In some deposits calderas and maars have been identified or postulated. Deposits may form linear arrays more than 100 km long and 40 km wide with known deposits spaced 10-30 km along trend.

ASSOCIATED DEPOSIT TYPES: Volcanic-hosted U (D06)?; alkaline porphyry Cu-Au deposits (L03); supergene uranium veins.

IRON OXIDE BRECCIAS
AND VEINS P-Cu-Au-Ag-U D07

COMMENTS: Hitzman *et al.* (1992) emphasize that these are low-Ti iron deposits, generally less than 0.5% TiO_2 and rarely above 2% TiO_2 which allows distinction from Fe oxides associated with anorthosites, gabbros and layered mafic intrusions. Fe and Cu sulphides may be more common with hematite Fe oxides.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalously high values for Cu, U, Au, Ag, Ce, La, Co, ± P, ± F, and ± Ba in associated rocks and in stream sediments.

GEOPHYSICAL SIGNATURE: Large positive gravity anomalies because of Fe oxides. Regional aeromagnetic anomalies related to magnetite and/or coeval igneous rocks. Radiometric anomaly (such as airborne gamma-ray spectrometer survey) expected with polymetallic deposits containing uranium.

OTHER EXPLORATION GUIDES: Proterozoic faulting with associated Fe oxides (particularly breccias), possibly related to intracratonic rifting. Widespread hematite, sericite or chlorite alteration related to faults. Possibly form linear arrays 100 or more kilometres long and up to tens of kilometres wide.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE : Deposits may exceed 1000 Mt grading greater than 20 % Fe and frequently are in 100 to 500 Mt range. Olympic Dam deposit has estimated reserves of 2000 Mt grading 1.6% Cu, 0.06% U_3O_8, 3.5 g/t Ag and 0.6 g/t Au with a measured and indicated resource in a large number of different ore zones of 450 Mt grading 2.5% Cu, 0.08 % U_3O_8, 6 g/t Ag and 0.6 g/t Au with ~5,000 g/t REE. The Ernest Henry deposit in Australia contains 100 Mt at 1.6% Cu and 0.8 g/t Au. Sue-Dianne deposit in the Northwest Territories contains 8 Mt averaging 0.8% Cu and 1000 g/t U and locally significant gold. The Kiruna district contains more than 3000 Mt of Fe oxide apatite ore grading 50-60% Fe and 0.5 -5 % P. The largest orebody at Bayan Obo deposit in Inner Mongolia, China contains 20 Mt of 35 % Fe and 6.19% REE.

ECONOMIC LIMITATIONS: Larger Fe oxide deposits may be mined for Fe only; however, polymetallic deposits are more attractive.

IMPORTANCE: These deposits continue to be significant producers of Fe and represent an important deposit type for producing Cu, U and possibly REE.

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ACKNOWLEDGEMENTS: This deposit profile represents the results of a literature review. The only "ground truthing" is thanks to instructive conversations with Sunil Gandhi of the Geological Survey of Canada and Tom Setterfield of Westminer Canada Ltd.

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CARBONATE HOSTED CU±Pb±Zn EO2

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

IDENTIFICATION

SYNONYMS: Tsumeb or Kipushi type.

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

EXAMPLES (British Columbia - *Canada/International*): Blue (Minfile 94F005); *Grinnell and Kanuyak Island (Northwest Territories, Canada), Kennecott, Ruby Creek and Omar (Alaska, USA), Apex (Utah, USA), Gortdrum (Ireland), Tsumeb and Kombat (Namibia), Kipushi (Zaire), M'Passa (Congo), Timna (Israel), Nifty (Australia), and portions of Dongchuan deposits (China).*

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

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

CARBONATE HOSTED CU±Pb±Zn EO2

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

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

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

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

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

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

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

CARBONATE HOSTED CU±Pb±Zn EO2

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

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

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

CARBONATE HOSTED CU±Pb±Zn EO2

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CARBONATE-HOSTED DISSEMINATED Au-Ag E03

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

IDENTIFICATION

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

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

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Golden Bear? (104K079*); parts of Brewery Creek (Yukon, Canada), Carlin, Getchell, Cortez, Gold Acres, Jerrett Canyon, Post and Gold Quarry (Nevada, USA), Mercur (Utah, USA), Mesel? (Indonesia),Guizhou (China).*

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

Schroeter, T. and Poulsen, H. (1996): Carbonate-hosted disseminated Au-Ag; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 9-12.

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CARBONATE-HOSTED DISSEMINATED Au-Ag E03

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

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

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

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

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

GENETIC MODELS:

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

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

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

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

CARBONATE-HOSTED DISSEMINATED Au-Ag E03

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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SEDIMENT-HOSTED Cu±Ag±Co E04

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

IDENTIFICATION

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

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

Lefebure, D.V. and Alldrick, D.J. (1996): Sediment-hosted Cu±Ag±Co; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 13-16.

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SEDIMENT-HOSTED Cu±Ag±Co E04

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

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

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

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

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

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

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

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

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

SEDIMENT-HOSTED Cu±Ag±Co E04

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

EXPLORATION GUIDES

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

GEOPHYSICAL SIGNATURE: Weak radioactivity in some deposits.

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

ECONOMIC FACTORS

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

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

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

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D. Lefebure draft #: 3a March 28, 1996

SANDSTONE-Pb E05

by D.F. Sangster[1]

IDENTIFICATION

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

Sangster, D.F. (1996): Sandstone-Pb; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 17-19.

[1] Geological Survey of Canada, Ottawa

SANDSTONE-Pb E05

TEXTURE/STRUCTURE: The preferred site of ore minerals is as cement between sand grains resulting in disseminated sulphide blebs or spots in massive sandstones or concentrations of sulphides along the lower, more porous portions of graded beds. The disseminated sulphides are not normally homogeneously dispersed throughout the sandstone. Two very common textures are:

i) spots, representing local accumulations of galena, as much as 2 cm in diameter. Spots may be randomly distributed in the sandstone or may show a slight preferential alignment parallel to bedding;

ii) discontinous galena-rich streaks distributed parallel to bedding, including crossbedding.

Where carbonaceous material is present, sulphides fill wood cells or replace cell walls. Concretionary-like sulphide concentrations are abundant in some deposits. Epitaxial quartz overgrowths on detrital quartz grains are very common and in some deposits more abundant within or near ore zones than regionally. Paragenetic studies indicate the epitaxial quartz predates galena.

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

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

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

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

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

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

EXPLORATION GUIDES

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

GEOPHYSICAL SIGNATURE: Induced polarization anomalies (?)

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

ECONOMIC FACTORS

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

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

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

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BENTONITE E06

by Z.D. Hora[1]

IDENTIFICATION

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

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

EXAMPLES (British Columbia (MINFILE #)- *Canada/International*): Hat Creek (0921NW084), Princeton (092HSE151), Quilchena (0921SE138), French Bar (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.*

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

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

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

BENTONITE E06

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

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

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

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

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Nil

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

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

ECONOMIC FACTORS

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

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

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 liqnite) 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 semiconchoidal 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.*

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

SEDIMENTARY KAOLIN E07

WEATHERING: The kaolin forms by weathering which results in decomposition of feldspars and other aluminosilicates 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. Paradisl[2]

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Simandl, G.J and Paradis, S. (1999): Carbonate-hosted talc; in Selected British Columbia Mineral Deposit Profiles, Volume 3, Industrial Minerals, G.J. Simandl, Z.D. Hora and D.V. Lefebure, Editors, British Columbia Ministry of Energy and Mines.

IDENTIFICATION

SYNONYMS: "Dolomite-hosted" talc deposits.

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

DEPOSIT FORM: In most cases, podiform or deformed, sheet-like bodies oriented subparallel to the compositional layering within marbles and to geologic contacts. They commonly pinch and swell. Typical dimensions would be 2 to 20 m thick and tens to hundreds of m 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*).*

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

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

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

ORE CONTROLS: The main controls are the presence of dolomite or magnesite protolith, availability of silica and favourable metamorphic/metasomatic conditions. Talc deposits hosted by carbonate rocks may be divided into several subtypes according to the source of silica and geological setting:

a) contacts between carbonates, usually dolomitic marbles, and silica-bearing rocks, such as biotite-quartz-feldspar gneisses, schists, cherts and quartzites;
b) horizons or lenses of siliceous dolomite or magnesite protolith;
c) crests of folds, breccia zones, faults, and intersections of fault systems that permit circulation of metasomatic fluids carrying silica within dolomite or magnesite host; and
d) carbonates within the contact metamorphic aureole of intrusions, where silica has been derived from adjacent host rock.

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

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

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: Systematic study of soils to identify anomalous concentrations of talc using the X-ray diffraction method 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 in residual soils. Talc occurs within belts of dolomitic rocks in metamorphosed terranes or adjacent to intrusive rocks. Contacts with silica-bearing metasediments or intrusions are favourable loci for deposits.

ECONOMIC FACTORS

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

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

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

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

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January 29, 1999

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),* d*eposits 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 (metres to tens of metres) is commonly normal to the bedding planes.

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

ORE MINERALOGY: Magnesite.

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

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

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

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

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SPARRY MAGNESITE E09

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

EXPLORATION GUIDES

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

GEOPHYSICAL SIGNATURE: N/A.

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

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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IRISH-TYPE CARBONATE-HOSTED Zn-Pb E13

By Trygve Höy[1]

IDENTIFICATION

SYNONYMS: Kootenay Arc Pb-Zn, Remac type.

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

Höy, T. (1996): Irish-type carbonate-hosted Zn-Pb; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 21-24.

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IRISH-TYPE CARBONATE-HOSTED Zn-Pb E13

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

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

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

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

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

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

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

GENETIC MODEL: Two models are commonly proposed:
(1) syngenetic seafloor deposition: evidence inludes stratiform geometry of some deposits, occurrence together of bedded and clastic sulphides, sedimentary textures in sulphides, and, where determined, similar ages for mineralization and host rocks.
(2) diagenetic to epigenetic replacement: replacement and open-space filling textures, lack of laminated sulphides in most deposits, alteration and mineralization above sulphide lenses, and lack of seafloor oxidation.

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

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

IRISH-TYPE CARBONATE-HOSTED Zn-Pb E13

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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T. Hoy Draft 3: March 27, 1996

SEDIMENTARY EXHALATIVE Zn-Pb-Ag E14

by Don MacIntyre[1]

IDENTIFICATION

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

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

MacIntyre, D. (1995): Sedimentary exhalative Zn-Pb-Ag; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 37-39.

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

SEDIMENTARY EXHALATIVE Zn-Pb-Ag E14

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

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

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

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

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

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

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

EXPLORATION GUIDES

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

SEDIMENTARY EXHALATIVE Zn-Pb-Ag E14

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

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

ECONOMIC FACTORS

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

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

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

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BLACKBIRD SEDIMENT-HOSTED Cu-Co E15

by Trygve Höy[1]

IDENTIFICATION

SYNONYM: Sediment-hosted Cu-Co deposit.

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

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

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

Höy, T. (1995): Blackbird sediment-hosted Cu-Co; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 41-43.

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BLACKBIRD SEDIMENT-HOSTED Cu-Co E15

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

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

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

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

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

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

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

EXPLORATION GUIDES

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

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

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

ECONOMIC FACTORS

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

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

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

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DRAFT # 2 February 6, 1995

SHALE-HOSTED Ni-Zn-Mo-PGE E16

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

IDENTIFICATION

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

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

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

GEOLOGICAL CHARACTERISTICS

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

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

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

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

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

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

Lefebure, D.V. and Coveney, R.M., Jr. (1995): Shale-hosted Ni-Zn-Mo-PGE; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 45-47.

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SHALE-HOSTED Ni-Zn-Mo-PGE E16

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

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

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

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

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

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

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

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

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

SHALE-HOSTED Ni-Zn-Mo-PGE E16

EXPLORATION GUIDES

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

GEOPHYSICAL SIGNATURE: Electromagnetic surveys should detect pyrite horizons.

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

ECONOMIC FACTORS

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

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

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

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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 metres in thickness and several kilometres in strike length. Barite-rich rocks (baritites) are commonly lateral distal equivalents of shale-hosted Pb-Zn (SEDEX) deposits. Some barite deposits are not associated with shale-hosted Zn-Pb deposits.

TECTONIC SETTINGS: Intracratonic or continental margin-type fault-controlled marine basins or half-grabens of second or third order and peripheral foreland (distal to the continental margin) basins.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Deep, starved marine basins to shallow water shelves. The barite-rich rocks (baritites) were deposited on the seafloor and commonly grade laterally into either shale-hosted Pb-Zn (SEDEX) deposits which formed closer to the submarine hydrothermal vents, or the more distal cherts, hematite-chert iron formations, silica and manganese-enriched sediments.

AGE OF MINERALIZATION: Deposits are hosted by rocks of Archean to Mesozoic ages but are most common in rocks of Phanerozoic, especially in the mid to late Paleozoic age.

HOST/ASSOCIATED ROCK TYPES: Major rock types hosting barite are carbonaceous and siliceous shales, siltstones, cherts, argillites, turbidites, sandstones, dolomites and limestones.

DEPOSIT FORM: Stratiform or lens-shaped deposits are commonly metres thick, but their thickness may exceed 50 metres. Their lateral extent may be over several square kilometres.

TEXTURE/STRUCTURE: The barite ore is commonly laminated, layered or massive. Barite may form rosettes, randomly oriented laths or nodules. Some of the barite deposits display breccias and slump structures. In metamorphosed areas, barite may be remobilized (forming veinlets) and/or recrystallized.

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

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, clay, organic material, celsian, hyalophane, cymrite, barytocalcite, calcite, dolomite, pyrite, *marcasite, sphalerite, galena, and in some cases witherite*.

ALTERATION MINERALOGY: None in most cases. Secondary barite veining. Weak to moderate sericitization reported in, or near, some deposits in Nevada.

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[3] United States Geological Survey, Tuscon, Arizona, USA

SEDIMENTARY-HOSTED, STRATIFORM BARITE E17

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.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits range from less than 1 to more than 25 million tonnes grading 30% to over 95% barite with a median size of 1.24 million tonnes containing 87.7 % $BaSO_4$ (Orris, 1992). Portions of some deposits may be direct shipping ore. The Magcobar mine in the Silvermines district of Ireland produced 4.6 Mt of 85% BaSO4 lump. Barite is produced at some metal mines, including the Ramelsburg and Meggen (8.9 Mt) mines in Germany.

ECONOMIC LIMITATIONS: Several modern applications require high brightness and whiteness values and high-purity products. There are different requirements for specific applications. Abrasivity, grade of concentrate, color, whiteness, density and type of impurities, oil index, water index, refractive index and base metal content are commonly reported for commercially available concentrates. Transportation cost, specific gravity and content of water-soluble alkaline earth metals, iron oxides and sulphides are important factors for barite used in drilling applications. Currently sulphide-free barite deposits are preferred by the barite producers. Some of the barite on the market is sold without complex upgrading. Selective mining and/or hand sorting, jigging, flotation and bleaching are commonly required. It is possible that in the future, due to technological progress, a substantial portion of barite on the market will originate as by-product of metal mining.

END USES: Barite is used mainly in drill muds, also as heavy aggregate, marine ballast, a source of chemicals, a component in ceramics, steel hardening, glass, fluxes, papers, specialized plastics and radiation shields, in sound proofing and in friction and pharmaceutical applications. Witherite is a desirable source of barium chemicals because it is soluble in acid, but it is not suitable for applications where inertness in acid environments is important..

IMPORTANCE: Competes for market with vein-type barite deposits. Celestite, ilmenite, iron oxides can replace barite in specific drilling applications. However the impact of these substitutes is minimized by relatively low barite prices.

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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 few to over 50 metres in thickness and extend from few to over 50 km laterally. They commonly have a “bathtub-ring" or “donut” shape. Some deposits may consist of a landward oxide facies and basinward reduced carbonate facies. Ore bodies represent discrete portions of these zones

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

ORE MINERALOGY [Principal and *subordinate*]: Manganese oxides: mainly manganite, psilomelane, pyrolusite; carbonates: mainly rhodochrosite, kutnohorite, calcio-rhodochrosite.

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GANGUE MINERALOGY [Principal and *subordinate*]: Kaolinite, goethite, smectite, glauconite, quartz, biogenic silica; *magnetite or other iron oxides, pyrite, marcasite, phosphate, ± barite, carbonaceous material, ± chlorite, ± siderite, manganocalcite.*

ALTERATION MINERALOGY: N/A.

WEATHERING: Grades of primary ore are relatively uniform; however, supergene enrichment may result in a two or three-fold grade increase. The contacts between primary ore and supergene-enriched zones are typically sharp. Mn carbonates may weather to brown, nondescript rock. Black secondary oxides are common.

ORE CONTROLS: Sedimentary manganese deposits formed along the margins of stratified basins where the shallow oxygenated water and deeper anoxic water interface impinged on shelf sediments. They were deposited at the intersection of an oxidation-reduction interface with platformal sediments. Sites protected from clastic sedimentation within transgressive sequences are most favourable for accumulation of high grade primary deposits.

GENETIC MODELS: Traditionally these deposits are regarded as shallow, marine Mn sediments which form rims around paleo-islands and anoxic basins. Manganese precipitation is believed to take place in stratified water masses at the interface between anoxic seawater and near surface oxygenated waters.. The Black Sea and stratified fjords, such as Saanich Inlet or Jervis inlet, British Columbia (Emerson 1982; Grill, 1982) are believed to represent modern analogues. Extreme Fe fractionation is caused by a low solubility of iron in low Eh environments where Fe precipitates as iron sulfide. A subsequent increase in Eh and/or pH of Mn-rich water may produce Mn-rich, Fe-depleted chemical sediments. The manganese oxide facies is preserved on oxidized substrates. Carbonate facies may be preserved either in oxidized or reduced substrates in slightly deeper waters.

ASSOCIATED DEPOSIT TYPES: Black shale hosted deposits, such as upwelling-type phosphates (F07), sediment-hosted barite deposits (E17), shale-hosted silver-vanadium and similar deposits (E-16) and sedimentary-hosted Cu (E04), may be located basinward from the manganese deposits. Bauxite and other laterite-type deposits (B04), may be located landward from these manganese deposits. No direct genetic link is implied between sedimentary manganese deposits and any of these associated deposits.

COMMENTS: A slightly different model was proposed to explain the origin of Mn-bearing black shales occurring in the deepest areas of anoxic basins by Huckriede and Meischner (1996).
Calvert and Pedersen (1996) suggest an alternative hypothesis, where high accumulation rate of organic matter in sediments will promote the development of anoxic conditions below the sediment surface causing surface sediments to be enriched in Mn oxyhydroxides. When buried they will release diagenetic fluids, supersaturated with respect to Mn carbonates, that will precipitate Ca-Mn carbonates.
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.

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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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ALGOMA-TYPE IRON-FORMATION G01

by G.A. Gross[1]

IDENTIFICATION

SYNONYMS: Taconite, itabirite, banded iron-formation.

COMMODITIES (BYPRODUCTS): Fe (Mn).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Falcon (093O016), Lady A (092B029); *McLeod (Helen), Sherman, Adams, Griffith (Ontario, Canada), Woodstock, Austin Brook (New Brunswick, Canada), Kudremuk (India), Cerro Bolivar (Venezuela), Carajas (Brazil), part of Krivoy Rog (Russia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Iron ore deposits in Algoma-type iron-formations consist mainly of oxide and carbonate lithofacies that contain 20 to 40 % Fe as alternating layers and beds of micro- to macro-banded chert or quartz, magnetite, hematite, pyrite, pyrrhotite, iron carbonates, iron silicates and manganese oxide and carbonate minerals. The deposits are interbedded with volcanic rocks, greywacke, turbidite and pelitic sediments; the sequences are commonly metamorphosed.

TECTONIC SETTINGS: Algoma-type iron-formations are deposited in volcanic arcs and at spreading ridges.

AGE OF MINERALIZATION: They range in age from 3.2 Ga to modern protolithic facies on the seafloor and are most widely distributed and achieve the greatest thickness in Archean terranes (2.9 to 2.5 Ga).

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: They formed both near and distal from extrusive centres along volcanic belts, deep fault systems and rift zones and may be present at any stage in a volcanic succession. The proportions of volcanic and clastic sedimentary rocks vary and are rarely mutually exclusive.

HOST/ASSOCIATED ROCKS: Rocks associated with Algoma-type iron-formations vary greatly in composition, even within local basins, and range from felsic to mafic and ultramafic volcanic rocks, and from greywacke, black shale, argillite, and chert interlayered with pyroclastic and other volcaniclastic beds or their metamorphic equivalents. Algoma-type iron-formations and associated stratafer sediments commonly show a prolific development of different facies types within a single stratigraphic sequence. Oxide lithofacies are usually the thickest and most widely distributed units of iron-formation in a region and serve as excellent metallogenetic markers.

DEPOSIT FORM: Iron ore deposits are sedimentary sequences commonly from 30 to 100 m thick, and several kilometres in strike length. In most economic deposits, isoclinal folding or thrust faulting have produced thickened sequences of iron-formation.

Gross, G.A. (1996): Algoma-type Iron-formation; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 25-27.

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ALGOMA-TYPE IRON-FORMATION G01

STRUCTURE/TEXTURE: Micro-banding, bedding and penecontemporaneous deformation features of the hydroplastic sediment, such as slump folds and faults, are common, and can be recognized in many cases in strongly metamorphosed oxide lithofacies. Ore mineral distribution closely reflects primary sedimentary facies. The quality of oxide facies crude ore is greatly enhanced by metamorphism which leads to the development of coarse granular textures and discrete grain enlargement.

ORE MINERALOGY: Oxide lithofacies are composed of magnetite and hematite. Some deposits consist of siderite interbedded with pyrite and pyrrhotite.

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, siderite or ferruginous ankerite and dolomite, manganoan siderite and silicate minerals. *Silicate lithofacies are characterized by iron silicate minerals including grunerite, minnesotaite, hypersthene, reibeckite and stilpnomelane, associated with chlorite, sericite, amphibole, and garnet.*

WEATHERING: Minor oxidation of metal oxide minerals and leaching of silica, silicate and carbonate gangue. Algoma-type iron-formations are protore for high-grade, direct shipping types of residual-enriched iron ore deposits.

GENETIC MODEL: Algoma-type iron deposits were formed by the deposition of iron and silica in colloidal size particles by chemical and biogenic precipitation processes. Their main constituents evidently came from hydrothermal-effusive sources and were deposited in euxinic to oxidizing basin environments, in association with clastic and pelagic sediment, tuff, volcanic rocks and a variety of clay minerals. The variety of metal constituents consistently present as minor or trace elements evidently were derived from the hydrothermal plumes and basin water and adsorbed by amorphous iron and manganese oxides and smectite clay components in the protolithic sediment. Their development and distribution along volcanic belts and deep-seated faults and rift systems was controlled mainly by tectonic rather than by biogenic or atmospheric factors. Sulphide facies were deposited close to the higher temperature effusive centres; iron oxide and silicate facies were intermediate, and manganese-iron facies were deposited from cooler hydrothermal vents and in areas distal from active hydrothermal discharge. Overlapping and lateral transitions of one kind of lithofacies to another appear to be common and are to be expected.

ORE CONTROLS: The primary control is favourable iron-rich stratigraphic horizons with little clastic sedimentation, often near volcanic centres. Some Algoma-type iron-formations contain ore deposits due to metamorphic enhancement of grain size or structural thickening of the mineralized horizon.

ASSOCIATED DEPOSITS: Algoma-type iron-formations can be protore for residual-enriched iron ore deposits (B01?). Transitions from Lake Superior to Algoma-type iron-formations occur in areas where sediments extend from continental shelf to deep-water environments along craton margins as reported in the Krivoy Rog iron ranges. Oxide lithofacies of iron-formation grade laterally and vertically into manganese-rich lithofacies (G02), and iron sulphide, polymetallic volcanic-hosted and sedex massive sulphide (G04, G05, G06, E14).

COMMENTS: Lithofacies selected for iron and manganese ore are part of the complex assemblage of stratiform units formed by volcanogenic-sedimentary processes that are referred to collectively as stratafer sedimentary deposits, and includes iron-formation (more than 15% Fe) and various other metalliferous lithofacies.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values for Fe and Mn; at times elevated values for Ni, Au, Ag, Cu, Zn Pb, Sn, W, REE and other minor elements.

GEOPHYSICAL SIGNATURE: Electromagnetic, magnetic, and electrical conductance and resistivity survey methods are used effectively in tracing and defining the distribution of Algoma-type beds, either in exploring for iron and manganese ore, or for using these beds as metallogenetic markers.

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OTHER EXPLORATION GUIDES: Discrete, well defined magnetite and hematite lithofacies of iron-formation are preferred with a minimum of other lithofacies and clastic sediment interbedded in the crude ore. Iron-formations are usually large regional geological features that are relatively easy to define. Detailed stratigraphic information is an essential part of the database required for defining grade, physical and chemical quality, and beneficiation and concentration characteristics of the ore. Basin analysis and sedimentation modeling enable definition of factors that controlled the development, location and distribution of different iron-formation lithofacies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Orebodies range in size from about 1000 to less than 100 Mt with grades ganging from 15 to 45% Fe, averaging 25% Fe. Precambrian deposits usually contain less than 2% Mn, but many Paleozoic iron-formations, such as those near Woodstock, New Brunswick, contain 10 to 40 % Mn and have Fe/Mn ratios of 40:1 to 1:50. The largest B.C. deposit, the Falcon, contains inferred reserves of 5.28 Mt grading 37.8% Fe.

ECONOMIC LIMITATIONS: Usually large-tonnage open pit operations. Granular, medium to coarse-grained textures with well defined, sharp grain boundaries are desirable for the concentration and beneficiation of the crude ore. Strongly metamorphosed iron-formation and magnetite lithofacies are usually preferred. Oxide facies iron-formation normally has a low content of minor elements, especially Na, K, S and As, which have deleterious effects in the processing of the ore and quality of steel produced from it.

IMPORTANCE: In Canada, Algoma-type iron-formations are the second most important source of iron ore after the taconite and enriched deposits in Lake Superior-type iron-formations. Algoma-type iron-formations are widely distributed and may provide a convenient local source of iron ore.

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BESSHI MASSIVE SULPHIDE G04

by Trygve Höy[1]

IDENTIFICATION

SYNONYMS: Besshi type, Kieslager.

COMMODITIES (*BYPRODUCTS*): Cu, Zn, Pb, Ag, (*Au, Co, Sn, Mo, Cd*).

EXAMPLES (British Columbia - *Canada/International*): Goldstream (082M141), Standard (082M090), Montgomery (082M085), True Blue (082F002), Granduc (?) (104B021), Windy Craggy (?) (114P020); *Greens Creek (Alaska, USA), Besshi (Japan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits typically comprise thin sheets of massive to well layered pyrrhotite, chalcopyrite, sphalerite, pyrite and minor galena within interlayered, terrigenous clastic rocks and calcalkaline basaltic to andesitic tuffs and flows.

TECTONIC SETTINGS: Oceanic extensional environments, such as back-arc basins, oceanic ridges close to continental margins, or rift basins in the early stages of continental separation.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Terrigenous clastic rocks associated with marine volcanic rocks and sometimes carbonate rocks; these may overlie platformal carbonate or clastic rocks.

AGE OF MINERALIZATION: Any age. In British Columbia, most deposits are Cambrian, Late Triassic and less commonly Mississippian-Permian in age.

HOST/ASSOCIATED ROCK TYPES: Clastic sediments and marine volcanic rocks; basaltic tuffs and flows, shale and siltstone, commonly calcareous; less commonly chert and Fe formations. Possibly ultramafics and metagabbro in sequence.

DEPOSIT FORM: Typically a concordant sheet of massive sulphides up to a few metres thick and up to kilometres in strike length and down dip; can be stacked lenses.

TEXTURE/STRUCTURE: Massive to well-layered, fine to medium-grained sulphides; gneissic sulphide textures common in metamorphosed and deformed deposits; durchbewegung textures; associated stringer ore is uncommon. Crosscutting pyrite, chalcopyrite and/or sphalerite veins with chlorite, quartz and carbonate are common.

ORE MINERALOGY [Principal and *subordinate*]: Pyrite, pyrrhotite, chalcopyrite, sphalerite, *cobaltite, magnetite, galena, bornite, tetrahedrite, cubanite, stannite, molybdenite, arsenopyrite, marcasite*.

GANGUE MINERALOGY (Principal and *subordinate*): Quartz, calcite, ankerite, siderite, albite, tourmaline, *graphite, biotite.*

ALTERATION MINERALOGY: Similar to gangue mineralogy - quartz, chlorite, calcite, siderite, ankerite, pyrite, sericite, graphite.

Höy, T. (1995): Besshi Massive Sulphide; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 49-50.

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

BESSHI MASSIVE SULPHIDE G04

ORE CONTROLS: Difficult to recognize; early (syndepositional) faults and mafic volcanic centres.

GENETIC MODEL: Seafloor deposition of sulphide mounds in back-arc basins, or several other tectonic settings, contemporaneous with volcanism.

ASSOCIATED DEPOSIT TYPES: Cu, Zn veins.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Cu, Zn, Ag, Co/Ni>1; Mn halos, Mg enrichment.

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

OTHER EXPLORATION GUIDES: Mafic volcanic rocks (tholeiitic, less commonly alkalic) associated with clastic rocks; Mn-rich garnets in metamorphosed exhalative horizons, possible structures, such as faults; possible association with ultramafic rocks.

ECONOMIC FACTORS

GRADE AND TONNAGE: Highly variable in size. B.C. deposits range in size from less than 1 Mt to more than 113 Mt. For example, Goldstream has a total resource (reserves and production) of 1.8 Mt containing 4.81 % Cu, 3.08 % Zn and 20.6 g/t Ag and Windy Craggy has reserves in excess of 113.0 Mt containing 1.9 % Cu, 3.9 g/t Ag and 0.08% Co. The type-locality Besshi deposits average 0.22 Mt, containing 1.5% Cu, 2-9 g/t Ag, and 0.4-2% Zn (Cox and Singer, 1986).

IMPORTANCE: Significant sources of Cu, Zn and Ag that can be found in sedimentary sequences that have not been thoroughly explored for this type of target.

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CYPRUS MASSIVE SULPHIDE Cu (Zn) G05

by Trygve Höy[1]

IDENTIFICATION

SYNONYMS: Cyprus massive sulphide, cuprous pyrite.

COMMODITY (*BYPRODUCTS*): Cu, (*Au, Ag, Zn, Co, Cd*).

EXAMPLES (British Columbia - *Canada/International*): Chu Chua (092F140), Lang Creek (104P008), Hidden Creek (103P021), Bonanza (103P023), Double Ed (103P025), ; *Cyprus; York Harbour and Betts Cove (Newfoundland, Canada); Turner-Albright (USA); Lokken (Norway).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits typically comprise one or more lenses of massive pyrite and chalcopyrite hosted by mafic volcanic rocks and underlain by a well developed pipe-shaped stockwork zone.

TECTONIC SETTINGS: Within ophiolitic complexes formed at oceanic or back-arc spreading ridges; possibly within marginal basins above subduction zones or near volcanic islands within an intraplate environment.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Lenses commonly are in tholeiitic or calcalkaline marine basalts, commonly pillowed, near a transition with overlying argillaceous sediments. Many lenses appear to be structurally controlled, aligned near steep normal faults.

AGE OF MINERALIZATION: Any age. Deposits in British Columbia are primarily Mississippian-Permian or Late Triassic.

HOST/ASSOCIATED ROCK TYPES: Tholeiitic or calcalkaline pillow and flow basalts, basaltic tuff, chert, argillite. Overlying "umbers" consist of ochre [Mn-poor, Fe-rich bedded mudstone containing goethite, maghemite (Fe_3O_4-Fe_2O_3 mixture) and quartz] or chert.

DEPOSIT FORM: Concordant massive sulphide lens overlying cross-cutting zone of intense alteration and stockwork mineralization and hydrothermally altered wallrock, and overlain by chert.

TEXTURE/STRUCTURE: Massive, fine-grained pyrite and chalcopyrite, sometimes brecciated or banded?; massive magnetite, magnetite-talc and talc with variable sulphide content; associated chert layers, locally brecciated, contain disseminated sulphides; disseminated, vein and stockwork mineralization beneath lenses.

ORE MINERALOGY (Principal and *subordinate*): Pyrite, chalcopyrite, magnetite, sphalerite, *marcasite, galena, pyrrhotite, cubanite, stannite-besterite, hematite*. Sometimes goethite alteration of top of sulphide layer.

GANGUE MINERALOGY: Talc, chert, magnetite, chlorite.

ALTERATION MINERALOGY: Chlorite, talc, carbonate, sericite and quartz veins in the core of the stringer zone, sometimes with an envelope of weak albite with illite alteration.

Höy, T. (1995): Cyprus Massive Sulphide Cu (Zn); *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 51-52.

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

CYPRUS MASSIVE SULPHIDE Cu (Zn) G05

ORE CONTROLS: Prominent structural control with clustering or alignment of sulphide lenses along early normal faults, near transition from mafic pillow basalts; less commonly mafic tuff; to overlying fine pelagic material.

GENETIC MODEL: Seafloor deposition of sulphide mounds contemporaneous with mafic volcanism, such as spreading ridges.

ASSOCIATED DEPOSIT TYPES: Vein and stockwork Cu (-Au) mineralization; Mn and Fe-rich cherts; massive magnetite (-talc) deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Cu, Zn; common depletion of Ca and Na; less common, local minor Na enrichment; possible local K enrichment; prominent Fe and Mn enrichment in footwall stringer zone.

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

OTHER EXPLORATION GUIDES: Mafic ophiolitic volcanic rocks; transition to argillite; clustering or alignment of deposits indicative of fault control; ochre and exhalite (chert) horizons; regional pyritic horizons.

ECONOMIC FACTORS

GRADE AND TONNAGE: Published average is 1.6 Mt containing 1.7 % Cu, 0-33 g/t Ag; 0-1.9 g/t Au, 0-2.1 % Zn (Cox and Singer, 1986). B.C. examples: Chu Chua reserves - 1.043 Mt, 2.97 % Cu, 0.4 % Zn, 8.0 g/t Ag, 1.0 g/t Au; Anyox deposits - 0.2 to 23.7 Mt, approx. 1.5% Cu, 9.9 g/t Ag and 0.17 g/t Au.

IMPORTANCE: Deposits at Anyox produced 335,846 tonnes copper, 215,057 kg silver and 3,859 kg gold. Worldwide these deposits are generally significant more for their higher grades and polymetallic nature, than their size.

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NORANDA/KUROKO MASSIVE SULPHIDE Cu-Pb-Zn
G06

by Trygve Höy[1]

IDENTIFICATION

SYNONYM: Polymetallic volcanogenic massive sulphide.

COMMODITIES (*BYPRODUCTS*): Cu, Pb, Zn, Ag, Au (*Cd, S, Se, Sn, barite, gypsum).*

EXAMPLES (British Columbia - *Canada/International*): Homestake (082M025), Lara (092B001), Lynx (092B129), Myra (092F072), Price (092F073), H-W (092F330), Ecstall (103h011), Tulsequah Chief (104K011), Big Bull (104K008), Kutcho Creek (104J060), Britannia (092G003); *Kidd Creek (Ontario, Canada), Buchans (Newfoundland, Canada), Bathurst-Newcastle district (New Brunswick, Canada), Horne-Quemont (Québec, Canada), Kuroko district (Japan), Mount Lyell (Australia), Rio Tinto (Spain), Shasta King (California, USA), Lockwood (Washington, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: One or more lenses of massive pyrite, sphalerite, galena and chalcopyrite commonly within felsic volcanic rocks in a calcalkaline bimodal arc succession. The lenses may be zoned, with a Cu-rich base and a Pb-Zn-rich top; low-grade stockwork zones commonly underlie lenses and barite or chert layers may overlie them.

TECTONIC SETTING: Island arc; typically in a local extensional setting or rift environment within, or perhaps behind, an oceanic or continental margin arc.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Marine volcanism; commonly during a period of more felsic volcanism in an andesite (or basalt) dominated succession; locally associated with fine-grained marine sediments; also associated with faults or prominent fractures.

AGE OF MINERALIZATION: Any age. In British Columbia typically Devonian; less commonly Permian-Mississippian, Late Triassic, Early (and Middle) Jurassic, and Cretaceous.

HOST/ASSOCIATED ROCK TYPES: Submarine volcanic arc rocks: rhyolite, dacite associated with andesite or basalt; less commonly, in mafic alkaline arc successions; associated epiclastic deposits and minor shale or sandstone; commonly in close proximity to felsic intrusive rocks. Ore horizon grades laterally and vertically into thin chert or sediment layers called informally “exhalites”.

DEPOSIT FORM: Concordant massive to banded sulphide lens which is typically metres to tens of metres thick and tens to hundreds of metres in horizontal dimension; sometimes there is a peripheral apron of "clastic" massive sulphides; underlying crosscutting “stringer” zone of intense alteration and stockwork veining.

TEXTURE/STRUCTURE: Massive to well layered sulphides, typically zoned vertically and laterally; sulphides with a quartz, chert or barite gangue (more common near top of deposit); disseminated, stockwork and vein sulphides (footwall).

Höy, T. (1995): Noranda/Kuroko Massive Sulphide Cu-Pb-Zn; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 53-54.

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

NORANDA/KUROKO MASSIVE SULPHIDE Cu-Pb-Zn G06

ORE MINERALOGY (Principal and *subordinate*): Upper massive zone: pyrite, sphalerite, galena, chalcopyrite, *pyrrhotite, tetrahedrite-tennantite, bornite, arsenopyrite*. Lower massive zone: pyrite, chalcopyrite, *sphalerite, pyrrhotite, magnetite*.

GANGUE MINERALOGY: Barite, chert, *gypsum, anhydrite and carbonate* near top of lens, carbonate quartz, chlorite and sericite near the base.

ALTERATION MINERALOGY: Footwall alteration pipes are commonly zoned from the core with quartz, sericite or chlorite to an outer zone of clay minerals, albite and carbonate (siderite or ankerite).

ORE CONTROLS: More felsic component of mafic to intermediate volcanic arc succession; near centre of felsic volcanism (marked by coarse pyroclastic breccias or felsic dome); extensional faults.

ASSOCIATED DEPOSIT TYPES: Stockwork Cu deposits; vein Cu, Pb, Zn, Ag, Au.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Zn, Hg and Mg halos, K addition and Na and Ca depletion of footwall rocks; closer proximity to deposit - Cu, Ag, As, Pb; within deposit - Cu, Zn, Pb, Ba, As, Ag, Au, Se, Sn, Bi, As.

GEOPHYSICAL SIGNATURE: Sulphide lenses usually show either an electromagnetic or induced polarization signature depending on the style of mineralization and presence of conductive sulphides. In recent years borehole electromagnetic methods have proven successful.

OTHER EXPLORATION GUIDES: Explosive felsic volcanics, volcanic centres, extensional faults, exhalite (chert) horizons, pyritic horizons.

ECONOMIC FACTORS

GRADE AND TONNAGE: Average deposit size is 1.5 Mt containing 1.3% Cu, 1.9 % Pb, 2.0 % Zn, 0.16 g/t Au and 13 g/T Ag (Cox and Singer, 1986). British Columbia deposits range from less than 1 to 2 Mt to more than 10 Mt. The largest are the H-W (10.1 Mt with 2.0 % Cu, 3.5 % Zn, 0.3 % Pb, 30.4 g/t Ag and 2.1 g/t Au) and Kutcho (combined tonnage of 17 Mt, 1.6 % Cu, 2.3 % Zn, 0.06 % Pb, 29 g/t Ag and 0.3 g/t Au).

IMPORTANCE: Noranda/Kuroko massive sulphide deposits are major producers of Cu, Zn, Ag, Au and Pb in Canada. Their high grade and commonly high precious metal content continue to make them attractive exploration targets.

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NORANDA/KUROKO MASSIVE SULPHIDE Cu-Pb-Zn G06

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DRAFT #: 1 February 5, 1995

SUBAQUEOUS HOT SPRING Au-Ag G07

by Dani J. Alldrick[1]

IDENTIFICATION

SYNONYMS: Epithermal massive sulphide; subaqueous-hydrothermal deposits; Eskay-type deposit; Osorezan-type deposit.

COMMODITIES (*BYPRODUCTS*): Ag, Au (*Cu, Pb, Zn, As, Sb, Hg*).

EXAMPLES (British Columbia - *Canada/International*): Eskay Creek (104B008), Lulu (104B376); *Osorezan, Vulcano Islands and Jade hydrothermal field (Japan), Mendeleev Volcano (Kurile Islands, Russia), Rabaul (Papua New Guinea), White Island (New Zealand), Bacon-Manito and Surigao del Norte (Phillippines).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Vein, replacement and synsedimentary bedded sulphides are deposited in volcanic rocks and associated sediments in areas of shallow lacustrine, fluvial or marine waters or in glacial subfloors.

TECTONIC SETTING: Active volcanic arcs (both oceanic island arcs and continental margin arcs) are likely setting.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: 1) Water-filled reservoirs in active continental volcanic areas (crater lakes, playa lakes, stream flood plains, glacier subfloors). 2) Sea-flooded, breached calderas, or unconsolidated shallow marine sediments at the foot of a volcano.

AGE OF MINERALIZATION: Presumably any age, oldest known example is Jurassic.

HOST/ASSOCIATED ROCK TYPES: Mineralization hosted by intermediate to felsic flows and tuffs and minor intercalated sedimentary rocks. Pillow lavas, coarse epiclastic debris flows, and assorted subvolcanic feeder dikes are all part of the local stratigraphic package.

DEPOSIT FORM: Highly variable. Footwall stockwork or stringer-style vein networks. Large, textureless massive sulphide pods, finely laminated stratiform sulphide layers and lenses, reworked clastic sulphide sedimentary beds, and epithermal-style breccia veins with large vugs, coarse sulphides and chalcedonic silica. All types may coexist in a single deposit.

TEXTURE/STRUCTURE: Range from fine clastic sulphides and "framboid"-like chemical precipitates to very coarse grained sulphide aggregates in breccia veins. Structural styles include: vein stockworks, major breccia veins, stratabound and stratiform sulphide lenses and layers.

Alldrick, D.J. (1995): Subaqueous Hot Spring Au-Ag; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 55-57.

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

SUBAQUEOUS HOT SPRING Au-Ag G07

ORE MINERALOGY (Principal and *subordinate*): Sphalerite, tetrahedrite, boulangerite, bournonite, native gold, native silver, amalgam, galena, chalcopyrite, enargite, pyrite, stibnite, realgar, arsenopyrite orpiment; *metallic arsenic, Hg-wurtzite, cinnabar, aktashite, unnamed Ag-Pb-As-S minerals, jordanite, wurtzite, krennerite, coloradoite, marcasite, magnetite, scorodite, jarosite, limonite, anglesite, native sulphur*.

GANGUE MINERALOGY (Principal and *subordinate*): Magnesian chlorite, muscovite (sericite), chalcedonic silica, amorphous silica, calcite, dolomite, pyrobitumen, gypsum, barite, potassium feldspar, alunite with minor *carbon, graphite, halite and cristobalite.*

ALTERATION MINERALOGY: Massive chlorite (clinochlore)-illite-quartz-gypsum-barite rock or quartz-muscovite-pyrite rock are associated with the near-footwall stockwork zones. Chlorite and pyrite alteration is associated with the deep-footwall stockwork zones where alteration minerals are restricted to fractures. Stratabound mineralization is accompanied by magnesian chlorite, muscovite, chalcedonic silica, calcite, dolomite and pyrobitumen. At the Osorezan hot spring deposits, pervasive silica and alunite microveinlets are the dominant alteration phases.

GENETIC MODEL: Deposits are formed by "hot spring" (i.e.: epithermal) fluids vented into a shallow water environment. Fluids are magmatic in character, rather than meteoric. This concept contrasts with some characteristics of the process model for volcanogenic massive sulphides. Lateral and vertical zoning has been recognized within a single lens. Lateral zoning shows changes from Sb, As and Hg-rich mineral suites to Zn, Pb and Cu-rich assemblages. Vertical zoning is expressed as a systematic increase in Au, Ag and base metal content up-section. Fluid conduits are fissures generated by seismic shock, aggradation of the volcano over a later expanding magma chamber, or fracturing in response to regional compressional tectonics. A near-surface subvolcanic magma body is an essential source of metals, fluids and heat.

ASSOCIATED DEPOSIT TYPES: Hot spring Hg (H02), hot spring Au-Ag (H03), epithermal veins (H04, H05), volcanogenic exhalative massive sulphides (G06).

COMMENTS: This deposit type is the shallow subaqueous analogue of hot spring Au-Ag, and both of these are subtypes of the "epithermal" class of mineral deposits. Considering the recent discoveries at Osorezan (1987) and Eskay Creek (1988), the brief discussion by Laznicka (1985, p. 907) seems especially prophetic.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ag, Au, Cu, Pb, Zn, As, Sb, Hg.

GEOPHYSICAL SIGNATURE: The pyrite associated with stockwork mineralization and ubiquitous alteration should produce a widespread induced polarization anomaly, but the best targets may be local peaks within this broad anomalous 'plateau'. Airborne magnetometer surveys may help delineate favourable strata and fault offsets.

OTHER EXPLORATION GUIDES: The geological deposit model and its regional setting may be the best exploration tools available. Broad hydrothermal systems marked by widespread sericite-pyrite alteration; evidence of a volcanic crater or caldera setting; accumulations of felsic volcanic strata: 1) in a local subaqueous setting in a regionally subaerial environment, 2) along the near shore zone of a regional subaerial/subaqueous volcanic facies transition (e.g.: the western margin of the Hazelton trough). Focus on the sedimentary intervals within the volcanic pile.

ECONOMIC FACTORS

GRADE AND TONNAGE: These deposits are not well known. The Eskay Creek deposit is attractive because of the polymetallic signature and high precious metal contents. It contains an estimated mining reserve of 1.08 Mt grading 65.5 g/t Au, 2930 g/t Ag, 5.7 % Zn, 0.77 % Cu and 2.89% Pb with geological reserves of 4.3 Mt grading 28.8 g/t Au and 1 027 g/t Ag.

IMPORTANCE: These deposits are attractive because of their bonanza grades and polymetallic nature.

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TRAVERTINE H01

by Z.D. Hora[1]

IDENTIFICATION

SYNONYMS: Tufa, calcareous sinter; certain varieties also referred to as onyx marble or Mexican onyx.

COMMODITIES (*BYPRODUCTS*): Decorative stone, building stone products, soil conditioner, agriculture lime; *onyx marble*.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Clinton (O92P079), Slocan (82KSW074,075), Wishing Well (Deep River, 094N001); *Gardiner (Montana, USA), Salida (Colorado, USA), Bridgeport (California, USA); Lazio, Tuscany (Italy); Pamukkale (Turkey); Mexico, Spain, Iran.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Mounds, sheets, sometimes terraced, shallow lake in-fills, valley in-fill.

TECTONIC SETTING: Young orogenic belts with carbonate sediments in the subsurface; thrusts and faults with deep water circulation. Also intercontinental rift zones with strike-slip faulting, with or without associated volcanic activity.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Subaerial precipitation of calcium carbonate from mineral springs; also in shallow lacustrine basins with influx of mineralized CO_2-rich water. Hotspring waters which give rise to travertine deposits usually do not originate at temperatures in excess of 100°C. Circulating ground waters are channeled by thrusts, faults and fractured rocks and mineralized by dissolution of subsurface carbonate rocks.

AGE OF MINERALIZATION: Tertiary to recent.

HOST/ASSOCIATED ROCK TYPES: Carbonate rocks in the subsurface; hydrothermal breccia and siliceous sinters, lacustrine sediments, carbonate veins (usually aragonite) in form of “Mexican onyx”.

DEPOSIT FORM: Conical mounds, sheets, basin in-fills. As it is deposited by precipitation from warm spring waters, it shows successive layers with sometimes different colours and textures. May be elongated above underlying feeder zones following faults and breccia zones.

TEXTURE: Banded, porous, brecciated; may be pisolitic. Generally fine-grained carbonate matrix with numerous irregular cavities ranging in size from a pin head to 1 cm or more across. The cavities are usually oriented in lines giving the rock parallel texture. Lacustrine varieties are more massive. The mounds may be criss-crossed by veins of “Mexican onyx”, a varicoloured banded aragonite.

ORE MINERALOGY [Principal and *subordinate*]: Calcite, aragonite, *silica, fluorspar, barite, native sulphur*.

WEATHERING: Clay/iron stains filling the voids, joints and bedding planes.

Hora, Z.D. (1995): Travertine; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 29-30.

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

TRAVERTINE HO1

ORE CONTROLS: Commonly developed along high-angle faults and shear zones in young orogenic belts.

GENETIC MODEL: Travertine forms as surface deposits from geothermal systems of generally less than 100°C in temperature. The carbonate deposition results from the loss of some of the carbon dioxide by cooling, evaporation or presence of algae.

ASSOCIATED DEPOSIT TYPES: Hotsprings Au-Ag (H03), Hotspring Hg (H02), marl, solfatara sulphur, geyserite silica.

COMMENTS: To be economically of interest, the size must be suitable to open a quarry face, the carbonate must be recrystallized and cemented to be strong and hard for ornamental stone applications. Sediments of similar texture and composition may occur in karst regions, where the carbonate precipitated from cold water.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mineral springs with carbon dioxide.

OTHER EXPLORATION GUIDES: Precipitation of tufa from small streams on moss and other organic matter, presence of thermal spring and solfatara exhalations.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Large deposits may reach 1-2 Mt, but even the small deposits of several tens to a hundred thousand tonnes may be of importance for local and custom type work. The travertine has to meet the minimum physical test requirements for intended use.

END USES: Interior and exterior facing, tile, ashlar, custom-made shapes as steps and sills, lapidary work and precious stone applications.

ECONOMIC LIMITATIONS: Even small occurrences can be exploited for local and custom markets.

IMPORTANCE: Locally important facing stone, however the usage does not match marble or granite. Mexican onyx is an important decorative stone.

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HOT-SPRING Hg H02

by A. Panteleyev[1]

IDENTIFICATION

SYNONYMS: (Epithermal) hotspring, subaerial siliceous sinter.

COMMODITIES (*BYPRODUCTS*): Hg, (*Au*).

EXAMPLES (British Columbia - *Canada/International*): Ucluelet; *Knoxville district, Sulphur Bank (California, USA), McDermitt and Steamboat Springs (Nevada, USA), Abuta mine(Japan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Uppermost portions of epithermal systems develop clay altered zones and siliceous caps a few metres to hundreds of metres below surface and silica sinter deposits above the groundwater table as hotspring deposits. Travertine ledges and other silica-carbonate accumulations may be present nearby as peripheral or deeper deposits.

TECTONIC SETTING: Continental margin rifting and strike-slip faulting associated with small volume mafic to intermediate volcanism.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Modern and fossil hotspring settings with silica and silica-carbonate deposition near the paleo groundwater table and as subaerial silica sinter precipitates.

AGE OF MINERALIZATION: Tertiary and younger; some currently active hotsprings.

HOST/ASSOCIATED ROCK TYPES: Intermediate to basic volcanic flows, tuffs and breccias, minor diabasic dykes; hydrothermal breccias, travertine and siliceous sinters, lacustrine sediments. Country rocks commonly include greywacke, shale and fault-related serpentinized ultramafic bodies.

DEPOSIT FORM: Lensoid hotspring deposits and tabular lithologic replacement zones; commonly with cone- or wedge-like underlying feeder zones centered on regional-scale fault and fracture zones. Commonly less than 300 metres in vertical extent from paleosurface. Locally phreatic explosion pits.

TEXTURE: Disseminated sulphides in country rocks and hydrothermal breccias, quartz stockworks of banded to vuggy, multiple-generation quartz-chalcedony veins. Hydrofracturing textures are common. Less frequently cinnabar occurs as grains, lenses and fracture coatings in opaline silica sinter deposits. In some deposits cinnabar is concentrated on surfaces of wood and other organic matter.

ORE MINERALOGY [Principal and *subordinate*]: Cinnabar, pyrite, *native sulphur and mercury, stibnite, gold, marcasite.*

GANGUE MINERALOGY [Principal and *subordinate]:* Quartz, chalcedony; *opal, carbonate, iron oxides, manganese oxides.*

Panteleyev, A. (1996): Hot Spring Hg; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 31-32.

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

HOT-SPRING Hg H02

ALTERATION MINERALOGY [Principal and *subordinate]*: Kaolinite, alunite, Fe-Mn oxides and sulphur above water table (minor amounts of cinnabar). Opaline quartz deposited at the water table, with cinnabar. Quartz, pyrite, zeolites, chlorite and minor *adularia* below the water table; silica-carbonate ± magnesite assemblages in mafic, commonly serpentinized, rocks.

GENETIC MODEL: Deposits form in geothermal systems from near surface hot waters at less than 150°C, and generally cooler. Organic materials in solution and high CO_2 vapour concentration may be important in the transporting of elevated amounts of Hg.

ORE CONTROLS: Located just below the paleo groundwater table within hotspring systems. Commonly developed along high-angle faults and generally in young volcanic terranes.

ASSOCIATED DEPOSIT TYPES: Hotspring Au-Ag (H03), epithermal Au-Ag (H04, H05), placer Au (C01, C02).

COMMENTS: There has been little work in recent years on this deposit type other than to examine their potential for related gold deposits, for example, McLaughlin mine in California (Gustafson, 1991). The significant Hg deposits typically contain no other recoverable constituents.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Hg, Sb, As. Generally <5 ppb Au but rare deposits with elevated gold are known.

GEOPHYSICAL SIGNATURE: VLF to identify favourable structures; magnetic lows in mafic volcanic hosts due to alteration envelope.

OTHER EXPLORATION GUIDES: Can be overlain by native sulphur occurrences or hot spring deposits with siliceous sinters and clay-altered rocks. Recent deposits are commonly associated with modern hot springs or geothermal fields. Silica-carbonate alteration with distinctive orange-coloured, amorphous limonite in weathered zones, typically in mafic and serpentizized hostrocks.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Commercially exploited deposits tend to be very small; the largest deposits rarely exceed 1 mt in size. The median production from 20 Cordilleran USA mines is <1000 tonnes with 0.35% Hg. Typical mineable reserves contain ores ranging from 0.2 to 0.6% Hg. Productive deposits are Sulphur Bank and 5 small mines in the Knoxville District in California which produced 4, 700 tonnes of Hg and ~5,520 tonnes Hg respectively.

ECONOMIC LIMITATIONS: There probably is no operating mine of this type in the world today.

IMPORTANCE: These are relatively small deposits from near surface geological environments that are easily eroded and therefore rarely preserved. They currently are not important sources of mercury but can be associated with auriferous epithermal deposits.

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HOT-SPRING Au-Ag H03

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYMS: (Epithermal) hotspring, subaerial siliceous sinter.

COMMODITIES (BYPRODUCTS): Au, (Ag, Hg).

EXAMPLES (British Columbia (MINFILE #) - *Canada*/*International*): Cinola (uppermost part, 103F034), Clisbako (093C016), Wolf? (093F045), Trout? (093F044); *McLaughlin (California, USA), Round Mountain (Nevada, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Auriferous chalcedonic or opaline silica and fine-grained quartz form veins, stockworks and matrix filling in breccias hosted by volcanic and, less commonly, sedimentary rocks. These are the uppermost parts of epithermal systems which develop mineralized siliceous caps a few metres to hundreds of metres below surface with subaerial siliceous sinter deposits at the water table and explosion breccias above.

TECTONIC SETTINGS: Continental margin rifting and district-scale fracture systems with associated bimodal or low volume mafic to intermediate volcanism. Commonly in regions of strike-slip faulting with transform faults and transtensional basin margins. Also extensional tectonism with related caldera development and resurgence, flow-dome complexes and high-level subvolcanic intrusive activity.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Shallow parts of fossil geothermal systems. Hotsprings deposit silica near the paleo groundwater table and as subaerial, ponded precipitates. Deeper fluids are channeled by permeable stratigraphic units, hydrothermal breccia bodies and faulted/fractured rocks. Subaerial volcanic centres including flow-dome or caldera complexes and related radial and ring fracture systems.

AGE OF MINERALIZATION: Tertiary and Quaternary are most common; some currently active hotsprings. Hotspring sinters as old as Late Devonian have been described (Cunneen and Sillitoe, 1989).

HOST/ASSOCIATED ROCK TYPES: Intermediate or bimodal basaltic-rhyolitic volcanics including volcanic flows, flow domes, tuffs and breccias; hydrothermal breccias and siliceous sinters. Any type of permeable or structurally prepared country rock can be mineralized, most commonly ash flow units and caldera-fill sediments. In some cases, serpentinized ultramafic and mafic rocks in major fault zones in areas of post-faulting volcanic activity are mineralized. Sedimentary rocks occur at Cinola and many other deposits.

DEPOSIT FORM: Near-surface, lensoid hotspring deposits and planar lithologic replacement zones. Individual zones are up to hundreds of metres in two dimensions and tens of metres in the third. Underlying these are cone or wedge-like hydrothermal feeder systems with quartz stockworks and veins centred on regional-scale fault and fracture zones, or their splays. Locally phreatic and phreatomagmatic explosion pits formed at the paleosurface.

Panteleyev, A. (1996): Hot Spring Au-Ag; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 33-35.

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

HOT-SPRING Au-Ag H03

TEXTURE/STRUCTURE: Generally very fine grained disseminated sulphides in silicified (opalized and chalcedonic) country rocks and silica sinter; hydrothermal breccias, quartz stockworks and banded to vuggy, sheeted, multiple-generation quartz-chalcedony veins. Hydrofracturing textures are common.

ORE MINERALOGY [Principal and *subordinate*]: Pyrite, marcasite, gold, electrum; *stibnite, sulphosalt minerals, realgar, cinnabar (cinnibar only near tops of deposits).*

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, chalcedony; *opal, calcite, dolomite, barite.* Strong silicification with quartz, chalcedony and opal in crustified, banded veins, sheeted veins and stockworks is characteristic in ores. Silica in some deposits contains abundant hydrocarbons that impart a characteristic brownish colour to the quartz.

ALTERATION MINERALOGY [Principal and *subordinate*]: Multiple episodes of silicification to form veins and stockworks, and pervasive silicified hostrocks adjacent to them, is typical. Country rocks containing the silicified zones have argillic and, less commonly, advanced argillic assemblages with quartz-kaolinite and rarely *alunite*. They are flanked, or underlain, by propylitic rocks with chlorite, Fe oxides, zeolites and minor *adularia*. Selenite, alunite and other sulphate minerals and native sulphur can be abundant locally near surface.

WEATHERING: Limonite (jarosite, hematite, goethite) is locally prominent near surface in strongly oxidized deposits.

ORE CONTROLS: A key element at the McLaughlin deposit was the superposition of multiple generations of auriferous veinlets each carrying a small amount of gold (Lehrman, 1986).

GENETIC MODEL: Hydrothermal breccias and multiple generations of veins with calcite replacement by silica attest to boiling of hydrothermal fluids as an important ore-depositing mechanism. The boiling levels are related to the paleosurface and commonly have a surficial expression as active or paleo-hotsprings. The deeper hydrothermal fluid systems, generaly within 500 m of surface (paleosurface for older deposits), can be developed along active, regional high-angle faults and other volcanic and subvolcanic intrusion-related structures. The structures commonly cut or flank domes in flow-dome complexes.

ASSOCIATED DEPOSIT TYPES: Hotspring Hg (H02), solfatara sulphur; epithermal Au-Ag (H04, H05), placer Au (C01, C02).

COMMENTS: Many deposits currently being exploited throughout the world have grades between 1 and 2 g/t Au and range from a few to tens of millions of tonnes in size. They are viable generally because the rocks are commonly strongly oxidized and the gold can be recovered by heap leaching methods. The siliceous sinters formed at or very near to the surface rarely contain economic mineralization These deposits have a greater depth extent then hotspring mercury deposits. In their deeper parts they may grade into precious metal bearing and base metal epithermal veins.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, Sb, As, Hg, Tl near surface, increasing Ag, Ba at depth; locally Ni, B, Li and W. The Ag/Au ratio varies from 1:1 at surface to 30:1 at a depth of a few hundred metres. Mineralized rocks can be strongly leached at surface. Notably absent are: Se, Te, F, Mo, Sn and Mn. Base metal content is relatively low, for example, common amounts are Cu <60 ppm, Pb <5 ppm and Zn <450 ppm.

GEOPHYSICAL SIGNATURE: Resistivity, VLF to identify faults.

OTHER EXPLORATION GUIDES: Siliceous sinter can be used to identify the paleosurface; Hg mineralization may overlie deeper gold ores.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Mineralization tends to be low grade. Economically attractive bulk-mineable deposits contain >10 Mt of 1 to 2 g/t Au, or greater. High-grade veins and stockworks within the larger mineralized zones can be exploited by underground methods. The McLaughlin deposit, a superior discovery, contained initial reserves of 17.5 Mt with 5.2 g/t Au and about 16 g/t Ag, including a sheeted vein zone with 2.45 Mt with 9.15 g/t Au. Reserves for Cinola are about 31 Mt with 2.19 g/t Au; the deposit has a feeder zone at depth that contains material containing in excess of 100 g/t Au.

ECONOMIC LIMITATIONS: Refractory primary ore in deposits that lack significant oxidation renders many of the lower grade deposits uneconomic.

IMPORTANCE: Individual deposits are attractive economically, for example, the McLaughlin mine in California.

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EPITHERMAL Au-Ag-Cu: HIGH SULPHIDATION H04

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYMS: (Epithermal) acid-sulphate, quartz-alunite Au, alunite-kaolinite ± pyrophyllite, advanced argillic, Nansatsu-type, enargite gold. The deposits are commonly referred to as *acid-sulphate* type after the chemistry of the hydrothermal fluids, *quartz-alunite* or *kaolinite-alunite* type after their alteration mineralogy, or *high-sulphidation* type in reference to the oxidation state of the acid fluids responsible for alteration and mineralization.

COMMODITIES (*BYPRODUCTS*): Au, Ag, Cu (*As, Sb*).

EXAMPLES (British Columbia (MINFILE #) - *International*): Mt. McIntosh/Hushamu (EXPO, 92L240), Taseko River deposits - Westpine (Empress) (92O033), Taylor-Windfall (92O028) and Battlement Creek (92O005); *Goldfield and Paradise Peak (Nevada, USA), Summitville (Colorado, USA); Nansatsu (Japan), El Indio (Chile); Temora (New South Wales, Australia), Pueblo Viejo (Dominica), Chinkuashih (Taiwan), Rodalquilar (Spain), Lepanto and Nalesbitan (Philippines).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Veins, vuggy breccias and sulphide replacements ranging from pods to massive lenses occur in volcanic sequences associated with high level hydrothermal systems marked by acid-leached, advanced argillic, siliceous alteration.

TECTONIC SETTING: Extensional and transtensional settings, commonly in volcano-plutonic continent-margin and oceanic arcs and back-arcs. In zones with high-level magmatic emplacements where stratovolcanoes and other volcanic edifices are constructed above plutons.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Subvolcanic to volcanic in calderas, flow-dome complexes, rarely maars and other volcanic structures; often associated with subvolcanic stocks and dikes, breccias. Postulated to overlie, and be genetically related to, porphyry copper systems in deeper mineralized intrusions that undelie the stratovolcanoes.

AGE OF MINERALIZATION: Tertiary to Quaternary; less commonly Mesozoic and rarely Paleozoic volcanic belts. The rare preservation of older deposits reflects rapid rates of erosion before burial of subaerial volcanoes in tectonically active arcs.

HOST/ASSOCIATED ROCK TYPES: Volcanic pyroclastic and flow rocks, commonly subaerial andesite to dacite and rhyodacite, and their subvolcanic intrusive equivalents. Permeable sedimentary intervolcanic units can be sites of mineralization.

DEPOSIT FORM: Veins and massive sulphide replacement pods and lenses, stockworks and breccias. Commonly irregular deposit shapes are determined by hostrock permeability and the geometry of ore-controlling structures. Multiple, crosscutting composite veins are common.

TEXTURE/STRUCTURE: Vuggy 'slaggy' silica derived as a residual product of acid leaching is characteristic. Drusy cavities, banded veins, hydrothermal breccias, massive wallrock replacements with fine-grained quartz.

Panteleyev, A. (1996): Epithermal Au-Ag-Cu: High Sulphidation; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 37-39.

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

EPITHERMAL Au-Ag-Cu: HIGH SULPHIDATION H04

ORE MINERALOGY (Principal and *subordinate*): pyrite, enargite/luzonite, chalcocite, covellite, bornite, gold, electrum; *chalcopyrite, sphalerite, tetrahedrite/tennantite, galena, marcasite, arsenopyrite, silver sulphosalts, tellurides including goldfieldite.* Two types of ore are commonly present: massive enargite-pyrite and/or quartz-alunite-gold.

GANGUE MINERALOGY (Principal and *subordinate*): Pyrite and quartz predominate. Barite may also occur; carbonate minerals are absent.

ALTERATION MINERALOGY (Principal and *subordinate)*: Quartz, kaolinite/dickite, alunite, barite, hematite; sericite/illite, amorphous clays and silica, pyrophyllite, andalusite, diaspore, corundum, tourmaline, *dumortierite, topaz, zunyite, jarosite, Al-P sulphates (hinsdalite, woodhouseite, crandalite, etc*.) and native sulphur. Advanced argillic alteration is characteristic and can be areally extensive and visually prominent. Quartz occurs as fine-grained replacements and, characteristically, as vuggy, residual silica in acid-leached rocks.

WEATHERING: Weathered rocks may contain abundant limonite (jarosite-goethite-hematite), generally in a groundmass of kaolinite and quartz. Fine-grained supergene alunite veins and nodules are common.

ORE CONTROLS: In volcanic edifices - caldera ring and radial fractures; fracture sets in resurgent domes and flow-dome complexes, hydrothermal breccia pipes and diatremes. Faults and breccias in and around intrusive centres. Permeable lithologies, in some cases with less permeable cappings of hydrothermally altered or other cap rocks. The deposits occur over considerable depths, ranging from high-temperature solfataras at paleosurface down into cupolas of intrusive bodies at depth.

GENETIC MODEL: Recent research, mainly in the southwest Pacific and Andes, has shown that these deposits form in subaerial volcanic complexes or composite island arc volcanoes above degassing magma chambers. The deposits can commonly be genetically related to high-level intrusions. Multiple stages of mineralization are common, presumably related to periodic tectonism with associated intrusive activity and magmatic hydrothermal fluid generation.

ASSOCIATED DEPOSIT TYPES: Porphyry Cu±Mo±Au deposits (L04), subvolcanic Cu-Ag-Au (As-Sb) (L01), epithermal Au-Ag deposits: low sulphidation type (H05), silica-clay-pyrophyllite deposits (Roseki deposits) (H09), hotspring Au-Ag (H03), placer Au deposits (C01,C02).

COMMENTS: High-sulphidation epithermal Au-Ag deposits are much less common in the Canadian Cordillera than low-sulphidation epithermal veins. However, they are the dominant type of epithermal deposit in the Andes.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, Cu, As dominate; also Ag, Zn, Pb, Sb, Mo, Bi, Sn, Te, W, B and Hg.

GEOPHYSICAL SIGNATURE: Magnetic lows in hydrothermally altered (acid-leached) rocks; gravity contrasts may mark boundaries of structural blocks.

OTHER EXPLORATION GUIDES: These deposits are found in second order structures adjacent to crustal-scale fault zones, both normal and strike-slip, as well as local structures associated with subvolcanic intrusions. The deposits tend to overlie and flank porphyry copper-gold deposits and underlie acid-leached siliceous, clay and alunite-bearing ‘lithocaps’.

EPITHERMAL Au-Ag-Cu: HIGH SULPHIDATION H04

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: There is wide variation in deposit types ranging from bulk-mineable, low-grade to selectively mined, high-grade deposits. Underground mines range in size from 2 to 25 Mt with grades from 178 g/t Au, 109 g/t Ag and 3.87% Cu in direct smelting ores (El Indio) to 2.8 g/t Au and 11.3 g/t Ag and 1.8% Cu (Lepanto). Open pit mines with reserves of <100 Mt to >200 Mt range from Au-Ag mines with 3.8 g/t Au and 20 g/t Ag (Pueblo Viejo, Dominica) to orebodies such as the Nansatsu deposits, Japan that contain a few million tonnes ore grading between 3 and 6 g/t Au. Porphyry Au (Cu) deposits can be overprinted with late-stage acid sulphate alteration zones which can contain in the order of ~1.5 g/t Au with 0.05 to 0.1% Cu in stockworks (Marte and Lobo) or high-grade Cu-Ag-Au veins (La Grande veins, Collahausi). More typically these late stage alteration zones carry <0.4 to 0.9 g/t Au and >0.4 to 2% Cu (Butte, Montana; Dizon, Philippines).

ECONOMIC LIMITATIONS: Oxidation of primary ores is commonly neccessary for desireable metallurgy; primary ores may be refractory and can render low-grade mineralization noneconomic.

IMPORTANCE: This class of deposits has recently become a focus for exploration throughout the circum-Pacific region because of the very attractive Au and Cu grades in some deposits. Silica-rich gold ores (3-4 g/t Au) from the Nansatsu deposits in Japan are used as flux in copper smelters.

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EPITHERMAL Au-Ag: LOW SULPHIDATION H05

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYMS: (Epithermal) adularia-sericite; quartz-adularia, Comstock, Sado-type; bonanza Au-Ag; alkali chloride (hydrothermal).

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

EXAMPLES (British Columbia (MINFILE #) - *International*): Toodoggone district deposits - Lawyers (94E066), Baker (94E026), Shas (94E050); Blackdome (92O050-053); Premier Gold (Silbak Premier), (104B054); Cinola (103F034); *Comstock, Aurora (Nevada, USA), Bodie (California, USA), Creede (Colorado, USA), Republic (Washington, USA), El Bronce (Chile), Guanajuato (Mexico), Sado, Hishikari (Japan), Colqui (Peru), Baguio (Philippines) Ladolam (Lihir, Papua-New Guinea).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Quartz veins, stockworks and breccias carrying gold, silver, electrum, argentite and pyrite with lesser and variable amounts of sphalerite, chalcopyrite, galena, rare tetrahedrite and sulphosalt minerals form in high-level (epizonal) to near-surface environments. The ore commonly exhibits open-space filling textures and is associated with volcanic-related hydrothermal to geothermal systems.

TECTONIC SETTING: Volcanic island and continent-margin magmatic arcs and continental volcanic fields with extensional structures.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level hydrothermal systems from depths of ~1 km to surficial hotspring settings. Regional-scale fracture systems related to grabens, (resurgent) calderas, flow-dome complexes and rarely, maar diatremes. Extensional structures in volcanic fields (normal faults, fault splays, ladder veins and cymoid loops, etc.) are common; locally graben or caldera-fill clastic rocks are present. High-level (subvolcanic) stocks and/or dikes and pebble breccia diatremes occur in some areas. Locally resurgent or domal structures are related to underlying intrusive bodies.

AGE OF MINERALIZATION: Any age. Tertiary deposits are most abundant; in B.C. Jurassic deposits are important. Deposits of Paleozoic age are described in Australia. Closely related to the host volcanic rocks but invariably slightly younger in age (0.5 to 1 Ma, more or less).

HOST/ASSOCIATED ROCK TYPES: Most types of volcanic rocks; calcalkaline andesitic compositions predominate. Some deposits occur in areas with bimodal volcanism and extensive subaerial ashflow deposits. A less common association is with alkalic intrusive rocks and shoshonitic volcanics. Clastic and epiclastic sediments in intra-volcanic basins and structural depressions.

Panteleyev, A. (1996): Epithermal Au-Ag: Low Sulphidation; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 41-43.

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EPITHERMAL Au-Ag: LOW SULPHIDATION H05

DEPOSIT FORM: Ore zones are typically localized in structures, but may occur in permeable lithologies. Upward-flaring ore zones centred on structurally controlled hydrothermal conduits are typical. Large (> 1 m wide and hundreds of metres in strike length) to small veins and stockworks are common with lesser disseminations and replacements. Vein systems can be laterally extensive but ore shoots have relatively restricted vertical extent. High-grade ores are commonly found in dilational zones in faults at flexures, splays and in cymoid loops.

TEXTURE/STRUCTURE: Open-space filling, symmetrical and other layering, crustification, comb structure, colloform banding and multiple brecciation.

ORE MINERALOGY (Principal and *subordinate*): Pyrite, electrum, gold, silver, argentite; *chalcopyrite, sphalerite, galena, tetrahedrite, silver sulphosalt and/or selenide minerals.* Deposits can be strongly zoned along strike and vertically. Deposits are commonly zoned vertically over 250 to 350 m from a base metal poor, Au-Ag-rich top to a relatively Ag-rich base metal zone and an underlying base metal rich zone grading at depth into a sparse base metal, pyritic zone. From surface to depth, metal zones contain: Au-Ag-As-Sb-Hg, Au-Ag-Pb-Zn-Cu, Ag-Pb-Zn. In alkalic hostrocks tellurides, V mica (roscoelite) and fluorite may be abundant, with lesser *molybdenite*.

GANGUE MINERALOGY (Principal and *subordinate*): Quartz, amethyst, chalcedony, quartz pseudomorphs after calcite, calcite; *adularia, sericite, barite, fluorite, Ca-Mg-Mn-Fe carbonate minerals such as rhodochrosite, hematite and chlorite.*

ALTERATION MINERALOGY: Silicification is extensive in ores as multiple generations of quartz and chalcedony are commonly accompanied by adularia and calcite. Pervasive silicification in vein envelopes is flanked by sericite-illite-kaolinite assemblages. Intermediate argillic alteration [kaolinite-illite-montmorillonite (smectite)] formed adjacent to some veins; advanced argillic alteration (kaolinite-alunite) may form along the tops of mineralized zones. Propylitic alteration dominates at depth and peripherally.

WEATHERING: Weathered outcrops are often characterized by resistant quartz ± alunite 'ledges' and extensive flanking bleached, clay-altered zones with supergene alunite, jarosite and other limonite minerals.

ORE CONTROLS: In some districts the epithermal mineralization is tied to a specific metallogenetic event, either structural, magmatic, or both. The veins are emplaced within a restricted stratigraphic interval generally within 1 km of the paleosurface. Mineralization near surface takes place in hotspring systems, or the deeper underlying hydrothermal conduits. At greater depth it can be postulated to occur above, or peripheral to, porphyry and possibly skarn mineralization. Normal faults, margins of grabens, coarse clastic caldera moat-fill units, radial and ring dike fracture sets and both hydrothermal and tectonic breccias are all ore fluid channeling structures. Through-going, branching, bifurcating, anastamosing and intersecting fracture systems are commonly mineralized. Ore shoots form where dilational openings and cymoid loops develop, typically where the strike or dip of veins change. Hangingwall fractures in mineralized structures are particularly favourable for high-grade ore.

GENETIC MODEL: These deposits form in both subaerial, predominantly felsic, volcanic fields in extensional and strike-slip structural regimes and island arc or continental andesitic stratovolcanoes above active subduction zones. Near-surface hydrothermal systems, ranging from hotspring at surface to deeper, structurally and permeability focused fluid flow zones are the sites of mineralization. The ore fluids are relatively dilute and cool solutions that are mixtures of magmatic and meteoric fluids. Mineral deposition takes place as the solutions undergo cooling and degassing by fluid mixing, boiling and decompression.

ASSOCIATED DEPOSIT TYPES: Epithermal Au-Ag: high sulphidation (H04); hotspring Au-Ag (H03); porphyry Cu±Mo±Au (L04) and related polymetallic veins (I05); placer gold (C01, C02).

EPITHERMAL Au-Ag: LOW SULPHIDATION H05

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values in rocks of Au, Ag, Zn, Pb, Cu and As, Sb, Ba, F, Mn; locally Te, Se and Hg.

GEOPHYSICAL SIGNATURE: VLF has been used to trace structures; radiometric surveys may outline strong potassic alteration of wallrocks. Detailed gravity surveys may delineate boundaries of structural blocks with large density contrasts.

OTHER EXPLORATION GUIDES: Silver deposits generally have higher base metal contents than Au and Au-Ag deposits. Drilling feeder zones to hotsprings and siliceous sinters may lead to identification of buried deposits. Prospecting for mineralized siliceous and silica-carbonate float or vein material with diagnostic open-space textures is effective.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The following data describe the median deposits based on worldwide mines and U.S.A. models:

- Au-Ag deposits (41 Comstock-type 'bonanza' deposits) - 0.77 Mt with 7.5 g/t Au, 110 g/t Ag and minor Cu, Zn and Pb. The highest base metal contents in the top decile of deposits all contain <0.1% Cu, Zn and 0.1% Pb
- Au-Cu deposits (20 Sado-type deposits) - 0.3 Mt with 1.3% g/t Au, 38 g/t Ag and >0.3% Cu; 10 % of the deposits contain, on average, about 0.75% Cu with one having >3.2% Cu.

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Sn-Ag VEINS H07

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYMS: Polymetallic Sn veins, Bolivian polymetallic veins, polymetallic tin-silver deposits, polymetallic xenothermal.

COMMODITIES (*BYPRODUCTS*): Ag, Sn (*Zn, Cu, Au, Pb, Cd, In, Bi, W*).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): D zone (104P044, 080,081) and Lang Creek veins ('Pant', 104P082), Cassiar district; *Cerro Rico de Potosi, Oruro, Chocaya, (Bolivia), Pirquitas (Argentina), Ashio, Akenobe and Ikuno (Japan).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sulphide and quartz-sulphide veins carrying cassiterite, a wide variety of other base metals and zones with silver minerals. They are associated with epizonal (subvolcanic) quartz-bearing intrusions, or their immediate hostrocks. In some places the ore is in volcanic rocks within dacitic to quartz latitic flow-dome complexes.

TECTONIC SETTING: Continental margin; synorogenic to late orogenic belts with high-level plutonism in intermediate to felsic volcanoplutonic arcs. In British Columbia the only significant Sn-bearing deposits occur with S or A-type granites in eastern tectonic assemblages underlain by continental rocks of North American origin.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: In faults, shears and fractures that cut or are proximal to high-level felsic intrusions and in flow-dome complexes, namely domes and their surrounding tuff rings and explosive breccias.

AGE OF MINERALIZATION: Tertiary in the type area of Bolivia; Cretaceous and Tertiary in Japan; Tertiary and older in British Columbia.

HOST/ASSOCIATED ROCK TYPES: Hostrocks for veins can be of any type and do not appear to be an important control on the occurrence of the deposits; they include sedimentary, volcanic and intrusive rocks and sometimes, metasedimentary rocks at depth. Intrusive rocks with which the mineralization is associated are quartz bearing and peraluminous, but seem to be restricted to intermediate compositions between 60 and 70% SiO_2 (dacite to rhyodacite); more felsic rocks are present, but are less common.

DEPOSIT FORM: Veins, commonly with swarms of closely spaced, splaying smaller veins in sheeted zones. Veins vary in width from microveinlets to a few metres, and commonly are less than a metre wide. The ore shoots in veins are commonly 200-300 m along strike and dip but the veins may extend to more than 1000 m in depth and strike length. Vein systems and related stockworks cover areas up to a square kilometre along the tops of conical domes or intrusions 1-2 km wide.

TEXTURE/STRUCTURE: Multistage composite banded veins with abundant ore minerals pass at depth into crystalline quartz veins and upwards into vuggy quartz-bearing veins and stockworks.

Panteleyev, A. (1996): Sn-Ag Veins; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 45-47.

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

Sn-Ag VEINS H07

ORE MINERALOGY [Principal and *subordinate*]: Pyrite, cassiterite; *pyrrhotite, marcasite*; *sphalerite, galena, chalcopyrite, stannite, arsenopyrite, tetrahedrite, scheelite, wolframite, andorite, jamesonite, boulangerite, ruby silver (pyrargyrite), stibnite, bismuthinite, native bismuth, molybdenite, argentite, gold and complex sulphosalt minerals.* These deposits are characterized by their mineralogical complexity. There is no consistency between deposits in vertical or lateral zoning, but individual deposits are markedly spatially and temporally zoned. In some deposits, notably intrusion or dome-hosted examples, core zones are denoted by the high-temperature minerals cassiterite, wolframite, bismuthinite and arsenopyrite. Surrounding ores have varying amounts of stannite and chalcopyrite with, most significantly, sphalerite, galena and various Pb sulphosalt and Ag minerals. Silver in the upper parts of the vein systems occurs in argentite, ruby silver and native silver and at depth is mainly present in tetrahedrite.

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, sericite, pyrite; *tourmaline at depth, kaolinite and chalcedony near surface; rare barite, siderite, calcite, Mn carbonate and fluorite.*

ALTERATION MINERALOGY: Quartz-sericite-pyrite is characteristic; elsewhere quartz-sericite-chlorite occurs in envelopes on veins. Near-surface argillic and advanced argillic alteration overprinting is present in some deposits.

WEATHERING: Prominent limonite cappings are derived from the oxidation of pyrite.

ORE CONTROLS: Sets of closely spaced veins, commonly in sheeted zones, fractures and joints within and surrounding plutons are related to the emplacement and cooling of the host intrusions. The open space filling and shear-replacement veins are associated with stockworks, breccia veins and breccia pipes. A few deposits occur in faults, shears, fold axes and cleavage or fracture zones related to regional tectonism. Some early wallrock replacement along narrow fissures is generally followed and dominated by open-space filling in many deposits.

GENETIC MODEL: Dacitic magma and the metal-bearing hydrothermal solutions represent the uppermost products of large magmatic/hydrothermal systems. The Sn is probably a remobilized component of sialic rocks derived from recycled continental crust.

ASSOCIATED DEPOSIT TYPES: Polymetallic veins Ag-Pb-Zn (I05); epithermal Au-Ag: low sulphidation (H05), mantos (J01, J02), porphyry Sn (L06), placers (C01, C02). This deposit type grades with depth into Sn veins and greissens (I13) associated with mesozonal granitic intrusions into sediments. Cassiterite in colluvium can be recovered by placer mining. Mexican-type rhyolite Sn or "wood tin" deposits represent a separate class of deposit (Reed *et al*., 1986).

COMMENTS: Many Sn-bearing base metal vein systems are known to occur in eastern British Columbia, but there is poor documentation of whether the Sn is present as cassiterite or stannite. The former can be efficiently recovered by simple metallurgy, the latter cannot.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ag, Cu, Zn, Pb, Sn, W, As, Bi.

OTHER EXPLORATION GUIDES: The vein systems may display impressive vertical and horizontal continuity with marked metal zoning. Bolivian polymetallic vein deposits have formed at depths of 0.5 to 2 km below the paleosurface. Deeper veins of mainly massive sulphide minerals contain Sn, W and Bi; the shallower veins with quartz-barite and chalcedony-barite carry Ag and rarely Au. Metal zoning from depth to surface and from centres outward shows: Sn + W, Cu + Zn, Pb + Zn, Pb + Ag and Ag ± Au; commonly there is considerable 'telescoping' of zones. Oxidized zones may have secondary Ag minerals, such as Ag chlorides.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Considerable variation in metal contents of ores is evident between deposits. Potentially bulk-mineable bedrock deposits contain in the order of 0.2% Sn with 70-179 g/t Ag (Cerro Rico, Potosi, Bolivia).

ECONOMIC LIMITATIONS: These veins tend to be narrow.

IMPORTANCE: These veins are an important source of cassiterite for economic placer deposits around the world and the lodes have been mined in South America. They are currently attractive only when they carry appreciable Ag. In some deposits Au content is economically significant and Au-rich zones might have been overlooked during past work. Future Sn production from these veins will probably be as a byproduct commodity, and only if cassiterite is the main Sn mineral.

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ALKALIC INTRUSION-ASSOCIATED Au-Ag
H08

by Tom G. Schroeter[1] and Robert Cameron[2]

IDENTIFICATION

SYNONYMS: Alkalic epithermal, Au-Ag-Te veins.

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

EXAMPLES (British Columbia - *Canada/International*): Flathead (082GSE070), Howell (082GSE037), Howe (082GSE048); *Cripple Creek (Colorado, USA), Zartman, Landusky, Golden Sunlight (Montana, USA), Golden Reward (South Dakota, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: These deposits include quartz veins with pyrite, sphalerite and galena in structural zones and stockworks within alkalic intrusions and/or disseminated pyritic zones in alkalic intrusions, diatremes, coeval volcanics (Cripple Creek) and surrounding sediments. Argillic alteration, +/- silicification, carbonatization, and barite and fluorite veins are common.

TECTONIC SETTINGS: Associated with alkalic intrusive rocks in sedimentary cover rocks above continental crust, generally associated with extensional faulting. Tertiary examples in the USA are related to continental rifting; Rio Grande rift for Cripple Creek, Great Falls tectonic zone for the Montana deposits. Flathead area of British Columbia is in a continental setting but the extensional component is not as apparent.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Diatreme-intrusive complexes, high-level alkalic plugs, and dikes that intrude Proterozoic to Mesozoic continental clastic and carbonate rocks. Cripple Creek is within a large maar diatreme complex. Flathead intrusions are coeval with chemically similar volcanic rocks, the Crowsnest volcanics, in southern Alberta.

AGE OF MINERALIZATION: Any age; Flathead intrusions are early Cretaceous (98.5 Ma)

HOST/ASSOCIATED ROCK TYPES: (Flathead area): Intrusions include alkali feldspar syenite, foid-bearing syenite (nepheline, leucite, nosean, analcite), mela-syenite and related diatreme breccias with 10 % to 100 % intrusive component. Textures include coarse porphyritic sanidine, micro-syenite, tinguaite. Host sedimentary rocks include clastic rocks, shales and argillites to sandstones, and impure fine-grained carbonaceoous limestone and massive calcarenitic limestone. Gold may be present in all rock types.

Schroeter, T.G. and Cameron, R. (1996): Alkalic Intrusion-associated Au-Ag; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 49-51.

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ALKALIC INTRUSION-ASSOCIATED Au-Ag
H08

DEPOSIT FORM: Deposits may be in the form of sheeted veins in structural zones within intrusions (*e.g*, Zortman, Cripple Creek) with dimensions of 50 m to 100 m in width and hundreds of metres in length to, less commonly, large disseminated, diffuse zones within diatremes (*e.g*., Montana Tunnels, Cripple Creek), volcanic rocks (*e.g*., Cripple Creek) or stratabound within favourable sedimentary lithologies.

TEXTURE/STRUCTURE: Ore minerals in quartz and quartz-adularia veins, vein stockworks, disseminated zones and minor breccias.

ORE MINERALOGY (Principal and *subordinate*): Fine-grained (auriferous, arsenical?) pyrite, galena, sphalerite, gold tellurides; *chalcopyrite, magnetite, gold, bismuth and tellurium minerals are suspected at Flathead from elevated geochemical values in samples (to 31 ppm Te, 356 ppm Bi).*

GAUNGE MINERALOGY (Principal and *subordinate*): Quartz, calcite; *adularia, barite, fluorite*.

ALTERATION MINERALOGY: Widespread pyrite and carbonate (calcite) alteration of intrusive rocks, silicic and argillic (illite, sericite, jarosite, *roscoelite*) alteration of wallrocks; also albite and adularia.

WEATHERING: Oxidation with limonite, jarosite, hydrozincite.

ORE CONTROLS: Mineralization is controlled by structural zones within or proximal to alkalic intrusions; also in permeable (*e.g*., sandstone) or chemically favourable units (impure carbonates or bedding contacts) in country rocks. Diatreme breccias are favourable permeable hosts for focused flow of volatiles.

ASSOCIATED DEPOSIT TYPES: Distal base metal mantos are indicated in the Flathead and South Dakota deposit areas. Possible link with porphyry Mo deposits; polymetallic (I05) veins.

COMMENTS: Some authors consider this deposit type to be a subset of the low-sulphidation epithermal suite of precious metal deposits. This deposit model relates to continental rift settings, but related deposit types are present in oceanic arc settings and include Emperor (Fiji), Porgera and Ladolam (Papua New Guinea) deposits. Similar British Columbia settings may include the Quesnel and Stikine Terrane alkalic volcanic belts which host the alkalic porphyry copper-gold deposits (LO3).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, Ag, As, Sb, Pb, Zn, F, Ba, V, Te, Bi

GEOPHYSICAL SIGNATURE: High chargeability (I.P.) will outline pyritic zones; magnetic surveys will outline magnetite-bearing zones.

ALKALIC INTRUSION-ASSOCIATED Au-Ag
H08

ECONOMIC FACTORS:

TYPICAL GRADE AND TONNAGE: Highly variable, from very low mineable grades (*e.g.*, 0.53 g/t Au at Zortman) to very high bonanza grades (*e.g.*, 126 g/t Au at the Cresson vug, Cripple Creek). Recovered gold from the Cripple Creek district totals in excess of 600 tonnes. Grades at Howell Creek include 58 m of 1.3 g/t Au in silicified limestone, with grab samples containing up to 184 g/t at Flathead. Tonnages and grades from a number of deposits include:

Cresson deposit, Cripple Creek	70 mt	0.99 g/t Au
Cripple Creek, historical prod'n (1891-1989)	41 mt	17.14 g/t Au
Golden Sunlight (Dec., 1994)	42.8 mt	1.9 g/t
Zortman (Dec., 1994)	55.7 mt	0.68 g/t Au
Montana Tunnels (Dec., 1994)	26.6 mt	0.61 g/T Au

IMPORTANCE: Although these deposits have not been mined in British Columbia, they remain a viable exploration target.

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Au-QUARTZ VEINS I01

by Chris Ash[1] and Dani Alldrick[1]

IDENTIFICATION

SYNONYMS: Mother Lode veins, greenstone gold, Archean lode gold, mesothermal gold-quartz veins, shear-hosted lode gold, low-sulphide gold-quartz veins, lode gold.

COMMODITIES (*BYPRODUCTS*): Au (Ag, Cu, Sb).

EXAMPLES (British Columbia (MINFILE #) - *Canada/ International*):

- Phanerozoic: Bralorne-Pioneer (092JNE001), Erickson (104P029), Taurus (104P012), Polaris-Taku (104K003), Mosquito Creek (093H010), Cariboo Gold Quartz (093H019), Midnight (082FSW119); *Carson Hill, Jackson-Plymouth, Mother Lode district; Empire Star and Idaho-Maryland, Grass Valley district (California, USA); Alaska-Juneau, Jualin, Kensington (Alaska, USA), Ural Mountains (Russia).*
- Archean: *Hollinger, Dome, McIntyre and Pamour, Timmins camp; Lake Shore, Kirkland Lake camp; Campbell, Madsen, Red Lake camp; Kerr-Addison, Larder Lake camp (Ontario, Canada), Lamaque and Sigma, Val d'Or camp (Quebec, Canada); Granny Smith, Kalgoorlie and Golden Mile (Western Australia); Kolar (Karnataka, India), Blanket-Vubachikwe (Zimbabwe, Africa).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold-bearing quartz veins and veinlets with minor sulphides crosscut a wide variety of hostrocks and are localized along major regional faults and related splays. The wallrock is typically altered to silica, pyrite and muscovite within a broader carbonate alteration halo.

TECTONIC SETTINGS:

- Phanerozoic: Contained in moderate to gently dipping fault/suture zones related to continental margin collisional tectonism. Suture zones are major crustal breaks which are characterized by dismembered ophiolitic remnants between diverse assemblages of island arcs, subduction complexes and continental-margin clastic wedges.
- Archean: Major transcrustal structural breaks within stable cratonic terranes. May represent remnant terrane collisional boundaries.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Veins form within fault and joint systems produced by regional compression or transpression (terrane collision), including major listric reverse faults, second and third-order splays. Gold is deposited at crustal levels within and near the brittle-ductile transition zone at depths of 6-12 km, pressures between 1 to 3 kilobars and temperatures from 200° to 400 ^{o}C. Deposits may have a vertical extent of up to 2 km, and lack pronounced zoning.

Ash, C. and Alldrick, D. (1996): Au-Quartz Veins; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 53-56.

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Au-QUARTZ VEINS I01

AGE OF MINERALIZATION: Mineralization is post-peak metamorphism (*i.e.* late syncollisional) with gold-quartz veins particularly abundant in the Late Archean and Mesozoic.

- Phanerozoic: In the North America Cordillera gold veins are post-Middle Jurassic and appear to form immediately after accretion of oceanic terranes to the continental margin. In British Columbia deposits are mainly Middle Jurassic (~ 165-170 Ma) and Late Cretaceous (~ 95 Ma). In the Mother Lode belt they are Middle Jurassic (~ 150 Ma) and those along the Juneau belt in Alaska are of Early Tertiary (~56-55 Ma).
- Archean: Ages of mineralization for Archean deposits are well constrained for both the Superior Province, Canadian Shield (~ 2.68 to 2.67 Ga) and the Yilgarn Province, Western Australia (~ 2.64 to 2.63 Ga).

HOST/ASSOCIATED ROCK TYPES: Lithologically highly varied, usually of greenschist metamorphic grade, ranging from virtually undeformed to totally schistose.

- Phanerozoic: Mafic volcanics, serpentinite, peridotite, dunite, gabbro, diorite, trondhjemite/plagiogranites, graywacke, argillite, chert, shale, limestone and quartzite, felsic and intermediate intrusions.
- Archean: Granite-greenstone belts - mafic, ultramafic (komaitiitic) and felsic volcanics, intermediate and felsic intrusive rocks, graywacke and shale.

DEPOSIT FORM: Tabular fissure veins in more competent host lithologies, veinlets and stringers forming stockworks in less competent lithologies. Typically occur as a system of en echelon veins on all scales. Lower grade bulk-tonnage styles of mineralization may develop in areas marginal to veins with gold associated with disseminated sulphides. May also be related to broad areas of fracturing with gold and sulphides associated with quartz veinlet networks.

TEXTURE/STRUCTURE: Veins usually have sharp contacts with wallrocks and exhibit a variety of textures, including massive, ribboned or banded and stockworks with anastamosing gashes and dilations. Textures may be modified or destroyed by subsequent deformation.

ORE MINERALOGY: [Principal and *subordinate*]: Native gold, pyrite, arsenopyrite, *galena, sphalerite, chalcopyrite, pyrrhotite, tellurides, scheelite, bismuth, cosalite, tetrahedrite, stibnite, molybdenite, gersdorffite (NiAsS), bismuthimite (Bi_2S_2), tetradymite (Bi_2Te_2S).*

GANGUE MINERALOGY: [Principal and *subordinate*]: Quartz, carbonates (ferroan-dolomite, ankerite ferroan-magnesite, calcite, siderite), *albite, mariposite (fuchsite), sericite, muscovite, chlorite, tourmaline, graphite.*

ALTERATION MINERALOGY: Silicification, pyritization and potassium metasomatism generally occur adjacent to veins (usually within a metre) within broader zones of carbonate alteration, with or without ferroan dolomite veinlets, extending up to tens of metres from the veins. Type of carbonate alteration reflects the ferromagnesian content of the primary host lithology; ultramafics rocks - talc, Fe-magnesite; mafic volcanic rocks - ankerite, chlorite; sediments - graphite and pyrite; felsic to intermediate intrusions - sericite, albite, calcite, siderite, pyrite. Quartz-carbonate altered rock (listwanite) and pyrite are often the most prominent alteration minerals in the wallrock. Fuchsite, sericite, tourmaline and scheelite are common where veins are associated with felsic to intermediate intrusions.

WEATHERING: Distinctive orange-brown limonite due to the oxidation of Fe-Mg carbonates cut by white veins and veinlets of quartz and ferroan dolomite. Distinctive green Cr-mica may also be present. Abundant quartz float in overburden.

ORE CONTROLS: Gold-quartz veins are found within zones of intense and pervasive carbonate alteration along second order or later faults marginal to transcrustal breaks. They are commonly closely associated with, late syncollisional, structurally controlled intermediate to felsic magmatism. Gold veins are more commonly economic where hosted by relatively large, competent units, such as intrusions or blocks of obducted oceanic crust. Veins are usually at a high angle to the primary collisional fault zone.

- Phanerozoic: Secondary structures at a high angle to relatively flat-lying to moderately dipping collisional suture zones.

- Archean:. Steep, transcrustal breaks; best deposits overall are in areas of greenstone.

ASSOCIATED DEPOSIT TYPES: Gold placers (C01, C02), sulphide manto Au (J04), silica veins (I07); iron formation Au (I04) in the Archean.

GENETIC MODEL: Gold quartz veins form in lithologically heterogeneous, deep transcrustal fault zones that develop in response to terrane collision. These faults act as conduits for CO_2-H_2O-rich (5-30 mol% CO_2), low salinity (<3 wt% NaCl) aqueous fluids, with high Au, Ag, As, (±Sb, Te, W, Mo) and low Cu, Pb, Zn metal contents. These fluids are believed to be tectonically or seismically driven by a cycle of pressure build-up that is released by failure and pressure reduction followed by sealing and repetition of the process (Sibson *et al.,* 1988). Gold is deposited at crustal levels within and near the brittle-ductile transition zone with deposition caused by sulphidation (the loss of H_2S due to pyrite deposition) primarily as a result of fluid-wallrock reactions, other significant factors may involve phase separation and fluid pressure reduction.

The origin of the mineralizing fluids remains controversial, with metamorphic, magmatic and mantle sources being suggested as possible candidates. Within an environment of tectonic crustal thickening in response to terrane collision, metamorphic devolitization or partial melting (anatexis) of either the lower crust or subducted slab may generate such fluids.

COMMENTS: These deposits may be a difficult deposit to evaluate due to "nugget effect", hence the adage, “Drill for structure, drift for grade”. These veins have also been mined in British Columbia as a source of silica for smelter flux.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Au, Ag, As, Sb, K, Li, Bi, W, Te and B ± (Cd, Cu, Pb, Zn and Hg) in rock and soil, Au in stream sediments.

GEOPHYSICAL SIGNATURE: Faults indicated by linear magnetic anomalies. Areas of alteration indicated by negative magnetic anomalies due to destruction of magnetite as a result of carbonate alteration.

OTHER EXPLORATION GUIDES: Placer gold or elevated gold in stream sediment samples is an excellent regional and property-scale guide to gold-quartz veins. Investigate broad 'deformation envelopes' adjacent to regional listric faults where associated with carbonate alteration. Alteration and structural analysis can be used to delineate prospective ground. Within carbonate alteration zones, gold is typically only in areas containing quartz, with or without sulphides. Serpentinite bodies, if present, can be used to delineate favourable regional structures. Largest concentrations of free gold are commonly at, or near, the intersection of quartz veins with serpentinized and carbonate-altered ultramafic rocks.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits average 30 000 t with grades of 16 g/t Au and 2.5 g/t Ag (Berger, 1986) and may be as large as 40 Mt. Many major producers in the Canadian Shield range from 1 to 6 Mt at grades of 7 g/t Au (Thorpe and Franklin, 1984). The largest gold-quartz vein deposit in British Columbia is the Bralorne-Pioneer which produced in excess of 117 800 kilograms of Au from ore with an average grade of 9.3 g/t.

ECONOMIC LIMITATIONS: These veins are usually less than 2m wide and therefore, only amenable to underground mining.

IMPORTANCE: These deposits are a major source of the world’s gold production and account for approximately a quarter of Canada’s output. They are the most prolific gold source after the ores of the Witwatersrand basin.

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INTRUSION-RELATED Au-PYRRHOTITE VEINS I02

by Dani J. Alldrick[1]

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IDENTIFICATION

SYNONYMS: Extension veins, transitional veins, contact aureole veins, “mesothermal veins”.

COMMODITIES (*BYPRODUCTS*): Au, Ag (*Cu*).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*]: Scottie Gold (104B034), Snip (104B250), Johnny Mountain (104B107), War Eagle (082FSW097), Le Roi (082FSW093), Centre Star (082FSW094); *Copper Rand, Portage, Merrill, Main, and Chib-Kayrand mines, Chibougamau, Quebec; Keating and Ohio-Keating mine, Elkhorn Mountains, Montana.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Parallel tabular to cymoid veins of massive sulphide and/or bull-quartz-carbonate with native gold, electrum and chalcopyrite are emplaced in a set of en echelon fractures around the periphery or within subvolcanic plutons. Many previous workers have called these mesothermal veins.

TECTONIC SETTINGS: Volcanic arcs in oceanic and continental margin settings. Older deposits are preserved in accreted arc terranes. Deposits in Archean greenstone belts perhaps formed in immature volcanic arc settings. Local setting is the extensional environment developed at moderate depths around sub-volcanic plutons.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The subvolcanic setting for these deposits is transitional between the setting for subvolcanic porphyry copper systems and for subvolcanic epithermal systems.

AGE OF MINERALIZATION: British Columbia examples are all Early Jurassic; those in Chibougamau camp are Archean.

HOST/ASSOCIATED ROCK TYPES: Hostrocks are andesitic to basaltic tuffs, turbidites or early intrusive phases around the periphery of phaneritic, locally porphyritic, felsic to intermediate stocks and batholiths.

DEPOSIT FORM: At various deposits the form has been described as: planar, en echelon vein sets, shear veins, cymoid veins, cymoid loops, sigmoidal veins, extension veins, tension gashes, ladder veins, and synthetic Reidel shear veins. Veins vary in width from centimetres to several metres and can be traced up to hundreds of metres.

Alldrick, D.J. (1996): Intrusion-related Au Pyrrhotite Veins; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 57-58.

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INTRUSION-RELATED Au-PYRRHOTITE VEINS I02

TEXTURE/STRUCTURE: Two dominant vein types may occur independently or together. Veins may be composed of (i) massive fine-grained pyrrhotite and/or pyrite, or (ii) massive bull quartz with minor calcite and minor to accessory disseminations, knots and crystal aggregates of sulphides. These two types of mineralization may grade into each other along a single vein or may occur in adjacent, but separate veins. Some veins have undergone ductile and brittle shearing that complicates textural and structural interpretations.

ORE MINERALOGY [Principal and *subordinate*]: Pyrrhotite, pyrite, chalcopyrite, native gold, electrum, sphalerite, galena, bornite, argentite, arsenopyrite, *magnetite, ilmenite, tetrahedrite, tennantite, molybdenite, cosalite, chalcocite, tellurobismuthite, hessite, volynskite, altaite, native bismuth, cubanite, vallerite.*

GANGUE MINERALOGY (Principal and *subordinate):* Quartz, calcite, ankerite, siderite, chlorite, *sericite, rhodochrosite, K-feldspar, biotite, albite.*

ALTERATION MINERALOGY: Regional chlorite alteration and proximal sericite alteration predominates; pyrite, silica, carbonate, rhodochrosite, biotite, epidote, K-feldspar, ankerite. Alteration occurs as narrow (4 cm) vein selvages and as moderate alteration haloes extending up to several metres into the country rock. At deeper structural levels, alteration envelopes are more extensive and may include skarn mineral assemblages with diopside, garnet, epidote, biotite, K-feldspar, plagioclase, amphibole and wollastonite.

ORE CONTROLS: Well defined faults and shears control the mineralization. Veins are peripheral to and spatially associated with porphyritic intrusive rocks which may host porphyry copper and/or molybdenum mineralization and copper-gold skarns.

GENETIC MODEL: Mineralization appears to be related to felsic to intermediate plutons that record syn to late volcanic arc magmatism. Deposits in British Columbia formed along the thermally controlled 'brittle-ductile transition envelope' that surrounds subvolcanic intrusions. Late magma movement caused local shear stress, and resultant en echelon vein sets opened and were filled by sulphides and gangue minerals precipitating from circulating hydrothermal fluids. Shearing may have superimposed foliation or brecciation onto these early-formed veins.

ASSOCIATED DEPOSIT TYPES: Typical deposits of a volcanic arc, especially those in the subvolcanic setting: porphyry Cu+/-Mo+/-Au (L04), skarns, epithermal veins and breccias (H04, H05), 'transitional' deposits (volcanogenic Cu-As-Sb-Au-Ag, L01) and surficial fumarolic hotspring (H03) and exhalative deposits.

COMMENTS: The genesis of these deposits remains controversial. Many have been interpreted as mesothermal veins; others, in deformed terrains, as exhalative massive sulphide deposits. Those in the Chibougamau camp have also been referred to as shear-hosted gold deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Au, Ag, Cu. (As, Zn).

GEOPHYSICAL SIGNATURE: Electromagnetic (ABEM and VLF-EM) anomalies and anomalous magnetometer lows (negative anomalies or 'magnetic troughs').

OTHER EXPLORATION GUIDES: Intense prospecting swath extending from 100 metres inside the intrusive contact to 1000 metres outside the intrusive contact of a prospective sub-volcanic pluton. Detailed soil geochemistry and detailed ground geophysics could be designed to investigate this same area. Small, 'hairline' mineralized fractures are good proximal indicators of a nearby major vein. Increased alteration intensity could also be a good proximal indicator, but this is a more subtle feature. Deposits are commonly located along shear zones. Once the vein orientation on an initial discovery is determined, additional parallel veins should be anticipated and investigated with fences of drill holes.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Gold/silver ratios are close to 1:1. Copper may also be recoverable. Typical grades are 10 to 20 g/t Au.

IMPORTANCE: The Snip gold mine is currently British Columbia's largest gold producer and the Rossland veins are the province's second largest gold camp. Two deposits in the Chibougamau camp, Copper Rand and Portage, are currently in production.

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TURBIDITE-HOSTED Au VEINS I03

by R.H. McMillan[1]

IDENTIFICATION

SYNONYMS: Saddle reefs, Bendigo-type.

COMMODITIES (*BYPRODUCTS*): Au (*Ag, W, Sb*).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Frasergold (093A150), Valentine Mountain (092B108), Island Mountain (093H019), Mosquito Creek (093H025), Sheep Creek Deposits - Reno (082FSW036), Queen (082FSW048), Kootenay Belle (082FSW044) and Gold Belt (082FSW040); *Ptarmigan, Burwash, Thompson-Ludmar and other Yellowknife district deposits (Northwest Territories, Canada), Meguma district (Nova Scotia, Canada), Bendigo and Ballarat (Victoria, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold-quartz veins, segregations, lodes and sheeted zones hosted by fractures, faults, folds and openings in anticlines, synclines and along bedding planes in turbidites and associated poorly sorted clastic sedimentary rocks.

TECTONIC SETTING: Hostrocks were deposited in submarine troughs, periarc basins, foreland basins and remnant ocean basins. The sediments were typically formed on continental margins or back-arc basins. Typically these sequences experienced one or two deformational phases with associated metamorphism.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Thick sediment sequences that have been deformed and metamorphosed; relatively few igneous rocks.

AGE OF MINERALIZATION: Archean to Tertiary; the Bendigo and Meguma districts are underlain by Early Paleozoic strata. The veins are generally considered to be related to later deformational event.

HOST/ ASSOCIATED ROCK TYPES: The predominant rock types are greywackes, siliceous wackes, shales and carbonaceous shales. Bedded cherts, iron formations, fine-grained impure carbonate rocks; minor polymictic conglomerate, tuffaceous members and minor marine volcanic flows may also be part of the stratigraphic sequence. There are younger granitic intrusions in many belts. Metamorphic grade is generally greenschist, but may reach amphibolite rank.

McMillan, R.H. (1996): Turbidite-hosted Au Veins; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 59-62.

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TURBIDITE-HOSTED Au VEINS I03

DEPOSIT FORM: Typically deposits are composed of multiple quartz veins up to a few metres in width that are commonly stratabound (either concordant or discordant), bedding-parallel, or discordant, and parallel to fold axial planes. Veins are variably deformed and occur as single strands, as sheeted arrays or as stockworks. Bedding-parallel veins within anticlines and synclines in the Bendigo-Ballarat and Meguma districts are commonly called saddle reefs or saddle troughs.

TEXTURE/STRUCTURE: Veins are well defined with sharp contacts. Bedding veins can be massive or laminated (ribbon texture) with columnar structures or stylolites, while discordant veins are generally massive. Veins can be associated with a variety of structures. Most common are folded veins and saddle reefs related to anticlinal folds. Sheeted, en echelon sigmoidal veins, ladder veins, tension gashes or stockworks may be related to zones of extension or to Reidel shear structures.

ORE MINERALOGY (Principal and *subordinate*): Native gold, pyrite, arsenopyrite, *pyrrhotite, chalcopyrite, sphalerite, galena, molybdenite, bismuth, stibnite, bournonite and other sulphosalt minerals.* Low sulphide content (<2.5%).

GANGUE MINERALOGY (Principal and *subordinate):* Quartz, carbonates (calcite, dolomite or ankerite), *feldspar (albite) and chlorite.*

ALTERATION: Generally not prominent, however, disseminated arsenopyrite, pyrite and tourmaline, and more pervasive silica, sericite and carbonate, may develop in wallrocks adjacent to veins.

WEATHERING: In unglaciated terrains deep weathering and alluvial recycling may produce related rich placer deposits, such as the Bendigo region.

ORE CONTROLS: A strong structural control within dilatent areas in fold crests (saddle and trough reefs), discordant veins and tension gashes. This structural control may extend to district scale alignment of deposits. In some districts the veins appear confined to a specific stratigraphic interval, often near a change in lithologies. In the Meguma district, a more subtle stratigraphic control related to the upper (pelitic) portions of individual bouma cycles as well as regionally to the upper portion of the turbidite section. In the Bendigo district there is a relationship between ore and an abundance of graphite in the adjacent wallrocks.

GENETIC MODEL: Genetic theories range from veins formed by magmatic hydrothermal fluids or metamorphogenic fluids to deformed syngenetic mineralization. Most current workers prefer the metamorphogenic-deformational or lateral secretion theories and interpret the laminations as “crack-seal” phenomena formed during episodic re-opening of the veins during their formation. Workers favoring a syngenetic origin interpret the laminations as primary layering. Structural relationships in the Meguma and Bendigo districts indicate that the veins formed contemporaneously with, or prior to the major deformational event and were metamorphically overprinted during the intrusion of Devonian batholithic granitic rocks. Late post-deformational tension veinlets are generally non-auriferous.

ASSOCIATED DEPOSIT TYPES: Placers (C01), iron formation hosted gold deposits (I04) are also mainly hosted in turbidites - some of the Northwest Territories turbidite-hosted deposits are associated with chemical sediments. In several camps, slate horizons carrying finely disseminated, very low grade gold have been reported.

TURBIDITE-HOSTED Au VEINS I03

COMMENTS: Although past classification schemes have not recognized this type of deposit in British Columbia, the Valentine Mountain deposit hosted in Leech River schists and Frasergold hosted in Late Triassic clastic Quesnel River Group can be included. Elsewhere, several important vein gold districts in clastic sedimentary (possibly turbiditic) rocks might also be included. For example, the Sheep Creek camp and some of the Barkerville deposits are hosted in siliceous wackes and phyllites.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Si, Fe, S, As, B, Au and Ag generally show strong enrichment in the deposits, while Cu, Mg, Ca, Zn, Cd, Pb, Sb, W and Mn generally show moderate enrichment, and Hg, In, Li, Bi, Se, Te, Mo, F, Co and Ni may show low levels of enrichment.

GEOPHYSICAL SIGNATURE: The low sulphide content of the majority of quartz veins renders most geophysical techniques ineffective as direct exploration tools. However, airborne and ground electromagnetic and magnetic surveys and induced polarization surveys can be useful where deposits show an association with iron formation, massive sulphides or graphite.

OTHER EXPLORATION GUIDES: Standard prospecting techniques to trace mineralization directly or in float trains in glacial till, talus or other debris derived from the gold mineralization remains the most effective prospecting tool. Areas where there has been past gold production from placers are good candidates for prospecting.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Gold production from the Meguma region has come from 60 deposits at grades ranging from 8 to 50 g/t - a total of 35.13 tonnes has been produced from the district. The Bendigo field is much more significant, having produced a minimum of more than 373.3 t (12 M.oz.) of non-alluvial gold from more than 40 Mt of ore since 1851 - grades ranged from a minimum of approximately 5 g/t to more than 30 g/t. The three Barkerville mines produced an aggregate of 2.75 Mt to yield 38.29 t of gold between 1933 and 1987.

ECONOMIC LIMITATIONS: Deposits such as those in the Bendigo and Barkerville districts constitute attractive exploration targets. Although the hand sorting required to recover gold from the Nova Scotia deposits would probably render them uneconomic today, new techniques such as photometric sorting might improve the economics.

IMPORTANCE: Some districts/deposits, such as Bendigo, rank as world class and remain attractive exploration targets. The limited information available about the immense Muruntau deposit suggest that it may be similar to this type.

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IRON FORMATION-HOSTED Au[1] I04

by R.H. McMillan[2]

IDENTIFICATION

SYNONYM: Mesothermal veins.

COMMODITIES *(BYPRODUCTS)*: Au (*Ag, Cu).*

EXAMPLES (British Columbia - *Canada/International*): No B.C. examples; *Lupin and Cullaton Lake B-Zone (Northwest Territories, Canada), Detour Lake, Madsen Red Lake, Pickle Crow, Musselwhite, Dona Lake, (Ontario, Canada), Homestake (South Dakota, USA), Mt. Morgans (Western Australia); Morro Vehlo and Raposos, Mineas Gerais (Brazil); Vubachikwe and Bar 20 (Zimbabwe); Mallappakoda, Kolar District (India).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold in crosscutting quartz veins and veinlets or as fine disseminations associated with pyrite, pyrrhotite and arsenopyrite hosted in iron-formations and adjacent rocks within volcanic or sedimentary sequences. The iron-formations may vary between carbonate-oxide iron-formation and arsenical sulphide-silicate iron-formation.

TECTONIC SETTING: In “greenstone belts” believed to be ancient volcanic arcs; and in adjacent submarine troughs.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Sedimentary and submarine volcanic sequences in a range of mutually overlapping settings ranging from turbiditic clastic sedimentary environments to distal mafic (and komatiitic) environments with associated felsic tuffaceous and intrusive porphyries.

AGE OF MINERALIZATION: Archean to Proterozoic.

HOST/ ASSOCIATED ROCK TYPES: Contained mainly within various facies of Algoma-type iron-formation and cherts, although veins may extend into other units. Associated with variolitic, tholeiitic and komatiitic volcanic and clastic (commonly turbiditic) rocks, rarely felsic volcanic and intrusive rocks. Metamorphic rank ranges from lowest greenschist to upper amphibolite facies. Silicate-facies iron-formations are associated in some cases but are generally not gold-bearing.

McMillan, R.H. (1996): Iron Formation-hosted Au; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 63-66.

[1] This deposit type overlaps with and is gradational into gold-quartz veins (I01) and also the turbidite-hosted gold veins (I03). Some classifications group the three deposit types together as “mesothermal veins”.

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IRON FORMATION-HOSTED Au I04

DEPOSIT FORM: In and near crosscutting structures, such as quartz veins, or stratiform zones within chemical sedimentary rocks. Host strata have generally been folded and deformed to varying degree, consequently the deposits may have developed in axial plane cleavage area or be thickened and remobilized in fold hinges.

TEXTURE/STRUCTURE: Highly variable: gold mineralization may be finely disseminated in sulphide minerals in the stratiform examples or occur as the native mineral or in sulphides in crosscutting quartz veins. Sulphidization features such as pyrite overgrowths on magnetite are present in some deposits.

ORE MINERALOGY (Principal and *subordinate*): Native Au, pyrite, arsenopyrite, magnetite, pyrrhotite, *chalcopyrite, sphalerite, galena, stibnite, rarely gold tellurides.*

GANGUE MINERALOGY (Principal and *subordinate*): Vein quartz, chert, carbonates (calcite, dolomite or ankerite), *graphite, grunerite, stilpnomelane, tourmaline, feldspar (albite).*

ALTERATION: In deposits at low metamorphic rank, carbonatization (generally ankeritic or ferroan dolomite) is generally prominent. Sulphidization (pyritization, arsenopyritization and pyrrhotitization) is common in wallrocks adjacent to crosscutting quartz veins.

WEATHERING: Highly variable: sulphide-rich, carbonate-poor deposits will produce significant gossans.

ORE CONTROLS: Mineralization is within, or near, favourable iron-formations. Most deposits occur adjacent to prominent regional structural and stratigraphic “breaks” and mineralization is often related to local structures. Contacts between ultramafic (commonly komatiitic) rocks and tholeiitic basalts or sedimentary rocks are important. All known deposits occur in Precambrian sequences, however, there are some potentially favourable chemical sediment horizons in Paleozoic rocks. Pinch outs and facies changes within geologically favourable units are important loci for ore deposition.

GENETIC MODELS: One model proposed for iron formation-hosted Au is that the mineralization may form due to deformation focusing metamorphogenic or magmatic hydrothermal fluids, from depth, into a chemically and structurally (brittle-ductile transition zone) favourable depositional environment, late in the orogenic cycle. This theory is consistent with both the crosscutting relationships and radiometric dates for the gold mineralization. Another model emphasizes a syngenetic origin for the widespread anomalous gold values, similarity of the geological environments to currently active submarine exhalative systems, and the association with chemical sedimentary strata. Replacement features could be explained as normal diagenetic features and contact areas between sulphide-rich ore and carbonate wallrock as facies boundaries.

ASSOCIATED DEPOSIT TYPES: Au-quartz veins (I01), turbidite-hosted Au-quartz veins (I03), Algoma-type iron-formations (G01).

IRON FORMATION-HOSTED Au I04

COMMENTS: This type of deposit has not been documented in British Columbia. The closest analogy is the 900 zone on the Debbie property (092F331) which contains gold in magnetite-jasper-sulphide-bearing bedded chert, in quartz veins and in stockworks cutting ankeritic aphyric pillow basalt. Some workers consider auriferous stratiform pyrite bodies, such as Bousquet, Doyon, and Agnico Eagle in the Canadian Shield, to be closely related to iron formation-hosted Au.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Si, Fe, S, As, B, Mg, Ca, Au and Ag generally show strong enrichment in the deposits, while Cu, Zn, Cd, Pb and Mn generally show moderate enrichment.

GEOPHYSICAL SIGNATURE: Airborne and ground electromagnetic and magnetic surveys and induced polarization surveys can be very useful to detect and map the high sulphide and magnetite content of many of the deposits.

OTHER EXPLORATION GUIDES: Standard prospecting techniques to trace mineralization directly or in float trains in glacial till, talus or other debris derived from the gold mineralization remains the most effective prospecting tool. Areas with gold placers are potential targets. Exploration programs should focus on the primary depositional environment for stratiform deposits.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The more significant deposits fall in the ranges from 6 to 17 g/t Au and 1 to 5 Mt (Thorpe and Franklin, 1984). At the adjacent properties of Morro Velho and Raposos in Brazil, approximately 10 million ounces of gold have been produced at a grade of between 15 and 16 g/t since 1834. In Ontario, the Detour Lake mine contains a resource of 48 t Au and the Madsen Red Lake deposit produced 75 t, the Pickle Crow Deposits 45 tonnes and the Central Patricia 19 tonnes. At the Lupin mine 6.66 Mt of ore grading 10.63 g/t Au were produced between 1982 and the end of 1993 with remaining reserves of 5.1 Mt averaging 9.11 g/t.

ECONOMIC LIMITATIONS: The narrow veins in some deposits require selective mining techniques which are no longer highly profitable. On the other hand, deposits, such as Lupin, are sufficiently large to be mined very profitably utilizing modern mechanized equipment.

IMPORTANCE: Although attention in recent years has been focused on the large epithermal volcanic-hosted gold deposits of the circum-Pacific Belt and on Carlin-type deposits, iron-formation hosted gold deposits, such as Lupin, rank as world class and remain attractive exploration targets. For example, the Homestake mine has produced approximately 300 t of gold since starting production in 1876.

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POLYMETALLIC VEINS Ag-Pb-Zn±Au I05

by David Lefebure[1] and B.N. Church[1]

IDENTIFICATION

SYNONYMS: Clastic metasediment-hosted silver-lead-zinc veins, silver/base metal epithermal deposits.

COMMODITIES (BYPRODUCTS): Ag, Pb, Zn (Cu, Au, Mn).

EXAMPLES (British Columbia (MINFILE # - *Canada/International*):

- Metasediment host: Silvana (082FNW050) and Lucky Jim (082KSW023), Slocan-New Denver-Ainsworth district, St. Eugene (082GSW025), Silver Cup (082KNW027), Trout Lake camp; *Hector-Calumet and Elsa*, Mayo *district (Yukon, Canada), Coeur d'Alene district (Idaho, USA), Harz Mountains and Freiberg district (Germany), Příbram district (Czechoslavakia).*
- Igneous host: Wellington (082ESE072) and Highland Lass - Bell (082ESW030, 133), Beaverdell camp; Silver Queen (093L002), Duthie (093L088), Cronin (093L127), Porter-Idaho (103P089), Indian (104B031); *Sunnyside and Idorado, Silverton district and Creede (Colorado, USA), Pachuca (Mexico).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Sulphide-rich veins containing sphalerite, galena, silver and sulphosalt minerals in a carbonate and quartz gangue. These veins can be subdivided into those hosted by metasediments and another group hosted by volcanic or intrusive rocks. The latter type of mineralization is typically contemporaneous with emplacement of a nearby intrusion.

TECTONIC SETTINGS: These veins occur in virtually all tectonic settings except oceanic, including continental margins, island arcs, continental volcanics and cratonic sequences.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING:

- Metasediment host: Veins are emplaced along faults and fractures in sedimentary basins dominated by clastic rocks that have been deformed, metamorphosed and intruded by igneous rocks. Veins postdate deformation and metamorphism.
- Igneous host: Veins typically occur in country rock marginal to an intrusive stock. Typically veins crosscut volcanic sequences and follow volcano-tectonic structures, such as caldera ring-faults or radial faults. In some cases the veins cut older intrusions.

AGE OF MINERALIZATION: Proterozic or younger; mainly Cretaceous to Tertiary in British Columbia.

HOST/ASSOCIATED ROCK TYPES: These veins can occur in virtually any host. Most commonly the veins are hosted by thick sequences of clastic metasediments or by intermediate to felsic volcanic rocks. In many districts there are felsic to intermediate intrusive bodies and mafic igneous rocks are less common. Many veins are associated with dikes following the same structures.

DEPOSIT FORM: Typically steeply dipping, narrow, tabular or splayed veins. Commonly occur as sets of parallel and offset veins. Individual veins vary from centimetres up to more than 3 m wide and can be followed from a few hundred to more than 1000 m in length and depth. Veins may widen to tens of metres in stockwork zones.

Lefebure, D.V. and Church, B.N. (1996): Polymetallic Veins Ag-Pb-Zn±Au; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 67-70.

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POLYMETALLIC VEINS Ag-Pb-Zn±Au I05

TEXTURE/STRUCTURE: Compound veins with a complex paragenetic sequence are common. A wide variety of textures, including cockade texture, colloform banding and crustifications and locally druzy. Veins may grade into broad zones of stockwork or breccia. Coarse-grained sulphides as patches and pods, and fine-grained disseminations are confined to veins.

ORE MINERALOGY [Principal and *subordinate*]: Galena, sphalerite, tetrahedrite-tennantite, *other sulphosalts including pyrargyrite, stephanite, bournonite and acanthite, native silver, chalcopyrite, pyrite, arsenopyrite, stibnite*. Silver minerals often occur as inclusions in galena. *Native gold and electrum in some deposits.* Rhythmic compostional banding sometimes present in sphalerite. Some veins contain more chalcopyrite and gold at depth and Au grades are normally low for the amount of sulphides present.

GANGUE MINERALOGY [Principal and *subordinate*]:

- Metasediment host: Carbonates (most commonly siderite with minor dolomite, ankerite and calcite), quartz, *barite, fluorite, magnetite, bitumen*.
- Igneous host: Quartz, carbonate (rhodochrosite, siderite, calcite, dolomite), *sometimes specular hematite, hematite, barite, fluorite*. Carbonate species may correlate with distance from source of hydrothermal fluids with proximal calcium and magnesium-rich carbonates and distal iron and manganese-rich species.

ALTERATION MINERALOGY: Macroscopic wall rock alteration is typically limited in extent (measured in metres or less). The metasediments typically display sericitization, silicification and pyritization. Thin veining of siderite or ankerite may be locally developed adjacent to veins. In the Coeur d'Alene camp a broader zone of bleached sediments is common. In volcanic and intrusive hostrocks the alteration is argillic, sericitic or chloritic and may be quite extensive.

WEATHERING: Black manganese oxide stains, sometimes with whitish melanterite, are common weathering products of some veins. The supergene weathering zone associated with these veins has produced major quantities of manganese. Galena and sphalerite weather to secondary Pb and Zn carbonates and Pb sulphate. In some deposits supergene enrichment has produced native and horn silver.

ORE CONTROLS: Regional faults, fault sets and fractures are an important ore control; however, veins are typically associated with second order structures. In igneous rocks the faults may relate to volcanic centers. Significant deposits restricted to competent lithologies. Dikes are often emplaced along the same faults and in some camps are believed to be roughly contemporaneous with mineralization. Some polymetallic veins are found surrounding intrusions with porphyry deposits or prospects.

GENETIC MODELS: Historically these veins have been considered to result from differentiation of magma with the development of a volatile fluid phase that escaped along faults to form the veins. More recently researchers have preferred to invoke mixing of cooler, upper crustal hydrothermal or meteoric waters with rising fluids that could be metamorphic, groundwater heated by an intrusion or expelled directly from a differentiating magma. Any development of genetic models is complicated by the presence of other types of veins in many districts. For example, the Freiberg district has veins carrying F-Ba, Ni-As-Co-Bi-Ag and U.

COMMENTS: Ag-tetrahedrite veins, such as the Sunshine and Galena mines in Idaho, contain very little sphalerite or galena. These may belong to this class of deposits or possibly the five-element veins. The styles of alteration, mineralogy, grades and different geometries can usually be used to distinguish the polymetallic veins from stringer zones found below syngenetic massive sulphide deposits.

ASSOCIATED DEPOSIT TYPES:

- Metasediment host: Polymetallic mantos (M01).
- Igneous host: May occur peripheral to virtually all types of porphyry mineralization (L01, L03, L04, L05, L06, L07, L08) and some skarns (K02, K03).

POLYMETALLIC VEINS Ag-Pb-Zn±Au I05

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Zn, Pb, Ag, Mn, Cu, Ba and As. Veins may be within arsenic, copper, silver, mercury aureoles caused by the primary dispersion of elements into wallrocks or broader alteration zones associated with porphyry deposit or prospects.

GEOPHYSICAL SIGNATURE: May have elongate zones of low magnetic response and/or electromagnetic, self potential or induced polarization anomalies related to ore zones.

OTHER EXPLORATION GUIDES: Strong structural control on veins and common occurrence of deposits in clusters can be used to locate new veins.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE : Individual vein systems range from several hundred to several million tonnes grading from 5 to 1500 g/t Ag, 0.5 to 20% Pb and 0.5 to 8% Zn. Average grades are strongly influenced by the minimum size of deposit included in the population. For B.C. deposits larger than 20 000 t the average size is 161 000 t with grades of 304 g/t Ag, 3.47 % Pb and 2.66 % Zn. Copper and gold are reported in less than half the occurrences, with average grades of 0.09 % Cu and 4 g/t Au.

ECONOMIC LIMITATIONS: These veins usually support small to medium-size underground mines. The mineralization may contain arsenic which typically reduces smelting credits.

IMPORTANCE: The most common deposit type in British Columbia with over 2 000 occurrences; these veins were a significant source of Ag, Pb and Zn until the 1960s. They have declined in importance as industry focused more on syngenetic massive sulphide deposits. Larger polymetallic vein deposits are still attractive because of their high grades and relatively easy benefication. They are potential sources of cadmium and germanium.

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ACKNOWLEDGEMENTS: Georges Beaudoin and Don Sangster are thanked for their suggestions to improve the profile.

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D. Lefebure draft #4a March 24, 1996

Cu±Ag QUARTZ VEINS I06

by David V. Lefebure[1]

IDENTIFICATION

SYNONYMS: Churchill-type vein copper, vein copper

COMMODITY (*BYPRODUCTS*): Cu (Ag, rarely Au).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Davis-Keays (094K012, 050), Churchill Copper (Magnum, 094K003), Bull River (082GNW002), Copper Road (092K060), Copper Star (092HNE036), Copper Standard (092HNE079), Rainbow (093L044); *Bruce Mines and Crownbridge (Ontario, Canada), Blue Wing and Seaboard (North Carolina, USA), Matahambre (Cuba), Inyati (Zimbabwe), Copper Hills (Western Australia), Tocopilla area (Chile), Burgas district (Bulgaria), Butte (Montana, USA), Rosario (Chile).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Quartz-carbonate veins containing patches and disseminations of chalcopyrite with bornite, tetrahedrite, covellite and pyrite. These veins typically crosscut clastic sedimentary or volcanic sequences, however, there are also Cu quartz veins related to porphyry Cu systems and associated with felsic to intermediate intrusions.

TECTONIC SETTINGS: A diversity of tectonic settings reflecting the wide variety of hostrocks including extensional sedimentary basins (often Proterozoic) and volcanic sequences associated with rifting or subduction-related continental and island arc settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Veins emplaced along faults; they commonly postdate major deformation and metamorphism. The veins related to felsic intrusions form adjacent to, and are contemporaneous with, mesozonal stocks.

AGE OF MINERALIZATION: Any age; can be much younger than hostrocks.

HOST/ASSOCIATED ROCK TYPES: Cu±Ag quartz veins occur in virtually any rocks although the most common hosts are clastic metasediments and mafic volcanic sequences. Mafic dikes and sills are often spatially associated with metasediment-hosted veins. These veins are also found within and adjacent to felsic to intermediate intrusions.

DEPOSIT FORM: The deposits form simple to complicated veins and vein sets which typically follow high-angle faults which may be associated with major fold sets. Single veins vary in thickness from centimetres up to tens of metres. Major vein systems extend hundreds of metres along strike and down dip. In some exceptional cases the veins extend more than a kilometre along the maximum dimension.

TEXTURE/STRUCTURE: Sulphides are irregularly distributed as patches and disseminations. Vein breccias and stockworks are associated with some deposits.

Lefebure, D.V. (1996): Cu±Ag Quartz Veins; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 71-73.

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Cu±Ag QUARTZ VEINS I06

ORE MINERALOGY (Principal and *subordinate*):

- Metasediment and volcanic-hosted: Chalcopyrite, pyrite, chalcocite*; bornite, tetrahedrite, argentite, pyrrhotite, covellite, galena*.
- Intrusion-related: Chalcopyrite, bornite, chalcocite, pyrite, pyrrhotite; *enargite, tetrahedrite-tennantite, bismuthinite, molybdenite, sphalerite, native gold and electrum*.

GANGUE MINERALOGY (Principal and *subordinate)*: Quartz and carbonate (calcite, dolomite, ankerite or siderite); *hematite, specularite, barite*.

ALTERATION MINERALOGY: Wallrocks are typically altered for distances of centimetres to tens of metres outwards from the veins.

- Metasediment and volcanic-hosted: The metasediments display carbonatization and silicification. At the Churchill and Davis-Keays deposits, decalcification of limy rocks and zones of disseminated pyrite in roughly stratabound zones are reported. The volcanic hostrocks exhibit abundant epidote with associated calcite and chlorite.
- Intrusion-related: Sericitization, in places with clay alteration and chloritization.

WEATHERING: Malachite or azurite staining; silicified linear “ridges”.

ORE CONTROLS: Veins and associated dikes follow faults. Ore shoots commonly localized along dilational bends within veins. Sulphides may occur preferentially in parts of veins which crosscut carbonate or other favourable lithologies. Intersections of veins are an important locus for ore.

GENETIC MODEL: The metasediment and volcanic-hosted veins are associated with major faults related to crustal extension which control the ascent of hydrothermal fluids to suitable sites for deposition of metals. The fluids are believed to be derived from mafic intrusions which are also the source for compositionally similar dikes and sills associated with the veins. Intrusion-related veins, like Butte in Montana and Rosario in Chile, are clearly associated with high-level felsic to intermediate intrusions hosting porphyry Cu deposits or prospects.

ASSOCIATED DEPOSIT TYPES:

- Metasediment and volcanic-hosted: Possibly related to sediment-hosted Cu (E04) and basaltic Cu (D03).
- Intrusion-related: High sulphidation (H04), copper skarns (K01), porphyries (L01?, L03, L04) and polymetallic veins (I05).

COMMENTS: Cu±Ag quartz veins are common in copper metallogenetic provinces; they often are more important as indicators of the presence of other types of copper deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: High Cu and Ag in regional silt samples. The Churchill-type deposits appear to have very limited wallrock dispersion of pathfinder elements; however, alteration halos of silica and carbonate addition or depletion might prove useful. Porpyhyry-related veins exhibit many of the geochemical signatures of porphyry copper systems.

GEOPHYSICAL SIGNATURE: Large veins with conductive massive sulphides may show up as electromagnetic conductors, particularly on ground surveys. Associated structures may be defined by ground magnetic, very low frequency or electromagnetic surveys. Airborne surveys may identify prospective major structures.

OTHER EXPLORATION GUIDES: Commonly camp-scale or regional structural controls define a dominant orientation for veins.

ECONOMIC FACTORS

GRADE AND TONNAGE: Typically range from 10 000 to 100 0000 t with grades of 1 to 4% Cu, nil to 300 g/t Ag. The Churchill deposit has reserves of 90 000 t of 3 % Cu and produced 501 019 t grading 3% Cu and the Davis-Keays deposit has reserves of 1 119 089 t grading 3.43 % Cu. The Big Bull deposit has reserves of 732 000 t grading 1.94% Cu. The intrusion-related veins range up to millions of tonnes with grades of up to 6% Cu. The Butte veins in Montana have produced several hundred million tonnes of ore with much of this production from open-pit operations.

ECONOMIC LIMITATIONS: Currently only the large and/or high-grade veins (usually associated with porphyry deposits) are economically attractive.

IMPORTANCE: From pre-historic times until the early 1900s, high-grade copper veins were an important source of this metal. With hand sorting and labour-intensive mining they represented very attractive deposits.

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ACKNOWLEDGEMENTS: This deposit profile represents the results of a literature review. It benefited from comments by David Sinclair and Vic Preto.

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SILICA-CARBONATE Hg I08

by Chris Ash[1]

IDENTIFICATION

SYNONYMS: Serpentinite-type, listwanite-type.

COMMODITIES (*BYPRODUCTS*): Hg (Sb, Ag, Au).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Pinchi (093K049), Bralorne Takla (093N008), Eagle Mercury (092JNE062), Silverquick (092O017), Manitou (092O023); *New Almaden, New Idria (California, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cinnabar occurs associated with quartz and carbonate alteration in zones of intense brittle fracturing at relatively shallow levels along major fault zones. Commonly occur in areas of active geothermal systems.

TECTONIC SETTING: Within orogenic belts.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: At shallow levels within high-angle, regional-scale, deep crustal faults marked by the presence of ophiolitic ultramafic rocks. Typically at brittle faulted contacts between competent lithologies, *e.g.* carbonate-altered ultramafics, limestone, etc. Locally associated with recent volcanism and hotspring activity. Mercury deposits in B.C. are concentrated along several north to northwest-trending, high-angle transcurrent fault zones which border oceanic terranes. These include the Pinchi, Yalakom and Germansen faults.

AGE OF MINERALIZATION: Eocene to Recent?

HOST/ASSOCIATED ROCK TYPES: Serpentinite, limestone, siltstone, graywacke, conglomerate, mafic volcanic rocks.

DEPOSIT FORM: Deposits are typically highly irregular within major fault zones.

TEXTURE/STRUCTURE: Thin discontinuous stringers or fracture and cavity coatings in areas of shattering and brecciation along major faults.

ORE MINERALOGY [Principal and *subordinate*]: Cinnabar, *native mercury (quicksilver), metacinnabar, livingstonite ($HgSb_4S_9$).*

GANGUE MINERALOGY: Pyrite, marcasite, quartz, carbonate, limestone, serpentinite.

ALTERATION MINERALOGY: "Silica-carbonate rock" or "listwanite/listvenite", magnesite, ankerite, dolomite, quartz, chalcedony, kaolinite, sericite (fuchsite/mariposite).

WEATHERING: Mineralized areas display distinctive limonite stain due to the presence of iron carbonates.

Ash, C. (1996): Silica-carbonate Hg; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 75-76.

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

SILICA-CARBONATE Hg I08

ORE CONTROLS: High-angle fault zones marginal to accreted oceanic terranes. In general, grade of ore increases with fracture density in the hostrock.

GENETIC MODELS: Deposits form where relatively low temperature (between 100° and 200^oC) CO_2-H_2O aqueous fluids (< 2 wt. % chlorine), charged with Hg migrate upward along permeable fault zones and precipitate cinnabar in fractured hostrocks at shallow levels due to cooling and mixing with meteoric water. At this stage a vapour phase evolves which emanates from hotsprings at surface.

ASSOCIATED DEPOSIT TYPES: Sb veins.

COMMENTS: Due to the liquid state of this metal, mercury is generally measured in "flasks" and quoted in dollar value per flask. Flasks are standard steel containers that hold 76 lb (about 2.5 L) of the liquid metal.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Hg, Sb (Cu, Zn).

GEOPHYSICAL SIGNATURE: Not generally applicable.

OTHER EXPLORATION GUIDES: Soil, stream sediment and geobotanical sampling for Hg has proven successful. The spatial association of hotsprings with major fault zones associated with ophiolitic ultramafic rocks.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits of this type are typically less than 1 Mt, but may be up to several million tonnes with mercury grades averaging 0.5% and ranging from 0.2 to 0.8%.

ECONOMIC LIMITATIONS: The low grade of these deposits relative to other mercury deposit types, extreme fluctuations in the price of the metal, and inherent pollution problems are all factors in the economics of this deposit type.

IMPORTANCE: Although historically significant as a source of mercury, these deposits are not currently mined due to their low grades and small size relative to the much larger and richer Almaden-type mercury deposits. The only significant past-producing mines in B.C. include the Pinchi and Bralorne Takla. Both deposits are along the Pinchi fault.

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March 27, 1996 Draft#3a

STIBNITE VEINS and DISSEMINATIONS I09

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYMS: Quartz-stibnite, simple antimony, syntectonic stibnite, mesothermal Sb-Au.

COMMODITIES (*BYPRODUCTS*): Sb (*Au*).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): a) Veins - Minto (092JNE075) and Congress (092JNE029), Bridge River area; Snowbird (093K036); *Becker-Cochran (Yukon, Canada), Lake George (New Brunswick, Canada), Beaver Brook (Newfoundland, Canada*), *Murchison Range deposits (South Africa), Caracota and numerous other deposits in the Cordillera Occidental (Bolivia).* b) Disseminated - *Caracota and Espiritu Santo (Bolivia), many deposits (Turkey).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stibnite veins, pods, disseminations and stibnite-bearing quartz and quartz-carbonate veins occur in, or adjacent to, shears, fault zones and brecciated rocks in sedimentary or metasedimentary sequences.

TECTONIC SETTING: Any orogenic area, particularly where large-scale fault structures are present

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Fault and shear zones, notably in fault splays and fault-related breccias in which shallow to intermediate-depth hydrothermal systems have been operative.

AGE OF MINERALIZATION: Deposits range from Paleozoic to Tertiary age.

HOST/ASSOCIATED ROCK TYPES: Any faulted lithologies with a wide variety of rock types; sedimentary and metasedimentary rocks are commonly present. British Columbia deposits tend to be near major fault zones with attendant serpentinized mafic and ultramafic rocks.

DEPOSIT FORM: Stibnite occurs in veins; also as fine to coarse grains in sheared or brecciated rocks. Some stibnite is disseminated in carbonate-altered wallrocks surrounding structures and may form within pressure shadows at crests of folds. Massive stibnite-pyrite replacements which may form pods or lenses up to tens of metres long, are relatively uncommon, but are sources of rich ore.

TEXTURE/STRUCTURE: Veins have fine to coarse-grained, commonly euhedral bladed crystals of stibnite, quartz and carbonate in masses of stibnite. Quartz and quartz-carbonate gangue minerals range from fine to coarse grained, commonly with white 'bull quartz" present.

ORE MINERALOGY [Principal and *subordinate*]: Stibnite, pyrite, arsenopyrite; *sphalerite, galena, tetrahedrite, marcasite, chalcopyrite, jamesonite, berthierite, gold, cinnabar, scheelite, argentite and sulphosalt minerals. Other than stibnite, the overall sulphide content of the veins is low.*

GANGUE MINERALOGY [Principal and *subordinate*]: Quartz, calcite, dolomite; *chalcedony, siderite, rare barite and fluorite.*

Panteleyev, A. (1996): Stibnite Veins and Disseminations; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 77-79.

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

STIBNITE VEINS and DISSEMINATIONS I09

ALTERATION MINERALOGY: Quartz-carbonate envelopes on veins; some silicification, sericite, and intermediate argillic alteration. Chlorite, serpentinization and 'listwanite' (quartz-carbonate-talc-chromian mica-sulphide minerals) green-coloured alteration may be present when mafic and untramafic rocks are involved.

WEATHERING: Stibnite weathers to various oxides of yellowish (kermsite) or whitish (cerrantite or stibiconite) colour.

ORE CONTROLS: Fissure, shear zones and breccia associated with faults. Some open-space filling in porous rocks and structurally induced openings (joints, saddle reefs, ladder veins). Minor replacement in limestones.

GENETIC MODEL: The origin is not well documented. Deposits are spatially closely associated with, and in many ways resemble, low-sulphide gold-quartz (mesothermal) veins. Their (mutual) origin is thought to be from dilute, CO_2 rich fluids generated by metamorphic dehydration. Structural channelways focus the hydrothermal fluids during regional deformation. Some deposits are associated with felsic intrusive bodies, for example a Tertiary rhyolite plug at Becker-Cochran deposit, Yukon, and with porphyry W-Mo mineralization in granitic rocks at the Lake George Sb deposit, New Brunswick.

ASSOCIATED DEPOSIT TYPES: Quartz-carbonate gold (low-sulphide gold-quartz vein or I01), polymetallic vein Ag-Pb-Zn (I05), epithermal Au-Ag: low sulphidation (H05), hotspring Au-Ag (H03), Sn-W vein (??), W-Mo porphyry (L07); silica-carbonate Hg (I08), placer gold (C01, C02); possibly Carlin-type sediment-hosted Ag-Ag (E03).

COMMENTS: Occurrences of typical stibnite veins in the Bridge River gold camp in British Columbia were thought to be part of a regional deposit zoning pattern. The deposits are now known to be younger than the gold deposits by about 15-20 Ma. Farther north, the Snowbird deposit near Stuart Lake, has been shown to be Middle Jurassic in age by radiometric dating and is interpreted to be related to large-scale crustal structures. This deformation possibly involves the Pinchi fault system in which the largest known mercury deposits in the province are found.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sb, As, Au, Ag, Pb, Zn; locally W or Hg.

GEOPHYSICAL SIGNATURE: VLF surveys may detect faults.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Veins typically have high grade but small ore shoots; the disseminated deposits are also relatively small. Grade-tonnage data from 81 "typical" vein deposits (predominately, hand-sorted ore from USA mines) is 180 t with 35 % Sb; 10 % of the deposits contained > 1 g/t Au and > 16 g/t Ag. The disseminated deposits average 88 000 t with an average grade of 3.6 % Sb.

ECONOMIC LIMITATIONS: Antimony is a low-priced metal so only high-grade deposits are mined. Deposits (veins and disseminations) containing gold offer the best potential.

IMPORTANCE: Bolivia, Turkey and China dominate the antimony market; Cordilleran production will likely be only as a byproduct from precious metal bearing deposits.

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VEIN BARITE I10

by Z.D. Hora[1]

IDENTIFICATION

SYNONYM: Epigenetic vein barite.

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

EXAMPLES (British Columbia (MINFILE #) - Canada/International): Parson (082N002), Brisco (082KNE013), Fireside (094M003); *Matchewan (Ontario, Canada), Lake Ainslie (Nova Scotia, Canada), Collier Cove (Newfoundland, Canada), Nevada, Montana, Virginia, Pennsylvania, Georgia in USA; Bonarta, Jbel Ighoud (Morocco); Wolfach, Bad Lauterberg (Germany); Roznava (Slovakia), China*.

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Barite in fissure-filling voids resulting from mechanical deformation, including dilatant zones along faults and folds, gash fractures, joints and bedding planes; also in shear and breccia zones along faults.

TECTONIC SETTINGS: Highly varied, frequently but not exclusively at or near the margins of basins with sedex or Kuroko type deposits, or abrupt deep basin-platform sedimentation facies change.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Highly varied; almost any type of sedimentary, metamorphic or intrusive rocks. Veins associated with regional faults and lineaments, also the breccia zones along the margins of rift basins. In carbonate rocks, barite may fill karst cavities and collapse structures and forms manto-like replacement orebodies.

AGE OF MINERALIZATION: Precambrian to Tertiary.

HOST/ASSOCIATED ROCK TYPES: Any sedimentary, metamorphic or even igneous rocks.

DEPOSIT FORM: Tabular/lenticular bodies and breccias, collapse breccias and related cavity fills, veins with manto-type orebodies in carbonate hostrocks. The veins are several hundreds up to over 1000 m in length and sometimes up to 20 m thick. Some veins are mined to the depth of 500 m from surface.

TEXTURE/STRUCTURE: Massive, banded, brecciated. Texture typical of high-level veins, occasional druzy textures.

ORE MINERALOGY [Principal and *subordinate*]: Barite, *fluorspar, siderite, Pb-Zn-Cu sulphides*.

GANGUE MINERALOGY: (Principal and *subordinate*): *Quartz, calcite, siderite, witherite, barytocalcite, cinnabar, pyrite.*

ALTERATION MINERALOGY: Insignificant.

WEATHERING: Barite float and detrital fragments as a result of physical weathering.

Hora, Z.D. (1996): Vein Barite; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 81-83.

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VEIN BARITE I10

ORE CONTROLS: Dominant structural control with veins along faults, fractures, and shear zones, sometimes related to dilatant zones in major fault systems.

GENETIC MODEL: Epithermal barite veins, with or without sulphides, are common at and near the margins of rift basins, both in continental and continental margin settings. The veins and orebodies occur as open-space fillings in high-angle faults or fractures in sedimentary rocks or adjacent crystalline rocks, sills, and irregular and stratabound collapse structures or mantos. The source fluids are inferred to have been brines of moderate salinity (10 to 16 equivalent weight percent NaCl) and temperatures of 100° to 250° C. Pre-existing fractures and faults are apparently important in localizing the veins and orebodies. Multiple mineralizing episodes and several pulses of fluid migration are evident in many of the vein systems.

ASSOCIATED DEPOSIT TYPES: Polymetallic veins (I05) and replacement deposits (J01, E10-E12), sedex (E14) and Kuroko massive sulphide (G06) deposits, carbonatites (N03).

COMMENTS: This type of barite vein is distinct from barite associated with fluorspar veins. These (fluorspar-barite) veins may have, at least in part, a different barium source and are closely associated with Mississippi Valley type deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ba, Sr, sometimes Hg, Ag, Pb, Zn and Cu anomalies in soils and silts.

GEOPHYSICAL SIGNATURE: Linear gravity highs over large veins.

OTHER EXPLORATION GUIDES: Clastic barite in stream sediments, both in sand and silt fractions.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Most deposits in production are selectively mining high-grade orebodies with over 80% barite. The deposit size varies from a few thousand up to some 3 Mt. Brisco mine produced approximately 250,000 tonnes during its life; Parson is expected to produce close to 1 Mt.

ECONOMIC LIMITATIONS: Dependant on the end use. White, high-purity barite is suitable for filler and chemical applications and can be mined from even very small deposits. Drilling mud is a lower priced grade and, if processing is required to reach the required 4.2 specific gravity, only large deposits can be operated successfully. Even a small amount of contamination by siderite or witherite may make the barite unusable in drilling mud applications. Barite which is contaminated with small quantities (ppm) of heavy metals like Pb, Zn, Cu and Hg may result in environmental problems with disposal of spent drilling mud.

END USES: Drilling muds, fillers, chemicals, radiation shields, speciality glass and ceramics.

IMPORTANCE: Probably the main source of barite worldwide, but in North America very subordinate to bedded barite deposits.

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VEIN FLUORITE-BARITE I11

by Z.D. Hora[1]

IDENTIFICATION

SYNONYM: Epigenetic fluorite/barite vein.

COMMODITIES (BYPRODUCTS): Fluorite, sometimes barite (occasionally Pb, Zn, and Cu. Some fluorites contain the recoverable Be minerals bertrandite and phenacite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Rock Candy (082ESE070), Eaglet (093A046), Rexspar (82M007); *Madoc (Ontario, Canada); St. Lawrence (Newfoundland, Canada); Nevada, Utah, New Mexico (USA); Nabburg-Woelsendorf, Ilmenau, Schoenbrunn (Germany); Torgola, Prestavel, Gerrai (Italy); Auvergne, Morvan (France); Mongolia, China.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Fluorite and barite fill dilatant shear and breccia zones along faults and folds, gash fractures, joints and bedding planes as well as stockworks. In carbonate rocks, the fissure veins are frequently associated with replacement bodies and mantos. Fluorite veins commonly show affinities with barite veins and may grade into polymetallic veins with barite gangue.

TECTONIC SETTINGS: Highly varied - but in terrains underlain by sialic crust. In young orogenic belts: postorogenic and lateorogenic granite intrusions or rift-related alkaline rocks (from syenites to nepheline syenites to carbonatites) may be associated with fluorite veins. In old orogenic belts: proximity of major tectonic zones, grabens, tensional rifts and lineaments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Highly varied, sometimes linked to volatile-rich intrusives of alkaline to granite composition. In the Cordillera, topaz rhyolites, particularly, are associated with many fluorite veins.

AGE OF MINERALIZATION: Precambrian to Tertiary; in B.C. Devono-Mississippian (Rexspar), Cretaceous (Eaglet) and Tertiary (Rock Candy).

HOST/ASSOCIATED ROCK TYPES: Any sedimentary, metamorphic or igneous rock; in volcanic environment usually associated with topaz rhyolite.

DEPOSIT FORM: Tabular or lenticular bodies and breccias or stockworks and breccia pipes. The veins are usually 1-5 m thick and may be over a 1000 m long. Some particularly large veins in Sardinia are 3 km in length; the Torgola vein is reported to be 20 m thick. Some vein deposits were mined up to 500 m below surface, however the usual mining depth is 200 to 300 m down the dip from the outcrop.

TEXTURE/STRUCTURE: Massive, banded, brecciated. Drusy textures are common, fluorspar may be coarse grained or fine grained with radiating texture. Banding of different colour varieties of fluorspar is very common (coontail type). Bands of barite in fluorite, or young silica replacement of fluorspar along the cleavage and crystal borders are common features.

Hora, Z.D. (1996): Vein Fluorite-Barite; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 85-87.

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VEIN FLUORITE-BARITE I11

ORE MINERALOGY [Principal and *subordinate*]: Fluorite, barite, *celestite, barytocalcite, galena, sphalerite, chalcopyrite, pyrite, adularia or K-feldspar, red jasper. Dark purple fluorite may contain uraninite. Bertrandite and other Be minerals are sometimes accessory components.* Fluorite is often the main or even only vein mineral.

GANGUE MINERALOGY: (Principal and *subordinate)* Gangue may be a variety of minerals such as quartz, chalcedony, jasper, barite and Ca-Fe-Mg carbonates. Barite commonly varies in colour from yellow to pink or red; jasper may have a red colour due to finely dispersed hematite.

ALTERATION MINERALOGY: Kaolinization and/or silicification of wallrocks, sometimes pervasive potassic alteration (Eaglet, Rexspar); occasionally montmorillonite in wallrocks.

WEATHERING: Physical weathering mostly; in high-sulphide environment fluorspar may be dissolved by sulphuric acid. Floats of vein quartz with voids after weathered out fluorspar crystals are a common feature.

ORE CONTROLS: Faults, fractures, shear zones. Vertical zoning of veins is a common feature, but not very well understood.

GENETIC MODEL: Fluorite veins are generally found in the proximity of continental rifts and lineaments. In young orogenic belts fluorite can be linked to late or postorogenic granitic intrusions, particularly in areas of sialic crust. Rift-related alkaline intrusions are also linked to some fluorite veins. In old orogenic belts, fluorite veins are also in fracture zones within major faults and graben structures which facilitated circulation of mineralized fluids far from original fluorine source. Fluorite is precipitated from fluids by cooling low-pH solutions or by an increase in the pH of acid ore fluids. The fluids usually have a high Na/K ratio.

ASSOCIATED DEPOSIT TYPES: Pb-Zn veins (I05), carbonatite plugs, dikes and sills with Nb-REE (N02); Sn-W greisen (I13), F/Be deposits (Spor Mountain), Pb-Zn mantos (J01) and Mississippi Valley type deposits (E10, E11, E12).

COMMENT: End uses of fluorine chemicals in aluminium and chemical industries are very sensitive to P and As contents of only a few ppm.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: F in stream waters.

GEOPHYSICAL SIGNATURE: Sometimes gamma radiometric anomalies as an expression of potassic alteration or uranium content in certain types of fluorite.

OTHER EXPLORATION GUIDES: Fault control in some districts; regional silicified zones and major quartz veins.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Past producers reported grades in general between 30% and 60% fluorite, with occasional higher grade orebodies. The deposit size varies; up to 6 Mt. In B.C., Eaglet reported 1.8 million tonnes of 15% CaF_2, Rexspar 1.4 million tonnes of 23% CaF_2.

ECONOMIC LIMITATIONS: In recent years, shipments of high quality fluorspar from China, at very low prices, resulted in the collapse of most fluorspar production centres worldwide.

END USES: Metallurgy of aluminum and uranium, fluorine chemicals, flux in iron and steel metallurgy, glass and ceramics.

IMPORTANCE: Main source of fluorspar worldwide. In B.C., the Rock Candy mine produced 51,495 t of 68% CaF_2 between 1918 and 1929.

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DRAFT #: 3a March 28, 1996

FIVE-ELEMENT VEINS Ag-Ni-Co-As±(Bi,U) I14

by David Lefebure[1]

IDENTIFICATION

SYNONYMS: Five-element (Ni-Co-As-Ag-Bi) veins, nickel-cobalt-native silver veins, Cobalt-type silver-sulpharsenide veins, Ni-Co-Bi-Ag-U (As) association, Ag-As (Ni,Co,Bi) veins, Schneeberg-Joachimsthal-type.

COMMODITY (*BYPRODUCTS*): Ag, U, Ni, Co, Bi (barite).

EXAMPLES (British Columbia - *Canada/International*): No B.C. examples; *Beaver and Timiskaming, Cobalt camp, Silver Islet, Thunder Bay district (Ontario, Canada), Echo Bay and Eldorado (Port Radium, Northwest Territories, Canada), Black Hawk district (New Mexico, USA), Batopilas district (Mexico), Johanngeogenstadt, Freiberg and Jachymov, Erzgebirge district (Germany), Konsberg-Modum (Norway).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Native silver occurs in carbonate veins associated with a variety of mineral assemblages that are rare in other settings, such as Ni-Co-Fe arsenides, Ni-Co-Fe-Sb sulpharsenides and bismuth minerals. In many cases only some of these minerals are present, although the best examples of this deposit type typically contain significant Ag-Ni-Co. In some deposits uraninite (pitchblende) is an important ore mineral.

TECTONIC SETTINGS: Virtually all occur in areas underlain by continental crust and are generally believed to have formed late or post-tectonically. In some cases the veins appear related to basinal subsidence and continental rifting.

DEPOSTIONAL ENVIRONMENT/GEOLOGICAL SETTING: Veins are believed to be emplaced at shallow depths in a continental setting along high-angle fault systems.

AGE OF MINERALIZATION: Proterozoic or younger, can be much younger than hostrocks.

HOST/ASSOCIATED ROCK TYPES: Found in a wide variety of hostrocks, although metasediments, metamorphosed intrusive rocks and granitic sequences are the most common. Diabase sills are an important host in the Cobalt camp and a number of the deposits in the Thunder Bay region are within a gabbro dike.

DEPOSIT FORM: Simple veins and vein sets. Veins vary from centimetre to metre thicknesses, typically changing over distances of less than tens of metres. Most vein systems appear to have limited depth extent, although some extend more than 500 m.

TEXTURE/STRUCTURE: Commonly open space filling with mineral assemblages and textures commonly due to multiple episodes of deposition. Sulphides are irregularly distributed as massive pods, bands, dendrites, plates and disseminations. The mineralization is more common near the interesections of veins or veins with crosscutting faults. Fragments of wallrock are common in some veins. Faults may be filled with graphite-rich gangue, mylonite or breccia.

Lefebure, D.V. (1996): Five-element Veins Ag-Ni-Co-As±(Bi,U); *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 89-91.

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

FIVE-ELEMENT VEINS Ag-Ni-Co-As±(Bi,U) I14

ORE MINERALOGY (Principal and *subordinate*): Native silver associated with Ni-Co arsenide minerals (rammelsbergite, safflorite, niccolite, cloanthite, maucherite), sulpharsenides of Co, Ni, Fe and Sb, native bismuth, bismuthinite, argentite, ruby silver, pyrite and uraninite (pitchblende). *Chalcopyrite, bornite and chalcocite are common, but minor, constituents of ore. Minor to trace galena, tetrahedrite, jamesonite, cosalite, sphalerite, arsenopyrite and rare pyrrhotite.* In many deposits only a partial mineral assemblage occurs containing a subset of the many elements which may occur in these veins. These veins are characterized by the absence of gold.

GANGUE MINERALOGY (Principal and *subordinate*): Calcite and dolomite are usually associated directly with native silver mineralization; quartz*, jasper, barite and fluorite are less common.* The carbonate minerals are common in the cores of some veins.

ALTERATION MINERALOGY: Not conspicuous or well documented. In the Cobalt camp calcite and chlorite alteration extends 2-5 cm from the vein, approximately equivalent in width to the vein.

WEATHERING: No obvious gossans because of the low sulphide content; locally “cobalt bloom”.

ORE CONTROLS: Veins occupy faults which often trend in only one or two directions in a particular district. Ore shoots may be localized at dilational bends within veins. Intersections of veins are an important locus for ore. Possibly five-element veins are more common in Proterozoic rocks.

GENETIC MODEL: In regions of crustal extension, faults controled the ascent of hydrothermal fluids to suitable sites for deposition of metals at depths of approximately 1 to 4 km below surface. The fluids were strongly saline brines at temperatures of 150° to 250°C, which may have been derived from late-stage differentiation of magmas, convective circulation of water from the country rocks driven by cooling intrusive phases or formation brines migrating upwards or towards the edge of sedimentary basins. Sulphide-rich strata (including Fahlbands) and carbonaceous shales in the stratigraphy are potential sources of the metals. Deposition occurs where the fluid encounters a reductant or structural trap.

ASSOCIATED DEPOSIT TYPES: ‘Classical’ U veins (I15), polymetallic veins (I05). In the Great Bear Lake area there are associated “giant” quartz veins with virtually no other minerals.

COMMENTS: Several Co-Ag±Ni±Bi veins are found in the Rossland Camp in British Columbia. These may be five-element veins, however, they also contain the atypical elements Au and Mo.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: The rare association of anomalous values of Ag with Ni, Co, Bi, U and As in rock samples is diagnostic.

GEOPHYSICAL SIGNATURE: Associated structures may be defined by ground magnetic or VLF-EM surveys. Airborne surveys may identify prospective major structures. Gamma ray scintillometers and spectrometers can be used to detect the uraninite-bearing veins in outcrop or in float trains in glacial till, frost boils, talus or other debris.

OTHER EXPLORATION GUIDES: Commonly camp or regional structural controls will define a dominant orientation for veins.

ECONOMIC FACTORS

GRADE AND TONNAGE: Typically range from tens of thousands of tonnes to a few hundreds of thousands of tonnes with very high grades of silver (more than 1000 g/t Ag for Canadian mines, with grades up to 30 000 g/t Ag).

IMPORTANCE: There has been no significant production from a native silver vein in British Columbia, however, these veins have historically been an important Canadian and world source of Ag and U with minor production of Co. More recently the narrow widths and discontinuous nature of these veins has led to the closure of virtually all mines of this type.

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“CLASSICAL” U VEINS I15

by R.H. McMillan[1]

IDENTIFICATION

SYNONYMS: Pitchblende veins, vein uranium, intragranitic veins, perigranitic veins.

COMMODITIES (*BYPRODUCTS*): U (*Bi, Co, Ni, As, Ag, Cu, Mo*).

EXAMPLES (British Columbia - *Canada/International*): In the Atlin area structurally controlled scheelite-bearing veins host uranium at the Purple Rose, Fisher, Dixie, Cy 4, Mir 3 and IRA occurrences, *Ace Fay-Verna and Gunnar, Beaverlodge area (Saskatchewan, Canada), Christopher Island-Kazan-Angikuni district, Baker Lake area (Northwest Territories, Canada), Millet Brook (Nova Scotia, Canada), Schwartzwalder (Colorado, USA), Xiazhuang district (China), La Crouzille area, Massif Central and Vendee district, Armorican Massif, (France), Jachymov and Pribram districts (Czeck Republic), Shinkolobwe (Shaba province, Zaire).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Pitchblende (Th-poor uraninite), coffinite or brannerite with only minor amounts of associated metallic minerals in a carbonate and quartz gangue in veins. These deposits show affinities with, and can grade into, five-element veins which have significant native silver, Co-Ni arsenides, Bi or other metallic minerals.

TECTONIC SETTING: Postorogenic continental environments, commonly associated with calcalkaline felsic plutonic and volcanic rocks. “Red beds” and sediments of extensional successor basins are common in the host sequence. The economic deposits appear confined to areas underlain by Proterozoic basement rocks.

DEPOSITIONAL ENVIRONMENT: Ore is deposited in open spaces within fracture zones, breccias and stockworks commonly associated with major or subsidiary, steeply dipping fault systems.

AGE OF MINERALIZATION: Proterozoic to Tertiary. None are older than approximately 2.2 Ga, the time when the atmosphere evolved to the current oxygen-rich condition.

HOST/ ASSOCIATED ROCK TYPES: A wide variety of hostrocks, including granitic rocks, commonly peraluminous two-mica granites and syenites, felsic volcanic rocks, and older sedimentary and metamorphic rocks. The uranium-rich veins tend to have an affinity to felsic igneous rocks. Some veins are closely associated with diabase and lamprophyre dikes and sills.

DEPOSIT FORM: Orebodies may be tabular or prismatic in shape generally ranging from centimetres up to a few metres thick and rarely up to about 15 m. Many deposits have a limited depth potential of a few hundred metres, however, some deposits extend from 700 m up to 2 km down dip. Disseminated mineralization is present within the alteration envelopes in some deposits.

McMillan, R.H. (1996): “Classical” U Veins; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 93-96.

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“CLASSICAL” U VEINS I15

TEXTURE/STRUCTURE: Features such as drusy textures, crustification banding, colloform, botryoidal and dendritic textures are common in deposits which have not undergone deformation and shearing. The veins typically fill subsidiary dilatant zones associated with major faults and shear zones. Mylonites are closely associated with the St. Louis fault zone at the Ace-Fay-Verna mines.

ORE MINERALOGY (Principal and *subordinate*): Pitchblende (Th-poor uraninite), coffinite, *uranophane, thucolite, brannerite, iron sulphides, native silver, Co-Ni arsenides and sulpharsenides, selenides, tellurides, vanadinites, jordesite, chalcopyrite, galena, sphalerite, native gold and platinum group elements.* Some deposits have a “simple” mineralogy of with only pitchblende and coffinite. Those veins with the more complex mineralogy are often interpreted to have had the other minerals formed at an earlier or later stage.

GANGUE MINERALOGY (Principal and *subordinate*): Carbonates (calcite and dolomite), quartz (often chalcedonic), hematite, *K-feldspar, albite, muscovite, fluorite, barite.*

ALTERATION: Chloritization, hematization, feldspathization. A few of the intrusive-hosted deposits are surrounded by desilicated, porous feldspar-mica rock called “episyenite” in the La Crouzille area of France and “sponge-rock” at the Gunnar mine in Saskatchewan. In most cases the hematization is due to oxidation of ferrous iron bearing minerals in the wallrocks during mineralization. The intense brick-red hematite adjacent to some high-grade uranium ores is probably due to loss of electrons during radioactive disintegration of uranium and its daughter products.

WEATHERING: Uranium is highly soluble in the +6 valence state above the water table. It will re-precipitate as uraninite and coffinite below the water table in the +4 valence state in the presence of reducing agents such as humic material or carbonaceous “trash”. Some uranium phosphates, vanadinites, sulphates, silicates and arsenates are semi-stable under oxidizing conditions, consequently autunite, torbernite, carnotite, zippeite, uranophane, uranospinite and numerous other secondary minerals may be found in the zone of oxidation , particularly in arid environments.

ORE CONTROLS: Pronounced structural control related to dilatant zones in major fault systems and shear zones. A redox control related to the loss of electrons associated with hematitic alteration and precipitation of uranium is evident but not completely understood. Many deposits are associated with continental unconformities and have affinities with unconformity-associated U deposits (I16).

GENETIC MODEL: Vein U deposits are generally found in areas of high uranium Clarke, and generally there are other types of uranium deposits in the vicinity. The veins might be best considered polygenetic. The U appears to be derived from late magmatic differentiates of granites and alkaline rocks with high K or Na contents. Uranium is then separated from (or enriched within) the parent rocks by aqueous solutions which may originate either as low-temperature hydrothermal, connate or meteoric fluids. Current opinion is divided on the source of the fluids and some authors prefer models that incorporate mixing fluids. Studies of carbon and oxygen isotopes indicate that the mineralizing solutions in many cases are hydrothermal fluids which have mixed with meteoric water. In some cases temperatures exceeding 400 °C were attained during mineralization. The uranium minerals are precipitated within faults at some distance from the source of the fluids. Wallrocks containing carbonaceous material, sulphide and

ferromagnesian minerals are favourable loci for precipitation of ore. Radiometric age dating indicates that mineralization is generally significantly younger than the associated felsic igneous rocks, but commonly close to the age of associated diabase or lamprophyre dikes.

ASSOCIATED DEPOSIT TYPES: Stratabound, disseminated and pegmatitic occurrences of U are commonly found in older metamorphic rocks. Sandstone-hosted U deposits (D05) are commonly found in associated red-bed supracrustal strata, and surficial deposits (B08) in arid or semi-arid environments.

COMMENTS:The Cretaceous to Tertiary Surprise Lake batholith in the Atlin area hosts several fracture-controlled veins with zeunerite, kasolite, autunite and Cu, Ag, W, Pb and Zn minerals. These include the Purple Rose, Fisher, Dixie, Cy 4, Mir 3 and IRA. Southwest of Hazelton, Th-poor uraninite associated with Au, Ag, Co-Ni sulpharsenides, Mo and W is found in high-temperature quartz veins within the Cretaceous Rocher Déboulé granodiorite stock at the Red Rose, Victoria and Rocher Deboule properties. Although the veins are past producers of Au, Ag, Cu and W, no U has been produced.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Uranium and sometimes any, or all, of Ni, Co, Cu, Mo, Bi, As and Ag are good pathfinder elements which can be utilized in standard stream silt, lake bottom sediment and soil surveys. Stream and lake bottom water samples can be analyzed for U and Ra. In addition, the inert gases He and Ra can often be detected above a U-rich source in soil and soil gas surveys, as well as in groundwater and springs.

GEOPHYSICAL SIGNATURE: Standard prospecting techniques using sensitive gamma ray scintillometers and spectrometers to detect U mineralization in place or in float trains in glacial till, frost boils, talus or other debris remains the most effective prospecting methods. Because most deposits do not contain more than a few percent metallic minerals, electromagnetic and induced polarization surveys are not likely to provide direct guides to ore. VLF-EM surveys are useful to map the fault zones which are hosts to the veins. Magnetic surveys may be useful to detect areas of magnetite destruction in hematite-altered wallrocks.

OTHER EXPLORATION GUIDES: Secondary uranium minerals are typically yellow and are useful surface indicators.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits are generally small (< 100 000 t) with grades of 0.15% to 0.25% U, however districts containing several deposits can aggregate considerable tonnages. The large Ace-Fay-Verna system produced 9 Mt of ore at an average grade of 0.21% U from numerous orebodies over a length of 4.5 km. and a depth of 1500 m. Gunnar produced 5 Mt of ore grading 0.15% U from a single orebody. The Schwartzwalder mine in Colorado was the largest “hardrock” uranium mine in the United States, producing approximately 4 300 tonnes U, and contains unmined reserves of approximately the same amount.

ECONOMIC LIMITATIONS: The generally narrow mining widths and grades of 0.15% to 0.25% U rendered most vein deposits uneconomic after the late 1960s discovery of the high-grade unconformity-type deposits.

IMPORTANCE: This type of deposit was the source of most of the world’s uranium until the 1950s. By 1988, significant production from veins was restricted to France, with production of 3 372 tonnes U or 9.2% of the world production for that year.

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UNCONFORMITY-ASSOCIATED U I16

by R.H. McMillan[1]

IDENTIFICATION

SYNONYMS: Unconformity-veins, unconformity-type uranium, unconformity U.

COMMODITIES (*BYPRODUCTS*): U (*Au, Ni).*

EXAMPLES (British Columbia - *Canada/International*): None in British Columbia; *Rabbit Lake, Key Lake, Cluff Lake, Midwest Lake, McClean Lake, McArthur River, Cigar Lake and Maurice Bay in the Athabasca uranium district (Saskatchewan, Canada), Lone Gull (Kiggavik) and Boomerang Lake, Thelon Basin district (Northwest Territories, Canada), Jabiluka, Ranger, Koongarra and Nabarlek, Alligator River district (Northern Territory, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Uranium minerals, generally pitchblende and coffinite, occur as fracture and breccia fillings and disseminations in elongate, prismatic-shaped or tabular zones hosted by sedimentary/metasedimentary rocks located below, above or across a major continental unconformity.

TECTONIC SETTING: Intracratonic sedimentary basins.

GEOLOGICAL SETTING/DEPOSITIONAL ENVIRONMENT: Structurally-prepared and porous zones within chemically favourable reduced or otherwise reactive strata.

AGE OF MINERALIZATION: Mid-Proterozoic, however, there is potential for younger deposits.

HOST/ ASSOCIATED ROCK TYPES: Shelf facies metasedimentary (amphibolite or granulite facies) rocks of Early Proterozoic age (graphitic or sulphide-rich metapelites, calcsilicate rocks and metapsammites), regolith and overlying continental sandstones of Middle Proterozoic age. The Early Proterozoic hostrocks in many cases are retrograded amphibolite-facies metamorphic rocks on the flanks of Archean gneiss domes. The overlying continental sandstones are well sorted fluviatile quartz-rich psammites; generally with a clay or siliceous matrix and red or pale in colour. Dikes and sills, commonly diabases and lamprophyres, occur in some districts.

McMillan, R.H. (1997): Unconformity-associated U; in Geological Fieldwork 1997, *British Columbia Ministry of Employment and Investment*, Paper 1998-1, pages 24G1-G4.

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UNCONFORMITY-ASSOCIATED U I16

DEPOSIT FORM: Orebodies may be tabular, pencil shaped or irregular in shape extending up to few kilometres in length. Most deposits have a limited depth potential below the unconformity of less than a 100 m, however, the Jabiluka and Eagle Point deposits are concordant within the Lower Proterozoic host rocks and extend for several hundred metres below the unconformity.

TEXTURE/STRUCTURE: Most deposits fill pore space or voids in breccias and vein stockworks. Some Saskatchewan deposits are exceptionally rich with areas of "massive" pitchblende/coffinite. Features such as drusy textures, crustification banding, colloform, botryoidal and dendritic textures are present in some deposits.

ORE MINERALOGY (Principal and *subordinate*): Pitchblende (Th-poor uraninite), coffinite, uranophane, thucolite, brannerite, iron sulphides, *native gold, Co-Ni arsenides and sulpharsenides, selenides, tellurides, vanadinites, jordesite (amorphous molybedenite), vanadates, chalcopyrite, galena, sphalerite, native Ag and PGE*. Some deposits are "simple" with only pitchblende and coffinite, while others are "complex" and contain Co-Ni arsenides and other metallic minerals.

GANGUE MINERALOGY: Carbonates (calcite, dolomite, magnesite and siderite), chalcedonic quartz, sericite (illite) chlorite and dravite (tourmaline).

ALTERATION: Chloritization, hematization, kaolinization, illitization and silicification. In most cases hematization is due to oxidation of ferrous iron bearing minerals in the wallrocks caused by oxidizing mineralizing fluids, however, the intense brick-red hematite adjacent to some high grade uranium ores is probably due to loss of electrons during radioactive disintegration of U and its daughter products. An interesting feature of the clay alteration zone is the presence of pseudomorphs of high grade metamorphic minerals, such as cordierite and garnet, in the retrograded basement wallrock.

WEATHERING: Uranium is highly soluble in the +6 valence state above the water table. It will re-precipitate as uraninite and coffinite below the water table in the +4 valence state in the presence of a reducing agents such as humic material or carbonaceous "trash". Some U phosphates, vanadates, sulphates, silicates and arsenates are semi-stable under oxidizing conditions, consequently autunite, torbernite, carnotite, zippeite, uranophane, uranospinite and numerous other secondary minerals may be found in the near-surface zone of oxidation, particularly in arid environments.

ORE CONTROLS: A pronounced control related to a mid-Proterozoic unconformity and to favourable stratigraphic horizons within Lower Proterozoic hostrocks - these strata are commonly graphitic. Local and regional fault zones that intersect the unconformity may be important features. Generally found close to basement granitic rocks with a high U clarke.

GENETIC MODEL: The exceptionally rich ore grades which characterize this type of deposit point to a complex and probably polygenetic origin.

- Some form of very early preconcentration of U in the Archean basement rocks seems to have been important.
- The hostrocks are commonly Lower Proterozoic in age, and are comprised of metamorphosed rocks derived from marginal marine and near-shore facies sedimentary rocks which may have concentrated U by syngenetic and diagenetic processes.

- Although the behaviour of U under metamorphic and ultrametamorphic conditions is poorly known, it is possible that U could have been mobilized in the vicinity of Archean gneiss domes and anatectic granites and precipitated in pegmatites and stratabound deposits as non-refractory, soluable uraninite.
- Supergene enrichment in paleo regoliths, that now underlie the unconformity, may have been an important process in the additional concentration of U.
- Typically the overlying quartz-rich fluviatile sandstones have undergone little deformation, but are affected by normal and reverse faults that are probably re-activated basement faults. In Saskatchewan, these faults carry ore in several deposits and in others appear to have facilitated the transport of U within the cover sandstones.
- Hydrothermal/diagenetic concentration of U through mixing of oxidized basinal and reduced basement fluids appear to have resulted in exceptional concentrations of U and Ni. There is a possibility that radiogenic heat developed in these extremely rich deposits may have been instrumental in heating formational fluids and in remobilizing the metals upwards above the deposit.
- Diabase dikes occur in faults near some deposits and some researchers have suggested that the dikes might have provided the thermal energy that remobilized and further upgraded U concentrations. Recent age dates of the Mackenzie dikes in the Athabaska district do not support this interpretation.

ASSOCIATED DEPOSIT TYPES: Sandstone-hosted U deposits (D05) are found in associated supracrustal quartz-rich arenites. Stratabound disseminated or skarn deposits , such as the Dudderidge Lake and Burbidge Lake deposits (Saskatchewan) and pegmatitic occurrences are commonly present in the metamorphosed basement rocks. In arid or semi-arid environments surficial deposits may be present in the overburden. The deposits have affinities to “Classical” U veins (I15).

COMMENTS: Virtually all the known unconformity-associated uranium deposits are found in the Athabasca Basin, Alligator River district and Thelon Basin. In British Columbia favourable target areas for this style of mineralization might be found within strongly metamorphosed shelf-facies Proterozoic strata near gneiss domes, particularly in plateau areas near the Cretaceous-Tertiary paleosurface. The Midnite mine, located 100 km south of Osoyoos, British Columbia, may be an unconformity-associated U deposit. The ore comprises fracture-controlled and disseminated U and alteration minerals (pitchblende, coffinite as well as autunite and other secondary minerals) within metamorphosed shelf-facies pelitic and calcareous rocks of the Precambrian Togo Formation. Production and reserves prior to closing at the Midnite mine are estimated at approximately 3.9 Mt grading 0.12% U.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: U, Ni, Co, As, Pb and Cu are good pathfinder elements which can be utilized in standard stream silt, lake bottom sediment and soil surveys. Stream and lake bottom water samples can be analyzed for U and Ra. In addition, the inert gases He and Ra can often be detected above a U-rich source in soil and soil gas surveys, as well as in groundwater and springs. In Saskatchewan, lithogeochemical signatures have been documented in Athabasca Group quartz arenites for several hundred metres directly above the deposits and in glacially dispersed boulders located “down ice” - the signature includes boron (dravite) and low, but anomalous U as well as K and/or Mg clay mineral alteration (illite and chlorite).

GEOPHYSICAL SIGNATURE: During early phases of exploration of the Athabasca Basin, airborne and ground radiometric surveys detected near surface uranium deposits and their glacial dispersions. Currently, deeply penetrating ground and airborne elecromagnetic surveys are used to map the graphitic argillites associated with most deposits. The complete spectrum of modern techniques (gravity, magnetic, magneto-telluric, electromagnetic, VLF-EM, induced polarization, resistivity) can be utilized to map various aspects of structure as well as hostrock and alteration mineral assemblages in the search for deep targets.

OTHER EXPLORATION GUIDES: Standard techniques using sensitive gamma ray scintillometers to detect mineralization directly in bedrock or in float trains in glacial till, frost boils, talus or other debris derived from U mineralization remain the most effective prospecting methods.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits are generally small, but can be exceedingly high-grade, up to several percent U. The median size for 36 Saskatchewan and Australian deposits is 260 000 t grading 0.42% U (Grauch and Mosier, 1986). Some deposits are exceptionally high grade such as the Key Lake Gaertner-Deilmann deposits (2.5 Mt @ 2.3% U), Cigar Lake deposits (900 000 t @ 12.2% U) and McArthur River (1.4 Mt @12.7% U).

ECONOMIC LIMITATIONS: Since the early 1980s, average ore grades have generally risen to exceed 0.25% U. Problems related to the pervasively clay-altered wallrocks and presence of radon gas and other potentially dangerous elements associated with some high-grade uranium deposits in Saskatchewan have resulted in exceptionally high mining costs in some cases.

IMPORTANCE: The Rabbit Lake mine, opened in 1975, was the first major producer of unconformity-type ore. Since then the proportion of the world's production to come from unconformity-type deposits has increased to 33% and is expected to rise in the future.

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CRYPTOCRYSTALLINE ULTRAMAFIC-HOSTED MAGNESITE VEINS[1] I17

by S. Paradis[2] and G.J. Simandl[3]

IDENTIFICATION

SYNONYMS: Cryptocrystalline or microcrystalline magnesite, "Kraubath-type" magnesite, "Bone magnesite", "amorphous magnesite".

COMMODITY: Magnesite.

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Sunny (092O014), Pinchi Lake (093K065); *Chalkidiky area (Greece); Kraubath (Austria); Eskisehir and Kutaya (Turkey).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cryptocrystalline magnesite deposits are related to faults cutting ultramafic rocks. Individual deposits may consist of two styles of mineralization. Steeply dipping magnesite veins, up to several metres thick, pass gradually upward into magnesite stockworks or breccias cemented by magnesite.

TECTONIC SETTINGS: Typically in allochthonous serpentinized ophiolitic sequences or along structural breaks within ultramafic layered complexes; however, other settings containing ultramafic rocks are also favourable.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The veins are emplaced along steep faults in near surface environments.

AGE OF MINERALIZATION: Post-date ultramafic hostrock that is Archean to Paleogene in age.

HOST/ASSOCIATED ROCK TYPES: Serpentinite, peridotite; other olivine-rich rocks of the typical ophiolitic sequence and layered ultramafic complexes.

DEPOSIT FORM: Stockworks, branching veins, single veins up to several metres in thickness, and less frequently, irregular masses. The maximum reported vertical extent is 200 m. The footwall of the deposits is commonly sharp and slickensided and coincides with a fault zone. The hangingwall of the fault contains magnesite veins and/or magnesite-cemented breccias.

TEXTURE/STRUCTURE: Magnesite is commonly cryptocrystalline and massive with microscopic "pinolite" texture; rarely granular, fibrous, or "cauliflower-like".

ORE MINERALOGY: Magnesite.

GANGUE MINERALOGY [Principal and *subordinate*]: Serpentine, chlorite, talc, iron oxides, dolomite, hydromagnesite, calcite, sepiolite, quartz, opal, chalcedony and quartz in vugs.

Paradis, S. and Simandl, G.J. (1996): Cryptocrystalline Ultramafic-hosted Magnesite Veins; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 97-99.

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CRYPTOCRYSTALLINE ULTRAMAFIC-HOSTED MAGNESITE VEINS I17

ALTERATION MINERALOGY: Ultramafic rocks hosting magnesite are typically, but not always, intensely serpentinised. Alteration minerals are dolomite, quartz, montmorillonite, sepiolite, talc, goethite and deweylite.

WEATHERING: Varies with climatic environment, gangue mineralogy and iron content in the crystal structure of magnesite.

ORE CONTROLS: Tectonic boundaries or major fault breaks, secondary fault zones parallel to major breaks cutting ultramafic rocks. The large magnesite-cemented breccias are commonly located below paleoerosional or erosional surfaces. Most contacts between the magnesite and country rock are sharp and irregular.

GENETIC MODEL: Two hypothesis competing to explain the origin of these deposits are:

1) hypogene low-temperature, CO_2-metasomatism of ultramafic rocks (Pohl, 1991):
2) low-temperature descending, meteoric waters containing biogenic CO_2 and enriched in Mg^{2+} (Zachmann and Johannes, 1989).

ASSOCIATED DEPOSIT TYPES: Lateritic deposits, chromite deposits and platinum deposits occur in the same geological environment but are not genetically related. The ultramafic-hosted talc deposits (M07) may be genetically related.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: May contain above average Hg.

GEOPHYSICAL SIGNATURE: N/A

OTHER EXPLORATION GUIDES: Favourable lithologic and structural setting. Commonly underlying unconformities. Near-surface (or paleosurface) magnesite deposits may be capped by stratiform magnesite, dolomite-quartz (chalcedony) or chert zones. Some of these deposits are overlain by laterites. Boulder tracing in glaciated areas.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: For stockwork (upper) portions of the deposits the grades vary from 20 to 40% magnesite and reserves ranging from hundreds of thousands to several millions tonnes are typical. The deeper vein portions of these deposits have higher grades and may be almost monomineralic. A representative specimen of Greek cryptocrystalline magnesite is reported to contain 46.6 % MgO, 49.9 % CO_2, 0.70 % SiO_2, 1.35 % CaO, 0.85% Fe_2O_3 and Al_2O_3 combined (Harben and Bates, 1990).

ECONOMIC LIMITATIONS: These deposits compete for markets with sediment-hosted sparry magnesite deposits and seawater or brine-derived magnesia compounds. In the past, European refractory producers preferred cryptocrystalline magnesite over sparry magnesite, because of its higher density and lower iron, manganese and boron content. Recently this advantage was largely lost by availability of excellent quality sparry magnesite exports and by new technical developments in the refractory industry. Natural magnesite-derived compounds in general have to compete with seawater and brine-derived magnesia compounds.

END USES: Source of wide variety of magnesia products used mainly in refractories, cements, insulation, chemicals, fertilizers, fluxes and environmental applications.

IMPORTANCE: These deposits are substantially smaller and, in the case of stockwork-type portions, lower grade than sparry magnesite deposits.

CRYPTOCRYSTALLINE ULTRAMAFIC-HOSTED MAGNESITE VEINS I17

COMMENTS: Stockworks and adjacent ultramafic hostrock are capped in some cases by sediments that may contain nodular magnesite concretions or magnesite/hydromagnesite layers and/or dolomite, quartz or chert. It is not well established if sediments are of sabkha /playa affinity or directly linked to fluids that formed stockworks and veins.

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POLYMETALLIC MANTOS Ag-Pb-Zn[1] J01

by J.L. Nelson[2]

IDENTIFICATION

SYNONYM: Polymetallic replacement deposits.

COMMODITIES (*BYPRODUCTS*): Ag, Pb, Zn (Au, Cu, Sn, Bi).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Midway (104O038) and Bluebell (082ENW026); *Sa Dena Hes (Yukon, Canada), Prairie Creek (Northwest Territories, Canada), Leadville District (Colorado, USA), East Tintic District (Utah, USA), Eureka District (Nevada, USA), Santa Eulalia, Naica, Fresnillo, Velardena, Providencia (Mexico).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Irregularly shaped, conformable to crosscutting bodies, such as massive lenses, pipes and veins, of sphalerite, galena, pyrite and other sulphides and sulphosalts in carbonate hosts; distal to skarns and to small, high-level felsic intrusions.

TECTONIC SETTING: Intrusions emplaced into miogeoclinal to platformal, continental settings.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: In northern Mexico, most are hosted by Cretaceous limestones. In Colorado, the principal host is the Devonian-Mississippian Leadville limestone; in Utah, the Permian Torweap Formation hosts the Deer Trail deposit. The most favourable hosts in the Canadian Cordillera are massive Lower Cambian and Middle Devonian limestones, rather than impure carbonates and dolostone-quartzite units.

AGE OF MINERALIZATION: Canadian Cordilleran examples are Cretaceous to Eocene age; those in the southern Cordillera are typically Tertiary.

HOST/ASSOCIATED ROCK TYPES: Hosted by limestone and dolostone. The carbonates are typically within a thick sediment package with siliciclastic rocks that is cut by granite, quartz monzonite and other intermediate to felsic hypabyssal, porphyritic lithologies. There may be volcanic rocks in the sequence, or more commonly above, which are related to the intrusive rocks.

DEPOSIT FORM: Irregular: mantos (cloak shaped), lenses, pipes, chimneys, veins; in some deposits the chimneys and/or mantos are stacked.

TEXTURE/STRUCTURE: Massive to highly vuggy, porous ore. In some cases fragments of wallrock are incorporated into the ore. Some deposits have breccias: fragments of wallrock and also of sulphide ore within a sulphide matrix.

ORE MINERALOGY (Principal and *subordinate*): Sphalerite, galena, pyrite, chalcopyrite, marcasite; *arsenopyrite, pyrargyrite/proustite, enargite, tetrahedrite, geocronite, electrum, digenite, jamesonite, jordanite, bournonite, stephanite, polybasite, rhodochrosite, sylvanite, calaverite.* Chimneys may be more Zn-rich, Pb-poor than mantos.

Nelson, J.L. (1996): Polymetallic Mantos Ag-Pb-Zn; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 101-103.

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[1] Manto is a Spanish mining term denoting a blanket-shaped orebody which is widely used for replacement deposits of Mexico. It has been used to describe the orientation of individual lenses and also to describe a class of orebodies.

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

POLYMETALLIC MANTOS Ag-Pb-Zn J01

GANGUE MINERALOGY (Principal and *subordinate*): Quartz, barite, gypsum; minor *calc-silicate minerals*.

ALTERATION MINERALOGY: Limestone wallrocks are commonly dolomitized and/or silicified, whereas shale and igneous rocks are argillized and chloritized. Jasperoid occurs in some U.S. examples.

WEATHERING: In some cases, a deep oxidation zone is developed. Mexican deposits have well developed oxide zones with cassiterite, hematite, Cu and Fe carbonates, cerusite and smithsonite.

ORE CONTROLS: The irregular shapes of these deposits and their occurrence in carbonate hosts emphasize the importance of ground preparation in controlling fluid channels and depositional sites. Controlling factors include faults, fault intersections, fractures, anticlinal culminations, bedding channelways (lithologic contrasts), karst features and pre-existing permeable zones. In several districts karst development associated with unconformities is believed to have led to development of open spaces subsequently filled by ore. Some deposits are spatially associated with dikes.

GENETIC MODEL: Manto deposits are high-temperature replacements as shown by fluid inclusion temperatures in excess of 300 °C, high contents of Ag, presence of Sn, W and complex sulphosalts, and association with skarns and small felsic intrusions. They are the product of pluton-driven hydrothermal solutions that followed a variety of permeable pathways, such as bedding, karst features and fracture zones.

ASSOCIATED DEPOSIT TYPES: There is probably an overall outward gradation from granite-hosted Mo-Cu porphyries (L04), endoskarns (K) and possibly W- and Sn mineralization (L06?), through exoskarns (K01, K02) and into Ag-Pb-Zn veins (I05), mantos (J01) and possibly Carlin-type sediment-hosted Au-Ag deposits (E03). Only some, or possibly one, of these types may be manifest in a given district. Ag-Pb-Zn vein, manto and skarn deposits belong to a continuum which includes many individual occurrences with mixed characteristics.

COMMENTS: In the Canadian Cordillera, most mantos are located in the miogeocline (western Ancestral North America, Cassiar and Kootenay terranes) because of the essential coincidence of abundant carbonate and presence of felsic intrusions. There is one known example in Upper Triassic limestone on Vancouver Island, which probably formed distal to skarn mineralization related to a mid-Jurassic intrusion. Most mantos in the Canadian Cordillera are Late Cretaceous to Eocene, coinciding with the age of youngest, F-rich intrusions of the A-type (anorogenic) granite suite. In Mexico, mantos are associated with Early to mid-Tertiary volcanic rocks and cogenetic intrusions. The Colorado deposits may be associated with Tertiary sills, and the Deer Trail deposit in Utah has given a 12 Ma sericite age.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: B.C.: Ag, Pb, Zn, Sn in stream silts, F in waters. U.S.: Districts show outward zoning from Cu-rich core through broad Ag-Pb zone to Zn-Mn fringe. Locally Au, As, Sb, Bi. Jasperoid contains elevated Ba + Ag.

GEOPHYSICAL SIGNATURE: Subsurface granite associated with Midway deposit has negative magnetic signature.

OTHER EXPLORATION GUIDES: Concentration of Ag-Pb-Zn vein deposits in or near carbonates.

POLYMETALLIC MANTOS Ag-Pb-Zn J01

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Individual deposits average about a million tonnes grading tens to hundreds of grams/tonne Ag and approximately 5 to 20% combined Pb-Zn. Mexico: Santa Eulalia district produced about 24 Mt in this century, grading about 300 g/t Ag, 8% Pb, 9% Zn. U.S.: Leadville deposit mined 30 Mt 70-130 g/t Ag, 12-15% Pb-Zn. B.C.: Midway geological resource is 1 Mt grading 400 g/t Ag 7% Pb, 9.6% Zn. In many mining districts the early production came from oxidized ore zones that can have higher grades and be easier to mine.

ECONOMIC LIMITATIONS: Generally, although not always, these deposits tend to be small, highly irregular and discontinuous. The Mexican deposits have yielded large quantities of ore because, due to low labour costs, mining provided an effective and low-cost exploration tool.

IMPORTANCE: As sources of base metals, manto deposits are overshadowed on a world scale by the giant syngenetic classes such as sedimentary exhalitive and volcanogenic massive sulphides. However, because of their high precious metal contents, they provide exciting targets for small producers.

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MANTO AND STOCKWORK Sn J02

by W. David Sinclair[1]

IDENTIFICATION

SYNONYMS: Replacement Sn, distal Sn skarn, Renison-type.

COMMODITIES (*BYPRODUCTS*): Sn (*Cu, Zn, Pb, Ag, Sb, Cd, Bi, In*).

EXAMPLES (British Columbia - *Canada/International*): *Renison Bell, Cleveland and Mt. Bischoff (Tasmania, Australia), Dachang and Gejiu districts (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Disseminated cassiterite occurs in massive sulphide replacement bodies in carbonate rocks and in associated veins, stockworks and breccias. Felsic intrusions are nearby, or adjacent to the deposits and may also be mineralized.

TECTONIC SETTING: Postorogenic underlain by cratonic crust containing carbonate rocks.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Carbonate rocks intruded by epizonal felsic intrusive rocks.

AGE OF MINERALIZATION: Mainly Paleozoic to Mesozoic, but other ages possible.

HOST/ASSOCIATED ROCK TYPES: Mainly limestone or dolomite; chert, pelitic and Fe-rich sediments, and volcanic rocks may also be present. Genetically-related granitic plutons and associated felsic dikes are typically F and/or B rich. They are commonly porphyritic.

DEPOSIT FORM: Variable: massive, lensoid to tabular, concordant sulphide-rich bodies in carbonate rocks; veins and irregular stockwork zones in associated rocks.

TEXTURE/STRUCTURE: Massive sulphide-rich bodies tend to follow bedding in host carbonate rocks; associated veins and stockworks include mineralized fractures, veinlets, quartz veins and breccias.

ORE MINERALOGY [Principal and *subordinate*]: Cassiterite, chalcopyrite, sphalerite and galena; *stannite, stibnite, bismuth, bismuthinite* and a wide variety of sulphosalt minerals including *jamesonite, bournonite, franckeite, boulangerite, geocronite, matildite and galenobismutite* may also be present.

GANGUE MINERALOGY [Principal and *subordinate*]: Pyrrhotite (often predominant sulphide) and/or pyrite, arsenopyrite, quartz, calcite, siderite, rhodochrosite, flourite and tourmaline.

ALTERATION MINERALOGY: Dolomite near massive sulphide bodies is typically altered to siderite, and, to a lesser extent, talc, phlogopite and quartz. Rocks hosting vein or stockwork zones may be tourmalinized. Greisen-type alteration, characterized by flourite and/or topaz, F-bearing micas and tourmaline, is best developed in and around genetically related felsic intrusive rocks.

WEATHERING: Oxidation of pyrite and pyrrhotite produces limonitic gossans. Deep weathering and erosion may result in residual concentrations of cassiterite *in situ* or in placer deposits downslope or downstream.

Sinclair, W.D. (1996): Manto and Stockwork Sn; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 105-107.

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

MANTO AND STOCKWORK SN J02

ORE CONTROLS: Carbonate rocks in the vicinity of F and B rich felsic intrusive rocks; faults and fracture zones in the carbonates and associated rocks provide channelways and also alternate sites of deposition for ore-forming fluids.

GENETIC MODEL: Magmatic-hydrothermal. Magmatic, highly saline aqueous fluids strip Sn and other ore metals from temporally- and genetically related magma. Early Sn deposition is dominantly from these magmatic fluids, mainly in response to increase in pH due to carbonate replacement. Mixing of magmatic with meteoric water during waning stages of the magmatic-hydrothermal system may result in deposition of Sn and other metals in late-stage veins and stockworks.

ASSOCIATED DEPOSIT TYPES: Sn-W skarn deposits (K06, K05), Sn-W vein deposits, Sb-Hg veins, placer deposits (C01, C02).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sn, Cu, Pb, Zn, As, Ag, Sb, Hg, F, W, Bi and In may be anomalously high in hostrocks adjacent to and overlying mineralized zones; Sb and Hg anomalies may extend as much as several hundred metres. Sn, W, F, Cu, Pb and Zn may be anomalously high in stream sediments and Sn, W, and B (tourmaline) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Massive pyrrhotite may be detected by magnetic surveys; massive sulphide zones may also be detected by electromagnetic and resistivity surveys.

OTHER EXPLORATION GUIDES: Deposits commonly occur in zoned, polymetallic districts; Sn and base metal bearing skarns and veins occur close to related intrusive rocks, carbonate-hosted Sn mantos and stockworks are at intermediate distances from the intrusive rocks, and Sb and Hg veins are the outermost deposits. Genetically related felsic intrusive rocks typically have high contents of silica (>74% SiO_2) and F (>0.1% F); tourmaline may also be present.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits are large and high grade, containing millions to tens of millions of tonnes averaging about 1% Sn. The following figures are for production plus reserves:

Renison Bell (Australia): 27 Mt at 1.1% Sn (Newnham, 1988)
Cleveland (Australia): 5.3 Mt at 0.5% Sn, 0.2% Cu (Cox and Dronseika, 1988)
Mt. Bischoff (Australia): 6.1 Mt at 0.49% Sn (Newnham, 1988)
Dachang (China): 100 Mt at 1% Sn, 3-5% combined Cu, Pb, Zn and Sb (Fu *et al*., 1993)
Gejiu (China): 100 Mt at 1% Sn, 2-5% Cu, 0.5% Pb (Sutphin *et al*., 1990)

IMPORTANCE: The large tonnage and relatively high grade of these deposits makes them attractive for exploration and development.The Renison Bell deposit in Australia and the Dachang and Gejiu deposits in China are currently major producers of tin on a world scale.

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Cu SKARNS K01

by Gerald E. Ray[1]

IDENTIFICATION

SYNONYMS: Pyrometasomatic and contact metasomatic copper deposits.

COMMODITIES (*BYPRODUCTS*): Cu (*Au, Ag, Mo, W, magnetite*)

EXAMPLES (British Columbia - *Canada/International*): Craigmont (092ISE 035), Phoenix (082ESE 020), Old Sport (092L 035), Queen Victoria (082FSW 082); *Mines Gaspé deposits (Québec, Canada), Ruth, Mason Valley and Copper Canyon (Nevada, USA), Carr Fork (Utah, USA), Ok Tedi (Papua New Guinea), Rosita (Nicaragua*).

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cu-dominant mineralization (generally chalcopyrite) genetically associated with a skarn gangue (includes calcic and magnesian Cu skarns).

TECTONIC SETTING: They are most common where Andean-type plutons intrude older continental-margin carbonate sequences. To a lesser extent (but important in British Columbia), they are associated with oceanic island arc plutonism.

AGE OF MINERALIZATION: Mainly Mesozoic, but may be any age. In British Columbia they are mostly Early to mid-Jurassic.

HOST/ASSOCIATED ROCK TYPES: Porphyritic stocks, dikes and breccia pipes of quartz diorite, granodiorite, monzogranite and tonalite composition, intruding carbonate rocks, calcareous volcanics or tuffs. Cu skarns in oceanic island arcs tend to be associated with more mafic intrusions (quartz diorite to granodiorite), while those formed in continental margin environments are associated with more felsic material.

DEPOSIT FORM: Highly varied; includes stratiform and tabular orebodies, vertical pipes, narrow lenses, and irregular ore zones that are controlled by intrusive contacts.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Some hornfelsic textures.

ORE MINERALOGY (Principal and *subordinate*): Moderate to high sulphide content. Chalcopyrite ± pyrite ± magnetite in inner garnet-pyroxene zone. Bornite ± chalcopyrite ± sphalerite ± tennantite in outer wollastonite zone. Either hematite, pyrrhotite or magnetite may predominate (depending on oxidation state). Scheelite and traces of *molybdenite, bismuthinite, galena, cosalite, arsenopyrite, enargite, tennantite, loellingite, cobaltite and tetrahedrite* may be present.

Ray, G.E. (1995): Cu Skarns; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 59-60.

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

Cu SKARNS K01

ALTERATION MINERALOGY: Exoskarn alteration: high garnet:pyroxene ratios. High Fe, low Al, Mn andradite garnet (Ad35-100), and diopsidic clinopyroxene (Hd2-50). The mineral zoning from stock out to marble is commonly: diopside + andradite (proximal); wollastonite ± tremolite ± garnet ± diopside ± vesuvianite (distal). Retrograde alteration to actinolite, chlorite and montmorillonite is common. In British Columbia, skarn alteration associated with some of the alkalic porphyry Cu-Au deposits contains late scapolite veining. Magnesian Cu skarns also contain olivine, serpentine, monticellite and brucite.
Endoskarn alteration: Potassic alteration with K-feldspar, epidote, sericite ± pyroxene ± garnet. Retrograde phyllic alteration generates actinolite, chlorite and clay minerals.

ORE CONTROLS: Irregular or tabular orebodies tend to form in carbonate rocks and/or calcareous volcanics or tuffs near igneous contacts. Pendants within igneous stocks can be important. Cu mineralization is present as stockwork veining and disseminations in both endo and exoskarn; it commonly accompanies retrograde alteration.

COMMENTS: Calcic Cu skarns are more economically important than magnesian Cu skarns. Cu skarns are broadly separable into those associated with strongly altered Cu-porphyry systems, and those associated with barren, generally unaltered stocks; a continuum probably exists between these two types (Einaudi *et al.*, 1981). Copper skarn deposits related to mineralized Cu porphyry intrusions tend to be larger, lower grade, and emplaced at higher structural levels than those associated with barren stocks. Most Cu skarns contain oxidized mineral assemblages, and mineral zoning is common in the skarn envelope. Those with reduced assemblages can be enriched in W, Mo, Bi, Zn, As and Au. Over half of the 340 Cu skarn occurrences in British Columbia lie in the Wrangellia Terrane of the Insular Belt, while another third are associated with intraoceanic island arc plutonism in the Quesnellia and Stikinia terranes. Some alkalic and calcalkalic Cu and Cu-Mo porphyry systems in the province (e.g. Copper Mountain, Mount Polley) are associated with variable amounts of Cu-bearing skarn alteration.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Rock analyses may show Cu-Au-Ag-rich inner zones grading outward through Au-Ag zones with high Au:Ag ratios to an outer Pb-Zn-Ag zone. Co-As-Sb-Bi-Mo-W geochemical anomalies are present in the more reduced Cu skarn deposits.

GEOPHYSICAL SIGNATURE: Magnetic, electromagnetic and induced polarization anomalies.

ASSOCIATED DEPOSIT TYPES: Porphyry Cu deposits (L04), Au (K04), Fe (K03) and Pb-Zn (K02) skarns, and replacement Pb-Zn-Ag deposits (M01).

ECONOMIC FACTORS

GRADE AND TONNAGE: Average 1 to 2 % copper. Worldwide, they generally range from 1 to 100 Mt, although some exceptional deposits exceed 300 Mt. Craigmont, British Columbia's largest Cu skarn, contained approximately 34 Mt grading 1.3 % Cu.

IMPORTANCE: Historically, these deposits were a major source of copper, although porphyry deposits have become much more important during the last 30 years . However, major Cu skarns are still worked throughout the world, including in China and the U.S.

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Pb-Zn SKARNS K02

by Gerald E. Ray[1]

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic Pb-Zn deposits.

COMMODITIES (*BYPRODUCTS*): Pb, Zn, Ag, (*Cu, Cd, W, Au*).

EXAMPLES (British Columbia - *Canada/International*): Piedmont (082FNW 129), Contact (104P 004), *Quartz Lake (Yukon, Canada), Groundhog (New Mexico, USA), Darwin (California, USA) San Antonio, Santa Eulalia and Naica (Mexico), Yeonhwa-Ulchin deposits (South Korea), Nakatatsu deposits (Japan), Shuikoushan and Tienpaoshan (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Galena and/or sphalerite-dominant mineralization genetically associated with a skarn gangue.

TECTONIC SETTING: Along continental margins where they are associated with late orogenic plutonism. Pb-Zn skarns occur at a wide range of depths, being associated with subvolcanic aphanitic dikes and high-level breccia pipes, as well as deep-level batholiths. In British Columbia, some Pb-Zn skarns are found in oceanic island arcs where they form distally to larger calcic Fe or Cu skarn systems.

AGE OF MINERALIZATION: Mainly Mesozoic, but may be any age. In British Columbia, the 80 Pb-Zn skarn occurrences identified have a wide age range; over 40 % are Early to mid-Jurassic, 22 % are Cretaceous, and a further 17 % are Eocene-Oligocene in age.

HOST/ASSOCIATED ROCK TYPES: Variable; from high-level skarns in thick limestones, calcareous tuffs and sediment to deeper level skarns in marbles and calcsilicate-bearing migmatites. Associated intrusive rocks are granodiorite to leucogranite, diorite to syenite (mostly quartz monzonite). Pb-Zn skarns tend to be associated with small stocks, sills and dikes and less commonly with larger plutons. The composition of the intrusions responsible for many distal Pb-Zn skarns is uncertain.

DEPOSIT FORM: Variable; commonly occurs along igneous or stratigraphic contacts. Can develop as subvertical chimneys or veins along faults and fissures and as subhorizontal blankets. Pb-Zn skarn deposits formed either at higher structural levels or distal to the intrusions tend to be larger and more Mn-rich compared to those formed at greater depths or more proximal.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn.

ORE MINERALOGY (Principal and *subordinate*): Sphalerite ± galena ± pyrrhotite ± pyrite ± magnetite ± arsenopyrite ± chalcopyrite ± bornite. Other trace minerals reported include *scheelite, bismuthinite, stannite, cassiterite, tetrahedrite, molybdenite, fluorite, and native gold*. Proximal skarns tend to be richer in Cu and W, whereas distal skarns contain higher amounts of Pb, Ag and Mn.

Ray, G.E. (1995): Cu Skarns; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 59-60.

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Pb-Zn SKARNS K02

ALTERATION MINERALOGY: Exoskarn alteration: Mn-rich hedenbergite (Hd30-90, Jo10-50), andraditic garnet (Ad20-100, Spess2-10) ± wollastonite ± bustamite ± rhodonite. Late-stage Mn-rich actinolite ± epidote ± ilvaite ± chlorite ± dannermorite ± rhodochrosite ± axinite. Endoskarn alteration: Highly variable in development, and in many of the distal Pb-Zn skarns the nature of the endoskarn is unknown. However, Zn-rich skarns formed near stocks are often associated with abundant endoskarn that may equal or exceed the exoskarn (Einaudi et al., 1981). Endoskarn mineralogy is dominated by epidote ± amphibole ± chlorite ± sericite with lesser rhodonite ± garnet ± vesuvianite ± pyroxene ± K-feldspar ± biotite and rare topaz. Marginal phases may contain greisen and/or tourmaline.

ORE CONTROLS: Carbonate rocks, particularly along structural and/or lithogical contacts (e.g. shale-limestone contacts or pre-ore dikes). Deposits may occur considerable distances (100-1000 m) from the source intrusions.

ASSOCIATED DEPOSIT TYPES: Pb-Zn-Ag veins (I05), Cu skarns (K01) and Cu porphyries (L03, L04). In B.C., small Pb-Zn skarns occur distally to some Fe (K03) and W (K04) skarns.

COMMENTS: Pb-Zn skarn occurrences are preferentially developed in: (1) continental margin sedimentary rocks of the Cassiar and Ancestral North America terranes, (2) oceanic island arc rocks of the Quesnellia and Stikinia terranes, and (3) arc rocks of the Wrangellia Terrane. Their widespread terrane distribution partly reflects their formation as small distal mineralized occurrences related to other skarns (notably Cu, Fe and W skarns), as well as some porphyry systems. British Columbia is endowed with some large and significant Pb-Zn reserves classified as manto deposits (Nelson, 1991; Dawson et al., 1991). These deposits lack skarn gangue, but are sometimes grouped with the Pb-Zn skarns.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Pb, Zn, Ag, Cu, Mn, As, Bi, W, F, Sn, Mo, Co, Sb, Cd and Au geochemical anomalies.

GEOPHYSICAL SIGNATURE: Generally good induced polarization response. Galena-rich orebodies may be marked by gravity anomalies whereas pyrrhotite-rich mineralization may be detected by magnetic surveys. CS-AMT may also be a useful exploration system.

OTHER EXPLORATION GUIDES: Thick limestones distal to small granitoid stocks; structural traps and lithological contacts; exoskarns with low garnet/pyroxene ratios.

ECONOMIC FACTORS

GRADE AND TONNAGE: Pb-Zn skarns tend to be small (<3 Mt) but can reach 45 Mt, grading up to 15 % Zn, 10 % Pb and > 150 g/t Ag with substantial Cd. Cu grades are generally < 0.2 %. Some deposits (e.g. Naica (Mexico) and Falun (Sweden)) contain Au. The 80 British Columbia Pb-Zn skarn occurrences are generally small and have had no major metal production.

IMPORTANCE: Important past and current producers exist in Mexico, China, U.S.A (New Mexico and California), and Argentina. No large productive Pb-Zn skarns have been discovered in B.C.

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Fe SKARNS K03

by Gerald E. Ray[1]

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic iron deposits.

COMMODITIES (*BYPRODUCTS*): Magnetite (*Cu, Ag, Au, Co, phlogopite, borate minerals*).

EXAMPLES (British Columbia - *Canada/International*): Tasu (103C003), Jessie (103B026), Merry Widow (092L044), Iron Crown (092L034), Iron Hill (092F075), Yellow Kid (092F258), Prescott (092F106), Paxton (092F107), Lake (092F259); *Shinyama (Japan), Cornwall Iron Springs (Utah, USA) Eagle Mountain (California, USA), Perschansk, Dashkesan, Sheregesh and Teya (Russia), Daiquiri (Cuba), San Leone (Italy).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Magnetite-dominant mineralization genetically associated with a skarn gangue (includes calcic and magnesian Fe skarns).

TECTONIC SETTING: Calcic Fe skarns: Intra and non-intraoceanic island arcs; rifted continental margins. Magnesian Fe skarns: Cordilleran-type, synorogenic continental margins.

AGE OF MINERALIZATION: Can be of any age, mainly Mesozoic to Cenozoic. Typically Early to mid-Jurassic in British Columbia.

HOST/ASSOCIATED ROCK TYPES: Calcic Fe skarns: Fe-rich, Si-poor intrusions derived from primitive oceanic crust. Large to small stocks and dikes of gabbro to syenite (mostly gabbro-diorite) intruding limestone, calcareous clastic sedimentary rocks, tuffs or mafic volcanics at a high to intermediate structural level. Magnesian Fe skarns: Small stocks, dikes and sills of granodiorite to granite intruding dolomite and dolomitic sedimentary rocks.

DEPOSIT FORM: Variable and includes stratiform orebodies, vertical pipes, fault-controlled sheets, massive lenses or veins, and irregular ore zones along intrusive margins.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Some hornfelsic textures. Magnetite varies from massive to disseminated to veins.

ORE MINERALOGY(Principal and *Subordinate*): Calcic Fe skarns: Magnetite ± chalcopyrite ± pyrite ± cobaltite ± pyrrhotite ± arsenopyrite ± sphalerite ± galena ± molybdenite ± bornite ± hematite ± martite ± gold. Rarely, can contain *tellurobismuthite* ± *fluorite* ± *scheelite*. Magnesian Fe skarns: Magnetite ± chalcopyrite ± bornite ± pyrite ± pyrhhotite ± sphalerite ± molybdenite.

EXOSKARN ALTERATION (both calcic and magnesian): High Fe, low Mn, diopside-hedenbergite clinopyroxene (Hd20-80) and grossular-andradite garnet (Ad20-95), ± epidote ± apatite. Late stage amphibole ± chlorite ± ilvaite ± epidote ± scapolite ± albite ± K-feldspar. Magnesian Fe skarns can contain olivine, spinel, phlogopite, xanthophyllite, brucite, serpentine, and rare borate minerals such as ludwigite, szaibelyite, fluorborite and kotoite.

Ray, G.E. (1995): Fe Skarns; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 63-65.

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

Fe SKARNS K03

ENDOSKARN ALTERATION: Calcic Fe skarns: Extensive endoskarn with Na-silicates ± garnet ± pyroxene ± epidote ± scapolite. Magnesian skarns: Minor pyroxene ± garnet endoskarn, and propyllitic alteration.

ORE CONTROLS: Stratigraphic and structural controls. Close proximity to contacts between intrusions and carbonate sequences, volcanics or calcareous tuffs and sediments. Fracture zones near igneous contacts can also be important.

ASSOCIATED DEPOSIT TYPES: Cu porphyries (L03, L04); Cu (K01) and Pb-Zn (K02) skarns; small Pb-Zn veins (I05).

COMMENTS: In both calcic and magnesian Fe skarns, early magnetite is locally intergrown with, or cut by, garnet and magnesian silicates (Korzhinski, 1964, 1965;. Sangster, 1969; Burt, 1977). Some calcic Fe skarns contain relatively small pockets of pyrrhotite-pyrite mineralization that postdate the magnetite; this mineralization can be Au-rich. Byproduct magnetite is also derived from some Sn, Cu and calcic Pb-Zn skarns. Over 90% of the 146 Fe skarn occurrences in British Columbia lie within the Wrangellia Terrane of the Insular Belt. The majority of these form where Early to mid-Jurassic dioritic plutons intrude Late Triassic limestones.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Calcic Fe skarn: enriched in Fe, Cu, Co, Au, Ni, As, Cr. Overall Cu and Au grades are low (<0.2% Cu and 0.5 g/t Au). Magnesian Fe skarn: enriched in Fe, Cu, Zn, Bo.

GEOPHYSICAL SIGNATURE: Strong positive magnetic, electromagnetic and induced polarization anomalies. Possible gravity anomalies.

OTHER EXPLORATION GUIDES: Magnetite-rich float. In the Wrangellia Terrane of British Columbia, the upper and lower contacts of the Late Triassic Quatsino limestone (or equivalent units) are favorable horizons for Fe skarn development.

ECONOMIC FACTORS

GRADE AND TONNAGE: Grades are typically 40 to 50 % Fe. Worldwide, calcic Fe skarns range from 3 to 150 Mt whereas magnesian Fe skarns can be larger (exceeding 250 Mt). In British Columbia, they reach 20 Mt and average approximately 4 Mt mined ore.

IMPORTANCE: Worldwide, these deposits were once an important source of iron, but in the last 40 years the market has been increasingly dominated by iron formation deposits. Nearly 90 % of British Columbia's historic iron production was from skarns.

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Au SKARNS K04

by Gerald E. Ray[1]

Revised 1997

IDENTIFICATION

SYNONYMS: Pyrometasomatic, tactite, or contact metasomatic Au deposits.

COMMODITIES (*BYPRODUCTS*): Au (*Cu, Ag*).

EXAMPLES (British Columbia - *Canada/International*): Nickel Plate (092HSE038), French (092HSE059), Canty (092HSE 064), Good Hope (092HSE060), QR - Quesnel River (093A121); *Fortitude, McCoy and Tomboy-Minnie (Nevada,USA), Buckhorn Mountain (Washington,USA), Diamond Hill, New World district and Butte Highlands (Montana,USA), Nixon Fork (Alaska, USA), Thanksgiving (Philippines), Browns Creek and Junction Reefs-Sheahan-Grants (New South Wales, Australia), Mount Biggenden (Queensland, Australia), Savage Lode, Coogee (Western Australia, Australia), Nambija (Ecuador), Wabu (Irian Jaya, Indonesia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Gold-dominant mineralization genetically associated with a skarn gangue consisting of Ca - Fe - Mg silicates, such as clinopyroxene, garnet and epidote. Gold is often intimately associated with Bi or Au-tellurides, and commonly occurs as minute blebs (<40 microns) that lie within or on sulphide grains. The vast majority of Au skarns are hosted by calcareous rocks (calcic subtype). The much rarer magnesian subtype is hosted by dolomites or Mg-rich volcanics. On the basis of gangue mineralogy, the calcic Au skarns can be separated into either pyroxene-rich, garnet-rich or epidote-rich types; these contrasting mineral assemblages reflect differences in the hostrock lithologies as well as the oxidation and sulphidation conditions in which the skarns developed.

TECTONIC SETTINGS: Most Au skarns form in orogenic belts at convergent plate margins. They tend to be associated with syn to late island arc intrusions emplaced into calcareous sequences in arc or back-arc environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Most deposits are related to plutonism associated with the development of oceanic island arcs or back arcs, such as the Late Triassic to Early Jurassic Nicola Group in British Columbia.

AGE OF MINERALIZATION: Phanerozoic (mostly Cenozoic and Mesozoic); in British Columbia Au skarns are mainly of Early to Middle-Jurassic age. The unusual magnesian Au skarns of Western Australia are Archean.

HOST/ASSOCIATED ROCK TYPES: Gold skarns are hosted by sedimentary carbonates, calcareous clastics, volcaniclastics or (rarely) volcanic flows. They are commonly related to high to intermediate level stocks, sills and dikes of gabbro, diorite, quartz diorite or granodiorite composition. Economic mineralization is rarely developed in the endoskarn. The I-type intrusions are commonly porphyritic, undifferentiated, Fe-rich and calc-alkaline. However, the *Nambija, Wabu* and *QR* Au skarns are associated with alkalic intrusions.

DEPOSIT FORM: Variable from irregular lenses and veins to tabular or stratiform orebodies with lengths ranging up to many hundreds of metres. Rarely, can occur as vertical pipe-like bodies along permeable structures.

Ray, G.E. (1997): Au Skarns; in Geological Fieldwork 1997, *British Columbia Ministry of Employment and Investment*, Paper 1998-1, pages 24H-H4.

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

Au SKARNS K04

TEXTURE/STRUCTURE: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to layered textures in exoskarn. Some hornfelsic textures. Fractures, sill-dike margins and fold hinges can be an important loci for mineralization.

ORE MINERALOGY (Principal and *subordinate*): The gold is commonly present as micron-sized inclusions in sulphides, or at sulphide grain boundaries. To the naked eye, ore is generally indistinguishable from waste rock. Due to the poor correlation between Au and Cu in some Au skarns, the economic potential of a prospect can be overlooked if Cu-sulphide-rich outcrops are preferentially sampled and other sulphide-bearing or sulphide-lean assemblages are ignored. The ore in pyroxene-rich and garnet-rich skarns tends to have low Cu:Au (<2000:1), Zn:Au (<100:1) and Ag/Au (<1:1) ratios, and the gold is commonly associated with Bi minerals (particularly Bi tellurides).

Magnesian subtype: Native gold ± pyrrhotite ± chalcopyrite ± pyrite ± *magnetite* ± *galena* ± *tetrahedrite*.

Calcic subtype:

Pyroxene-rich Au skarns: Native gold ± pyrrhotite ± arsenopyrite ± *chalcopyrite* ± *tellurides* (e.g. *hedleyite*, *tetradymite*, *altaite* and *hessite*) ± *bismuthinite* ± *cobaltite* ± *native bismuth* ± *pyrit*e ± *sphalerite* ± *maldonite*. They generally have a high sulphide content and high pyrrhotite:pyrite ratios. Mineral and metal zoning is common in the skarn envelope. At Nickel Plate for example, this comprises a narrow proximal zone of coarse-grained, garnet skarn containing high Cu:Au ratios, and a wider, distal zone of finer grained pyroxene skarn containing low Cu:Au ratios and the Au-sulphide orebodies.

Garnet-rich Au skarns: Native gold ± chalcopyrite ± pyrite ± arsenopyrite ± sphalerite ± magnetite ± hematite ± *pyrrhotite* ± *galena* ± *tellurides* ± *bismuthinite*. They generally have a low to moderate sulphide content and low pyrrhotite:pyrite ratios.

Epidote-rich Au skarn: Native gold ± chalcopyrite ± pyrite ± arsenopyrite ± hematite ± magnetite ± *pyrrhotite* ± *galena* ± *sphalerite* ± *tellurides*. They generally have a moderate to high sulphide content with low pyrrhotite:pyrite ratios.

EXOSKARN MINERALOGY (GANGUE):

Magnesian subtype: Olivine, clinopyroxene (Hd2-50), garnet (Ad7-30), chondrodite and monticellite. Retrograde minerals include serpentine, epidote, vesuvianite, tremolite-actinolite, phlogopite, talc, K-feldspar and chlorite.

Calcic subtype:

Pyroxene-rich Au skarns: Extensive exoskarn, generally with high pyroxene:garnet ratios. Prograde minerals include diopsidic to hedenbergitic clinopyroxene (Hd 20-100), K-feldspar, Fe-rich biotite, low Mn grandite garnet (Ad 10-100), wollastonite and vesuvianite. Other less common minerals include rutile, axinite and sphene. Late or retrograde minerals include epidote, chlorite, clinozoisite, vesuvianite, scapolite, tremolite-actinolite, sericite and prehnite.

Garnet-rich Au skarns: Extensive exoskarn, generally with low pyroxene:garnet ratios. Prograde minerals include low Mn grandite garnet (Ad 10-100), K-feldspar, wollastonite, diopsidic clinopyroxene (Hd 0-60), epidote, vesuvianite, sphene and apatite. Late or retrograde minerals include epidote, chlorite, clinozoisite, vesuvianite, tremolite-actinolite, sericite, dolomite, siderite and prehnite.

Epidote-rich Au skarns: Abundant epidote and lesser chlorite, tremolite-actinolite, quartz, K-feldspar, garnet, vesuvianite, biotite, clinopyroxene and late carbonate. At the *QR* deposit, epidote-pyrite and carbonate-pyrite veinlets and coarse aggregates are common, and the best ore occurs in the outer part of the alteration envelope, within 50 m of the epidote skarn front.

ENDOSKARN MINERALOGY (GANGUE): Moderate endoskarn development with K-feldspar, biotite, Mg-pyroxene (Hd 5-30) and garnet. Endoskarn at the epidote-rich *QR* deposit is characterized by calcite, epidote, clinozoisite and tremolite whereas at the *Butte Highlands* Mg skarn it contains argillic and propyllitic alteration with garnet, clinopyroxene and epidote.

WEATHERING: In temperate and wet tropical climates, skarns often form topographic features with positive relief.

Au SKARNS K04

ORE CONTROLS: The ore exhibits strong stratigraphic and structural controls. Orebodies form along sill-dike intersections, sill-fault contacts, bedding-fault intersections, fold axes and permeable faults or tension zones. In the pyroxene-rich and epidote-rich types, ore commonly develops in the more distal portions of the alteration envelopes. In some districts, specific suites of reduced, Fe-rich intrusions are spatially related to Au skarn mineralization. Ore bodies in the garnet-rich Au skarns tend to lie more proximal to the intrusions.

GENETIC MODEL: Many Au skarns are related to plutons formed during oceanic plate subduction. There is a worldwide spatial, temporal and genetic association between porphyry Cu provinces and calcic Au skarns. Pyroxene-rich Au skarns tend to be hosted by siltstone-dominant packages and form in hydrothermal systems that are sulphur-rich and relatively reduced. Garnet-rich Au skarns tend to be hosted by carbonate-dominant packages and develop in more oxidising and/or more sulphur-poor hydrothermal systems.

ASSOCIATED DEPOSIT TYPES: Au placers (C01,C02), calcic Cu skarns (K01), porphyry Cu deposits (L04) and Au-bearing quartz and/or sulphide veins (I01, I02). Magnesian subtype can be associated with porphyry Mo deposits (L05) and possibly W skarns (K05). In British Columbia there is a negative spatial association between Au and Fe skarns at regional scales, even though both classes are related to arc plutonism. Fe skarns are concentrated in the Wrangellia Terrane whereas most Au skarn occurrences and all the economic deposits lie in Quesnellia.

COMMENTS: Most Au skarns throughout the world are calcic and are associated with island arc plutonism. However, the *Savage Lode* magnesian Au skarn occurs in the Archean greenstones of Western Australia and the *Butte Highlands* magnesian Au skarn in Montana is hosted by Cambrian platformal dolomites. Note: although the Nickel Plate deposit lies distal to the Toronto stock in the pyroxene-dominant part of the skarn envelope, the higher grade ore zones commonly lie adjacent to sills and dikes where the exoskarn contains appreciable amounts of garnet with the clinopyroxene.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Au, As, Bi, Te, Co, Cu, Zn or Ni soil, stream sediment and rock anomalies, as well as some geochemical zoning patterns throughout the skarn envelope (notably in Cu/Au, Ag/Au and Zn/Au ratios). Calcic Au skarns (whether garnet-rich or pyroxene-rich) tend to have lower Zn/Au, Cu/Au and Ag/Au ratios than any other skarn class. The intrusions related to Au skarns may be relatively enriched in the compatible elements Cr, Sc and V, and depleted in lithophile incompatible elements (Rb, Zr, Ce, Nb and La), compared to intrusions associated with most other skarn types.

GEOPHYSICAL SIGNATURE: Airborne magnetic or gravity surveys to locate plutons. Induced polarization and ground magnetic follow-up surveys can outline some deposits.

OTHER EXPLORATION GUIDES: Placer Au. Any carbonates, calcareous tuffs or calcareous volcanic flows intruded by arc-related plutons have a potential for hosting Au skarns. Favorable features in a skarn envelope include the presence of: (a) proximal Cu-bearing garnet skarn and extensive zones of distal pyroxene skarn which may carry micron Au, (b) hedenbergitic pyroxene (although diopsidic pyroxene may predominate overall), (c) sporadic As-Bi-Te geochemical anomalies, and, (d) undifferentiated, Fe-rich intrusions with low Fe_2O_3/FeO ratios. Any permeable calcareous volcanics intruded by high-level porphyry systems (particularly alkalic plutons) have a potential for hosting epidote-rich skarns with micron Au. During exploration, skarns of all types should be routinely sampled and assayed for Au, even if they are lean in sulphides.

ECONOMIC IMPORTANCE

TYPICAL GRADE AND TONNAGE: These deposits range from 0.4 to 13 Mt and from 2 to 15 g/t Au. Theodore *et al*. (1991) report median grades and tonnage of 8.6 g/t Au, 5.0 g/t Ag and 213 000 t. *Nickel Plate* produced over 71 tonnes of Au from 13.4 Mt of ore (grading 5.3 g/t Au). The 10.3 Mt *Fortitude* (Nevada) deposit graded 6.9 g/t Au whereas the 13.2 Mt *McCoy* skarn (Nevada) graded 1.5 g/t Au. The *QR* epidote-rich Au skarn has reserves exceeding 1.3 Mt grading 4.7 g/t Au.

IMPORTANCE: Recently, there have been some significant Au skarn deposits discovered around the world (e.g. *Buckhorn Mountain*, *Wabu*, *Fortitude*). Nevertheless, total historic production of Au from skarn (more than 1 000 t of metal) is minute compared to production from other deposit types. The *Nickel Plate* deposit (Hedley, British Columbia) was probably one of the earliest major Au skarns in the world to be mined. Skarns have accounted for about 16 % of British Columbia's Au production, although nearly half of this was derived as a byproduct from Cu and Fe skarns.

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W SKARNS K05

by Gerald E. Ray[1]

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic tungsten deposits.

COMMODITIES (*BYPRODUCTS*): W (*Mo, Cu, Sn, Zn*).

EXAMPLES (British Columbia - *Canada/International*): Emerald Tungsten (082FSW010), Dodger (082FSW011), Feeney (082FSW247), Invincible (082FSW218), Dimac (082M123); *Fostung (Ontario, Canada), MacTung (Yukon, Canada), Cantung (Northwest Territories, Canada), Pine Creek and Strawberry(California, USA), Osgood Range (Nevada, USA), King Island (Tasmania, Australia), Sang Dong (South Korea).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Scheelite-dominant mineralization genetically associated with a skarn gangue.

TECTONIC SETTING: Continental margin, synorogenic plutonism intruding deeply buried sequences of eugeoclinal carbonate-shale sedimentary rocks. Can develop in tectonically thickened packages in back-arc thrust settings.

AGE OF MINERALIZATION: Mainly Mesozoic, but may be any age. Over 70% of the W skarns in British Columbia are related to Cretaceous intrusions.

HOST/ASSOCIATED ROCK TYPES: Pure and impure limestones, calcareous to carbonaceous pelites. Associated with tonalite, granodiorite, quartz monzonite and granite of both I and S-types. W skarn-related granitoids, compared to Cu skarn-related plutonic rocks, tend to be more differentiated, more contaminated with sedimentary material, and have crystallized at a deeper structural level.

DEPOSIT FORM: Stratiform, tabular and lens-like orebodies. Deposits can be continous for hundreds of metres and follow intrusive contacts.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Biotite hornfelsic textures common.

ORE MINERALOGY (Principal and *subordinate*): Scheelite ± molybdenite ± chalcopyrite ± pyrrhotite ± sphalerite ± arsenopyrite ± pyrite ± powellite. May contain *trace wolframite, fluorite, cassiterite, galena, marcasite and bornite*. Reduced types are characterized by pyrrhotite, magnetite, bismuthinite, native bismuth and high pyrrhotite:pyrite ratios. Variable amounts of quartz-vein stockwork (with local molybdenite) can cut both the exo and endoskarn. The Emerald Tungsten skarns in British Columbia include pyrrhotite-arsenopyrite veins and pods that carry up to 4 g/t Au.

Ray, G.E. (1995):W Skarns; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 71-73.

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

W SKARNS K05

ALTERATION MINERALOGY: Exoskarn alteration: Inner zone of diopside-hedenbergite (Hd60-90, Jo5-20) ± grossular-andradite (Ad 10-50, Spess5-50) ± biotite ± vesuvianite, with outer barren wollastonite-bearing zone. An innermost zone of massive quartz may be present. Late-stage spessartine ± almandine ± biotite ± amphibole ± plagioclase ± phlogopite ± epidote ± fluorite ± sphene. Reduced types are characterized by hedenbergitic pyroxene, Fe-rich biotite, fluorite, vesuvianite, scapolite and low garnet:pyroxene ratios, whereas oxidized types are characterized by salitic pyroxene, epidote and andraditic garnet and high garnet:pyroxene ratios. Exoskarn envelope can be associated with extensive areas of biotite hornfels. Endoskarn alteration: Pyroxene ± garnet ± biotite ± epidote ± amphibole ± muscovite ± plagioclase ± pyrite ± pyrrhotite ± trace tourmaline and scapolite; local greisen developed.

ORE CONTROLS: Carbonate rocks in extensive thermal aureoles of intrusions; gently inclined bedding and intrusive contacts; structural and/or stratigraphic traps in sedimentary rocks, and irregular parts of the pluton/country rock contacts.

ASSOCIATED DEPOSIT TYPES: Sn (K06), Mo (K07) and Pb-Zn (K02) skarns. Wollastonite-rich industrial mineral skarns (K09).

COMMENTS: W skarns are separable into two types (Newberry, 1982): reduced skarns (e.g. Cantung, Mactung), formed in carbonaceous rocks and/or at greater depths, and oxidized skarns (e.g. King Island), formed in hematitic or non-carbonaceous rocks, and/or at shallower depths. Late retrograde alteration is an important factor in many W skarns because, during retrogression, the early low-grade mineralization is often scavenged and redeposited into economic high-grade ore zones (e.g. Bateman, 1945; Dick, 1976, 1980). Dolomitic rocks tend to inhibit the development of W skarns; consequently magnesian W skarns are uncommon. In British Columbia they are preferentially associated with Cretaceous intrusions and hosted by calcareous, Cambrian age cratonic, pericratonic and displaced continental margin rocks in the Cassiar, Kootenay-Barkerville, Dorsay and Ancestral North American terranes.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: W, Cu, Mo, As, Bi and B. Less commonly Zn, Pb, Sn, Be and F geochemical anomalies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Grades range between 0.4 and 2 % WO_3 (typically 0.7 %). Deposits vary from 0.1 to >30 Mt.

IMPORTANCE: Skarn deposits have accounted for nearly 60 % of the western world's production, and over 80 % of British Columbia's production.

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Sn SKARNS K06

by Gerald E. Ray[1]

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic tin deposits.

COMMODITIES (*BYPRODUCTS*): Sn (*W, Zn, magnetite*).

EXAMPLES (British Columbia - *Canada/International*): Only three in British Columbia - Silver Diamond, Atlin Magnetite, and Daybreak (104N069, 126 and 134 respectively); *JC (Yukon, Canada), Moina, Mount Lindsay, Hole 16 and Mt. Garnet (Tasmania, Australia), Lost River (Alaska, USA).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Cassiterite-dominant mineralization genetically associated with a skarn gangue (includes calcic and magnesian Sn skarns).

TECTONIC SETTINGS: Late to post orogenic granites emplaced into thick and deeply buried continental margin sedimentary sequences, or sequences in rifted or stable cratonic environments.

AGE OF MINERALIZATION: Most economic deposits are Mesozoic or Paleozoic, but occurrences may be any age (the occurrences in British Columbia are Late Cretaceous).

HOST/ASSOCIATED ROCK TYPES: Carbonates and calcareous sedimentary sequences. Associated with differentiated (low Ca, high Si and K) ilmenite-series granite, adamellite and quartz monzonitic stocks and batholiths (of both I and S-type) intruding carbonate and calcareous clastic rocks. Sn skarns tend to develop in reduced and deep-level environments and may be associated with greisen alteration.

DEPOSIT FORM: Variable; can occur as either stratiform, stockwork, pipe-like or irregular vein-like orebodies.

TEXTURES: Igneous textures in endoskarn. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn; wrigglite skarns contain thin rhythmic and alternating layers rich in either magnetite, fluorite, vesuvianite or tourmaline. Some hornfelsic textures.

ORE MINERALOGY: Cassiterite ± scheelite ± arsenopyrite ± pyrrhotite ± chalcopyrite ± stannite ± magnetite ± bismuthinite ± sphalerite ± pyrite ± ilmenite.

ALTERATION MINERALOGY: Exoskarn alteration: Grandite garnet (Ad15-75, Pyralsp 5-30) (sometimes Sn, F, and Be enriched), hedenbergitic pyroxene (Hd40-95) ± vesuvianite (sometimes Sn and F-enriched) ± malayaite ± Fe and/or F-rich biotite ± stanniferous sphene ± gahnite ± rutile ± Sn-rich ilvaite ± wollastonite ± adularia. Late minerals include muscovite, Fe-rich biotite, chlorite, tourmaline, fluorite, sellaite, stilpnomelane, epidote and amphibole (latter two minerals can be Sn rich). Associated greisens include quartz and muscovite ± tourmaline ± topaz ± fluorite ± cassiterite ± sulphides. Magnesian Sn skarns can also contain olivine, serpentine, spinel, ludwigite, talc and brucite.

Ray, G.E. (1995): Sn Skarns; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 75-76.

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Sn SKARNS K06

ORE CONTROLS: Differentiated plutons intruding carbonate rocks; fractures, lithological or structural contacts. Deposits may develop some distance (up to 500 m) from the source intrusions.

ASSOCIATED DEPOSIT TYPES: W skarns (K05), Sn ± Be greisens (I13), Sn-bearing quartz-sulphide veins and mantos (J02). In British Columbia, some of the Sn and W skarn-related intrusions (e.g. Cassiar batholith, Mount Haskin stock) are associated with small Pb-Zn skarn occurrences (K02).

COMMENTS: Sn skarns generally form at deep structural levels and in reduced oxidation states. However, wrigglite Sn skarns tend to develop in relatively near-surface conditions, such as over the cupolas of high-level granites. The three Sn skarn occurrences in British Columbia are all associated with an S-type, fluorine-rich accretionary granite, the Surprise Lake batholith. However, they are unusual in being hosted in allochthonous oceanic rocks of the Cache Creek Terrane.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sn, W, F, Be, Bi, Mo, As, Zn, Cu, Rb, Li, Cs and Re geochemical anomalies. Borate-bearing magnesian Sn skarns may exhibit B enrichment.

GEOPHYSICAL SIGNATURE: Magnetic, induced polarization and possible radiometric anomalies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Deposits can grade up to 1 % Sn, but much of the metal occurring in malayaite, garnet, amphibole and epidote is not economically recoverable. Worldwide, deposits reach 30 Mt, but most range between 0.1 and 3 Mt.

IMPORTANCE: Worldwide, Sn skarns represent a major reserve of tin. However, current production from skarn is relatively minor compared to that from placer Sn deposits and Sn-rich greissens and mantos. British Columbia has had no Sn production from skarns.

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Mo SKARNS K07

by Gerald E. Ray[1]

IDENTIFICATION

SYNONYMS: Pyrometasomatic or contact metasomatic Mo deposits.

COMMODITIES (*BYPRODUCTS*): Mo (*W, Cu, Pb, Zn, Sn, Bi, U, Au*).

EXAMPLES (British Columbia - *Canada/International*): Coxey (082FSW110), Novelty (082FSW107); *Mount Tennyson (New South Wales, Australia), Little Boulder Creek (Idaho, USA), Cannivan Gulch (Montana, USA), Azegour (Morocco), Yangchiachangtze (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Molybdenite-dominant mineralization genetically associated with a skarn gangue (includes calcic and magnesian Mo skarns). Mo skarns are broadly separable into polymetallic and "molybdenite-only" types (see comments below).

TECTONIC SETTING: Late orogenic plutonism (derived from transitional crust) intruding continental margin carbonate sequences. Also, some are associated with Mo-bearing porphyry systems developed within intra-oceanic island arcs.

AGE OF MINERALIZATION: Mainly Mesozoic and Paleozoic, but may be any age. In British Columbia, they are mainly of Early to mid-Jurassic in age.

HOST/ASSOCIATED ROCK TYPES: Stocks and dikes of evolved, commonly leucocratic quartz monzonite to granite (some containing primary biotite and muscovite) intruding calcareous clastic rocks. Deposits tend to develop close to intrusive contacts. Some of the Mo skarns in British Columbia are associated with high-level intrusions that have explosive breccia textures.

DEPOSIT FORM: Irregular orebodies along, and controlled by, the intrusive contacts.

TEXTURES: Igneous textures in endoskarn; local explosive breccia textures. Coarse to fine-grained, massive granoblastic to mineralogically layered textures in exoskarn. Some hornfelsic textures.

ORE MINERALOGY (Principal and *subordinate*): Molybdenite ± scheelite ± pyrrhotite ± powellite ± chalcopyrite ± arsenopyrite ± pyrite ± pyrrhotite ± bismuthinite ± sphalerite ± fluorite. In rare instances also *galena* ± *magnetite* ± *uraninite* ± *pitchblende* ± *cassiterite* ± *cobalite* ± *stannite* ± *gold*.

EXOSKARN ALTERATION: Calcic Mo skarns: Hedenbergite pyroxene (Hd50-80, Jo1-3) ± low Mn grossular-andradite garnet (Ad40-95) ± wollastonite ± biotite ± vesuvianite. Magnesian Mo skarns: olivine (Fo96). Retrograde minerals: Calcic skarns: amphibole ± epidote ± chlorite and muscovite. Magnesian skarns: serpentine ± tremolite ± chlorite.

ENDOSKARN ALTERATION: Clinopyroxene, K-feldspar, hornblende, epidote, quartz veining, sericite, molybdenite.

ORE CONTROLS: Carbonate or calcareous rocks in thermal aureoles adjacent to intrusive margins.

Ray, G.E. (1995): Sn Skarns; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 75-76.

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

Mo SKARNS K07

ASSOCIATED DEPOSIT TYPES: Mo porphyries of quartz monzonite type (L05), Mo-sulphide veins, and Zn-sulphide veins (I05). Some Mo skarns in China are associated with distal, sphalerite-rich mineralization.

COMMENTS: Mo skarns are broadly separable into two types: polymetallic (containing molybdenite with other W, Zn, Pb, Bi, Sn, Co or U-rich minerals), and "molybedenite-only" (containing mainly molybdenite with no or few other sulphides). Over 85% of the 21 Mo skarns recorded in British Columbia occur in the Omineca Belt. More than 60% are hosted in cratonic, pericratonic and displaced continental margin rocks of the Kootenay, Cassiar and Ancestral North America terranes, and a further 19% are found in the Quesnellia Terrane.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Enriched in Mo, Zn, Cu, Sn, Bi, As, F, Pb, U, Sb, Co (Au).

GEOPHYSICAL SIGNATURE: Positive magnetic and induced polarization anomalies.

ECONOMIC FACTORS

GRADE AND TONNAGE: Worldwide, grades range from 0.1 to 2 % MoS_2, and tonnages between 0.1 and 2 Mt. In British Columbia, the Coxey deposit produced 1 Mt of ore grading approximately 0.17 % MoS_2. The Novelty and Giant are polymetallic Mo skarns near Rossland, British Columbia with unusually high grades of up to 47 g/t Au, 1.4 % Ni, 30.5 % As and 4.84 % Co.

IMPORTANCE: Mo skarns tend to be smaller tonnage and less economically important than porphyry Mo deposits.

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DRAFT #: 7 February 5, 1995

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).

[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
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[3] United States Geological Survey, Tuscon, Arizona, United States

WOLLASTONITE SKARNS K09

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).

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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SUBVOLCANIC Cu-Au-Ag (As-Sb) L01

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYMS: Transitional, intrusion-related (polymetallic) stockwork and vein.

COMMODITIES (*BYPRODUCTS*): Cu, Au, Ag (*As, Sb*).

EXAMPLES (British Columbia - *Canada/International*): Equity Silver (93L001); Thorn prospect (104K031,116); *Rochester District (Nevada, USA), Kori Kollo (Bolivia), the 'epithermal gold' zones at Lepanto (Philippines), parts of Recsk (Hungary) and Bor (Serbia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Pyritic veins, stockworks and breccias in subvolcanic intrusive bodies with stratabound to discordant massive pyritic replacements, veins, stockworks, disseminations and related hydrothermal breccias in country rocks. These deposits are located near or above porphyry Cu hydrothermal systems and commonly contain pyritic auriferous polymetallic mineralization with Ag sulphosalt and other As and Sb-bearing minerals.

TECTONIC SETTINGS: Volcano-plutonic belts in island arcs and continental margins; continental volcanic arcs. Subvolcanic intrusions are abundant. Extensional tectonic regimes allow high-level emplacement of the intrusions, but compressive regimes are also permissive.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Uppermost levels of intrusive systems and their adjoining fractured and permeable country rocks, commonly in volcanic terrains with eroded stratovolcanoes. Subvolcanic domes and flow-dome complexes can also be mineralized; their uppermost parts are exposed without much erosion.

AGE OF MINERALIZATION: Mainly Tertiary, a number of older deposits have been identified.

HOST/ASSOCIATED ROCK TYPES: Subvolcanic (hypabyssal) stocks, rhyodacite and dacite flow-dome complexes with fine to coarse-grained quartz-phyric intrusions are common. Dike swarms and other small subvolcanic intrusions are likely to be present. Country rocks range widely in character and age. Where coeval volcanic rocks are present, they range from andesite to rhyolite in composition and occur as flows, breccias and pyroclastic rocks with related erosion products (epiclastic rocks).

Pantleyev, A. (1995): Subvolcanic Cu-Au-Ag (As-Sb); *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 79-82.

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SUBVOLCANIC Cu-Ag-Au (As-Sb) L01

DEPOSIT FORM: Stockworks and closely-spaced to sheeted sets of sulphide-bearing veins in zones within intrusions and as structurally controlled and stratabound or bedding plane replacements along permeable units and horizons in hostrocks. Veins and stockworks form in transgressive hydrothermal fluid conduits that can pass into pipe-like and planar breccias. Breccia bodies are commonly tens of metres and, rarely, a few hundred metres in size. Massive sulphide zones can pass outward into auriferous pyrite-quartz-sericite veins and replacements.

TEXTURE/STRUCTURE: Sulphide and sulphide-quartz veins and stockworks. Open space filling and replacement of matrix in breccia units. Bedding and lithic clast replacements by massive sulphide, disseminations and veins. Multiple generations of veins and hydrothermal breccias are common. Pyrite is dominant and quartz is minor to absent in veins.

ORE MINERALOGY [Principal and *subordinate*]: Pyrite, commonly as auriferous pyrite, chalcopyrite, terahedrite/tennantite; *enargite/luzonite, covellite, chalcocite, bornite, sphalerite, galena, arsenopyrite, argentite, sulphosalts, gold, stibnite, molybdenite, wolframite or scheelite, pyrrhotite, marcasite, realgar,hematite, tin and bismuth minerals.* Depth zoning is commonly evident with pyrite-rich deposits containing enargite near surface, passing downwards into tetrahedrite/tennantite + chalcopyrite and then chalcopyrite in porphyry intrusions at depth.

GANGUE MINERALOGY [Principal and *subordinate*]: Pyrite, sericite, quartz; *kaolinite, alunite, jarosite (mainly in supergene zone).*

ALTERATION MINERALOGY [Principal and *subordinate*]: Pyrite, sericite, quartz; kaolinite, dickite, pyrophyllite, andalusite, diaspore, corundum, tourmaline, alunite, anhydrite, barite, chalcedony, dumortierite, lazulite (variety scorzalite), rutile and chlorite. Tourmaline as schorlite (a black Fe-rich variety) can be present locally; it is commonly present in breccias with quartz and variable amounts of clay minerals. Late quartz-alunite veins may occur.

WEATHERING: Weathering of pyritic zones can produce limonitic blankets containing abundant jarosite, goethite and, locally, alunite.

GENETIC MODEL: These deposits represent a transition from porphyry copper to epithermal conditions with a blending and blurring of porphyry and epithermal characteristics. Mineralization is related to robust, evolving hydrothermal systems derived from porphyritic, subvolcanic intrusions. Vertical zoning and superimposition of different types of ores is typical due, in large part, to overlapping stages of mineralizations. Ore fluids with varying amounts of magmatic-source fluids have temperatures generally greater than those of epithermal systems, commonly in the order of 300° C and higher. Fluid salinities are also relatively high, commonly more than 10 weight per cent NaCl-equivalent and rarely in the order of 50 %, and greater.

ORE CONTROLS: Strongly fractured to crackled zones in cupolas and internal parts of intrusions and flow-dome complexes; along faulted margins of high-level intrusive bodies. Permeable lithologies, both primary and secondary in origin, in the country rocks. Primary controls are structural features such as faults, shearz, fractured and crackled zones and breccias. Secondary controls are porous volcanic units, bedding plane contacts and unconformities. Breccia pipes provide channelways for hydrothermal fluids originating from porphyry Cu systems and commonly carry elevated values of Au and Ag. The vein and replacement style deposits can be separated from the deeper porphyry Cu mineralization by 200 to 700 m.

ASSOCIATED DEPOSIT TYPES: Porphyry Cu-Au±Mo (L04); epithermal Au-Ag commonly both high-sulphidation (H04) and low-sulphidation (H05) pyrite-sericite-bearing types; auriferous quartz-pyrite veins, enargite massive sulphide also known as enargite gold.

SUBVOLCANIC Cu-Ag-Au (As-Sb) L01

COMMENTS: This deposit type is poorly defined and overall, uncommon. It is in large part stockworks and a closely spaced to sheeted sulphide vein system with local massive to disseminated replacement sulphide zones. It forms as a high-temperature, pyrite-rich, commonly tetrahderite, and rarely enargite-bearing, polymetallic affiliate of epithermal Au-Ag mineralization. Both low and high-sulphidation epithermal styles of mineralization can be present. As and Sb enrichments in ores are characteristic. If abundant gas and gas condensates evolve from the hydrothermal fluids there can be extensive acid leaching and widespread, high-level advanced argillic alteration. This type of alteration is rarely mineralized.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Elevated values of Au, Cu, Ag, As, Sb, Zn, Cd, Pb, Fe and F; at deeper levels Mo, Bi, W and locally Sn. In some deposits there is local strong enrichment in B, Co, Ba, K and depletion of Na. Both depth zoning and lateral zoning are evident.

GEOPHYSICAL SIGNATURE: Induced polarization to delineate pyrite zones. Magnetic surveys are useful in some cases to outline lithologic units and delineate contacts. Electromagnetic surveys can be used effectively where massive sulphide bodies are present.

OTHER EXPLORATION GUIDES: Association with widespread sericite-pyrite and quartz-sericite-pyrite that might be high-level leakage from buried porphyry Cu ± Au ± Mo deposits. Extensive overprinting of sericite/illite by kaolinite; rare alunite. In some deposits, high-temperature aluminous alteration minerals pyrophyllite and andalusite are present but are generally overprinted by abundant sericite and lesser kaolinite. Tourmaline and phosphate minerals can occur. There is commonly marked vertical mineralogical and geochemical depth-zoning.

ECONOMIC FACTORS

GRADE AND TONNAGE: The deposits have pyritic orebodies of various types; vertical stacking and pronounced metal zoning are prevalent. Small, high-grade replacement orebodies containing tetrahedrite/tennantite, and rarely enargite, can form within larger zones of pyritization. The massive sulphide replacement ores have associated smaller peripheral, structurally controlled zones of sericitic alteration that constitute pyritic orebodies grading ~ 4 g/t gold. Similar tetrahedrite-bearing ores with bulk mineable reserves at Equity Silver were in the order of 30 Mt with 0.25% Cu and ~86 g/t Ag and 1 g/t Au. At the Recsk deposit, Hungary, shallow breccia-hosted Cu-Au ores overlie a porphyry deposit containing ~1000 Mt with 0.8 % Cu. The closely spaced pyritic fracture and vein systems at Kollo, La Joya district, Bolivia contained 10 Mt oxide ore with 1.62 g/t Au and 23.6 g/t Ag and had sulphide ore reserves of 64 Mt at 2.26 g/t Au and 13.8 g/t Ag.

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PORPHYRY Cu-Au: ALKALIC L03

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYMS: Porphyry copper, porphyry Cu-Au, diorite porphyry copper.

COMMODITIES (*BYPRODUCTS*): Cu, Au (*Ag*).

EXAMPLES (British Columbia - *Canada/International*): Iron Mask batholith deposits - Afton (092INE023), Ajax (092INE012, 013), Mt. Polley (Cariboo Bell, 093A008), Mt. Milligan (093N196, 194), Copper Mt./Ingerbelle (092HSE001, 004), Galore Creek(104G090), Lorraine? (093N002); *Ok Tedi (Papua New Guinea); Tai Parit and Marian? (Philippines).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockworks, veinlets and disseminations of pyrite, chalcopyrite, bornite and magnetite occur in large zones of economically bulk-mineable mineralization in or adjoining porphyritic intrusions of diorite to syenite composition. The mineralization is spatially, temporally and genetically associated with hydrothermal alteration of the intrusive bodies and hostrocks.

TECTONIC SETTING(S): In orogenic belts at convergent plate boundaries, commonly oceanic volcanic island arcs overlying oceanic crust. Chemically distinct magmatism with alkalic intrusions varying in composition from gabbro, diorite and monzonite to nepheline syenite intrusions and coeval shoshonitic volcanic rocks, takes place at certain times in segments of some island arcs. The magmas are introduced along the axis of the arc or in cross-arc structures that coincide with deep-seated faults. The alkalic magmas appear to form where there is slow subduction in steeply dipping, tectonically thickened lithospheric slabs, possibly when polarity reversals (or `flips') take place in the subduction zones. In British Columbia all known deposits are found in Quesnellia and Stikinia terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High level (epizonal) stock emplacement levels in magmatic arcs, commonly oceanic volcanic island arcs with alkalic (shoshonitic) basic flows to intermediate and felsic pyroclastic rocks. Commonly the high-level stocks and related dikes intrude their coeval and cogenetic volcanic piles.

AGE OF MINERALIZATION: Deposits in the Canadian Cordillera are restricted to the Late Triassic/Early Jurassic (215-180 Ma) with seemingly two clusters around 205-200 and ~ 185 Ma. In southwest Pacific island arcs, deposits are Tertiary to Quaternary in age.

Panteleyev, A. (1995): Porphyry Cu-Au: Alkalic; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 83-86.

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

PORPHYRY Cu-Au: ALKALIC L03

HOST/ASSOCIATED ROCK TYPES: Intrusions range from fine through coarse-grained, equigranular to coarsely porphyritic and, locally, pegmatitic high-level stocks and dike complexes. Commonly there is multiple emplacement of successive intrusive phases and a wide variety of breccias. Compositions range from (alkalic) gabbro to syenite. The syenitic rocks vary from silica-undersaturated to saturated compositions. The most undersaturated nepheline normative rocks contain modal nepheline and, more commonly, pseudoleucite. The silica-undersaturated suites are referred to as nepheline alkalic whereas rocks with silica near-saturation, or slight silica over saturation, are termed quartz alkalic (Lang *et al.*, 1993). Coeval volcanic rocks are basic to intermediate alkalic varieties of the high-K basalt and shoshonite series and rarely phonolites.

DEPOSIT FORM: Stockworks and veinlets, minor disseminations and replacements throughout large areas of hydrothermally altered rock, commonly coincident wholly or in part with hydrothermal or intrusion breccias. Deposit boundaries are determined by economic factors that outline ore zones within larger areas of low-grade, laterally zoned mineralization.

TEXTURE/STRUCTURE: Veinlets and stockworks; breccia, sulphide and magnetite grains in fractures and along fracture selvages; disseminated sulphides as interstitial or grain and lithic clast replacements. Hydrothermally altered rocks can contain coarse-grained assemblages including feldspathic and calcsilicate replacements ('porphyroid' textures) and open space filling with fine to coarse, granular and rarely pegmatitic textures.

ORE MINERALOGY [Principal and *subordinate*]: Chalcopyrite, pyrite and magnetite; bornite, chalcocite and *rare galena, sphalerite, tellurides, tetrahderite, gold and silver*. Pyrite is less abundant than chalcopyrite in ore zones.

GANGUE MINERALOGY: Biotite, K-feldspar and sericite; garnet, clinopyroxene (diopsidic) and anhydrite. Quartz veins are absent but hydrothermal magnetite veinlets are abundant.

ALTERATION MINERALOGY: Biotite, K-feldspar, sericite, anhydrite/gypsum, magnetite, hematite, actinolite, chlorite, epidote and carbonate. Some alkalic systems contain abundant garnet including the Ti-rich andradite variety - melanite, diopside, plagioclase, scapolite, prehnite, pseudoleucite and apatite; rare barite, fluorite, sodalite, rutile and late-stage quartz. Central and early formed potassic zones, with K-feldspar and generally abundant secondary biotite and anhydrite, commonly coincide with ore. These rocks can contain zones with relatively high-temperature calcsilicate minerals diopside and garnet. Outward there can be flanking zones in basic volcanic rocks with abundant biotite that grades into extensive, marginal propylitic zones. The older alteration assemblages can be overprinted by phyllic sericite-pyrite and, less commonly, sericite-clay-carbonate-pyrite alteration. In some deposits, generally at depth in silica-saturated types, there can be either extensive or local central zones of sodic alteration containing characteristic albite with epidote, pyrite, diopside, actinolite and rarer scapolite and prehnite.

ORE CONTROLS: Igneous contacts, both internal between intrusive phases and external with wallrocks; cupolas and the uppermost, bifurcating parts of stocks, dike swarms and volcanic vents. Breccias, mainly early formed intrusive and hydrothermal types. Zones of most intensely developed fracturing give rise to ore-grade vein stockworks.

PORPHYRY Cu-Au: ALKALIC L03

ASSOCIATED DEPOSIT TYPES: Skarn copper (K01); Au-Ag and base metal bearing mantos (M01, M04), replacements and breccias in carbonate and non-carbonate rocks; magnetite-apatite breccias (D07); epithermal Au-Ag : both high and low sulphidation types (H04, H05) and alkalic, Te and F-rich epithermal deposits (H08); auriferous and polymetallic base metal quartz and quartz-carbonate veins (I01, I05); placer Au (C01, C02).

COMMENTS: Subdivision of porphyry deposits is made on the basis of metal content, mainly ratios between Cu, Au and Mo. This is a purely arbitrary, economically based criterion; there are few differences in the style of mineralization between the deposits. Differences in composition between the hostrock alkalic and calcalkalic intrusions and subtle, but significant, differences in alteration mineralogy and zoning patterns provide fundamental geologically based contrasts between deposit model types. Porphyry copper deposits associated with calcalkaline hostrocks are described in mineral deposit profile L04.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Alkalic cupriferous systems do not contain economically recoverable Mo (< 100 ppm) but do contain elevated Au (> 0.3 g/t) and Ag (>2 g/t). Cu grades vary widely but commonly exceed 0.5 % and rarely 1 %. Many contain elevated Ti, V, P, F, Ba, Sr, Rb, Nb, Te, Pb, Zn, PGE and have high CO_2 content. Leaching and supergene enrichment effects are generally slight and surface outcroppings normally have little of the copper remobilized. Where present, secondary minerals are malachite, azurite, lesser copper oxide and rare sulphate minerals; in some deposits native copper is economically significant (e.g. Afton, Kemess).

GEOPHYSICAL SIGNATURE: Ore zones, particularly those with high Au content, are frequently found in association with magnetite-rich rocks and can be located by magnetic surveys. Pyritic haloes surrounding cupriferous rocks respond well to induced polarization surveys. The more intensely hydrothermally altered rocks produce resistivity lows.

OTHER EXPLORATION GUIDES: Porphyry deposits are marked by large-scale, markedly zoned metal and alteration assemblages. Central parts of mineralized zones appear to haver higher Au/Cu ratios than the margins. The alkalic porphyry Cu deposits are found exclusively in Later Triassic and Early Jurassic volcanic arc terranes in which emergent subaerial rocks are present. The presence of hydrothermally altered clasts in coarse pyroclastic deposits can be used to locate mineralized intrusive centres.

ECONOMIC FACTORS

GRADE AND TONNAGE:

- Worldwide according to Cox and Singer (U.S. Geological Survey Open File Report 88-46, 1988) 20 typical porphyry Cu-Au deposits, including both calcalkaline and some alkalic types, contain on average:

  160 Mt with 0.55 % Cu, 0.003 % Mo, 0.38 g/t Au and 1.7 g/t Ag.
- British Columbia alkalic porphyry deposits range from <10 to >300 Mt and contain from 0.2 to 1.5 % Cu, 0.2 to 0.6 g/t Au and >2 g/t Ag; Mo contents are negligible. Median values for 22 British Columbia deposits with reported reserves (with a heavy weighting from a number of small deposits in the Iron Mask batholith) are: 15.5 Mt with 0.58 % Cu, 0.3 g/t Au and >2 g/t Ag.

PORPHYRY Cu-Au: ALKALIC L03

END USES: Production of chalcopyrite or chalcopyrite-bornite concentrates with significant Au credits..

IMPORTANCE: Porphyry deposits contain the largest reserves of Cu and close to 50 % of Au reserves in British Columbia; alkalic porphyry systems contain elevated Au values.

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PORPHYRY Cu ± Mo ± Au L04

by Andre Panteleyev[1]

IDENTIFICATION

SYNONYM: Calcalkaline porphyry Cu, Cu-Mo, Cu-Au.

COMMODITIES (*BYPRODUCTS*): Cu. Mo and Au are generally present but quantities range from insufficient for economic recovery to major ore constituents. *Minor Ag in most deposits; rare recovery of Re from Island Copper mine.*

EXAMPLES (British Columbia - *Canada/International*):

- Volcanic type deposits (Cu + Au ± Mo) - Fish Lake (092O041), Kemess (094E021,094), Hushamu (EXPO, 092L240), Red Dog (092L200), Poison Mountain (092O046), Bell (093M001), Morrison (093M007), Island Copper (092L158); *Dos Pobres (USA); Far Southeast (Lepanto/Mankayan), Dizon, Guianaong, Taysan and Santo Thomas II (Philippines), Frieda River and Panguna (Papua New Guinea).*
- Classic deposits (Cu + Mo ± Au) - Brenda (092HNE047), Berg (093E046), Huckleberrry (093E037), Schaft Creek (104G015); *Casino (Yukon, Canada), Inspiration, Morenci, Ray, Sierrita-Experanza, Twin Buttes, Kalamazoo and Santa Rita (Arizona, USA), Bingham (Utah, USA),El Salvador, (Chile), Bajo de la Alumbrera (Argentina).*
- Plutonic deposits (Cu ± Mo) - Highland Valley Copper (092ISE001,011,012,045), Gibraltar (093B012,007), Catface (092F120); *Chuquicamata, La Escondida and Quebrada Blanca (Chile).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockworks of quartz veinlets, quartz veins, closely spaced fractures and breccias containing pyrite and chalcopyrite with lesser molybdenite, bornite and magnetite occur in large zones of economically bulk-mineable mineralization in or adjoining porphyritic intrusions and related breccia bodies. Disseminated sulphide minerals are present, generally in subordinate amounts. The mineralization is spatially, temporally and genetically associated with hydrothermal alteration of the hostrock intrusions and wallrocks.

TECTONIC SETTINGS: In orogenic belts at convergent plate boundaries, commonly linked to subduction-related magmatism. Also in association with emplacement of high-level stocks during extensional tectonism related to strike-slip faulting and back-arc spreading following continent margin accretion.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level (epizonal) stock emplacement levels in volcano-plutonic arcs, commonly oceanic volcanic island and continent-margin arcs. Virtually any type of country rock can be mineralized, but commonly the high-level stocks and related dikes intrude their coeval and cogenetic volcanic piles.

Pantleyev, A. (1995): Porphyry Cu±Mo±Au; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 87-91.

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

PORPHYRY Cu ± Mo ± Au L04

AGE OF MINERALIZATION: Two main periods in the Canadian Cordillera: the Triassic/Jurassic (210-180 Ma) and Cretaceous/Tertiary (85-45 Ma). Elsewhere deposits are mainly Tertiary, but range from Archean to Quaternary.

HOST/ASSOCIATED ROCK TYPES: Intrusions range from coarse-grained phaneritic to porphyritic stocks, batholiths and dike swarms; rarely pegmatitic. Compositions range from calcalkaline quartz diorite to granodiorite and quartz monzonite. Commonly there is multiple emplacement of successive intrusive phases and a wide variety of breccias. Alkalic porphyry Cu-Au deposits are associated with syenitic and other alkalic rocks and are considered to be a a distinct deposit type (see model L03).

DEPOSIT FORM: Large zones of hydrothermally altered rock contain quartz veins and stockworks, sulphide-bearing veinlets; fractures and lesser disseminations in areas up to 10 km^2 in size, commonly coincident wholly or in part with hydrothermal or intrusion breccias and dike swarms. Deposit boundaries are determined by economic factors that outline ore zones within larger areas of low-grade, concentrically zoned mineralization. Cordilleran deposits are commonly subdivided according to their morphology into three classes - classic, volcanic and plutonic (see Sutherland Brown, 1976; McMillan and Panteleyev, 1988):

- Volcanic type deposits (e.g. Island Copper) are associated with multiple intrusions in subvolcanic settings of small stocks, sills, dikes and diverse types of intrusive breccias. Reconstruction of volcanic landforms, structures, vent-proximal extrusive deposits and subvolcanic intrusive centres is possible in many cases, or can be inferred. Mineralization at depths of 1 km, or less, is mainly associated with breccia development or as lithologically controlled preferential replacement in hostrocks with high primary permeability. Propylitic alteration is widespread and generally flanks early, centrally located potassic alteration; the latter is commonly well mineralized. Younger mineralized phyllic alteration commonly overprints the early mineralization. Barren advanced argillic alteration is rarely present as a late, high-level hydrothermal carapace.
- Classic deposits (e.g., Berg) are stock related with multiple emplacements at shallow depth (1 to 2 km) of generally equant, cylindrical porphyritic intrusions. Numerous dikes and breccias of pre, intra, and post-mineralization age modify the stock geometry. Orebodies occur along margins and adjacent to intrusions as annular ore shells. Lateral outward zoning of alteration and sulphide minerals from a weakly mineralized potassic/propylitic core is usual. Surrounding ore zones with potassic (commonly biotite-rich) or phyllic alteration contain molybdenite ± chalcopyrite, then chalcopyrite and a generally widespread propylitic, barren pyritic aureole or 'halo'.
- Plutonic deposits (e.g., the Highland Valley deposits) are found in large plutonic to batholithic intrusions immobilized at relatively deep levels, say 2 to 4 km. Related dikes and intrusive breccia bodies can be emplaced at shallower levels. Hostrocks are phaneritic coarse grained to porphyritic. The intrusions can display internal compositional differences as a result of differentiation with gradational to sharp boundaries between the different phases of magma emplacement. Local swarms of dikes, many with associated breccias, and fault zones are sites of mineralization. Orebodies around silicified alteration zones tend to occur as diffuse vein stockworks carrying chalcopyrite, bornite and minor pyrite in intensely fractured rocks but, overall, sulphide minerals are sparse. Much of the early potassic and phyllic alteration in central parts of orebodies is restricted to the margins of mineralized fractures as selvages. Later phyllic-argillic alteration forms envelopes on the veins and fractures and is more pervasive and widespread. Propylitic alteration is widespread but unobtrusive and is indicated by the presence of rare pyrite with chloritized mafic minerals, saussuritized plagioclase and small amounts of epidote.

PORPHYRY Cu ± Mo ± Au L04

TEXTURE/STRUCTURE: Quartz, quartz-sulphide and sulphide veinlets and stockworks; sulphide grains in fractures and fracture selvages. Minor disseminated sulphides commonly replacing primary mafic minerals. Quartz phenocrysts can be partially resorbed and overgrown by silica.

ORE MINERALOGY (Principal and *subordinate*): Pyrite is the predominant sulphide mineral; in some deposits the Fe oxide minerals magnetite, and rarely hematite, are abundant. Ore minerals are chalcopyrite; molybdenite, lesser bornite and rare (primary) chalcocite. Subordinate minerals are *tetrahedrite/tennantite, enargite and minor gold , electrum and arsenopyrite*. In many deposits late veins commonly contain galena and sphalerite in a gangue of quartz, calcite and barite.

GANGUE MINERALOGY (Principal and *subordinate*): Gangue minerals in mineralized veins are mainly quartz with lesser *biotite, sericite, K-feldspar, magnetite, chlorite, calcite, epidote, anhydrite and tourmaline*. Many of these minerals are also pervasive alteration products of primary igneous mineral grains.

ALTERATION MINERALOGY: Quartz, sericite, biotite, K-feldspar, albite, anhydrite/gypsum, magnetite, actinolite, chlorite, epidote, calcite, clay minerals, tourmaline. Early formed alteration can be overprinted by younger assemblages. Central and early formed potassic zones (K-feldspar and biotite) commonly coincide with ore. This alteration can be flanked in volcanic hostrocks by biotite-rich rocks that grade outward into propylitic rocks. The biotite is a fine-grained, 'shreddy' looking secondary mineral that is commonly referred to as an early developed biotite (EDB) or a 'biotite hornfels'. These older alteration assemblages in cupriferous zones can be partially to completely overprinted by later biotite and K-feldspar and then phyllic (quartz-sericite-pyrite) alteration, less commonly argillic, and rarely, in the uppermost parts of some ore deposits, advanced argillic alteration (kaolinite-pyrophyllite) .

WEATHERING: Secondary (supergene) zones carry chalcocite, covellite and other $Cu_{2}S$ minerals (digenite, djurleite, etc.), chrysocolla, native copper and copper oxide, carbonate and sulphate minerals. Oxidized and leached zones at surface are marked by ferruginous 'cappings' with supergene clay minerals, limonite (goethite, hematite and jarosite) and residual quartz.

ORE CONTROLS: Igneous contacts, both internal between intrusive phases and external with wallrocks; cupolas and the uppermost, bifurcating parts of stocks, dike swarms. Breccias, mainly early formed intrusive and hydrothermal types. Zones of most intensely developed fracturing give rise to ore-grade vein stockworks, notably where there are coincident or intersecting multiple mineralized fracture sets.

ASSOCIATED DEPOSIT TYPES: Skarn Cu (K01), porphyry Au (K02), epithermal Au-Ag in low sulphidation type (H05) or epithermal Cu-Au-Ag as high-sulphidation type enargite-bearing veins (L01), replacements and stockworks; auriferous and polymetallic base metal quartz and quartz-carbonate veins (I01, I05), Au-Ag and base metal sulphide mantos and replacements in carbonate and non-carbonate rocks (M01, M04), placer Au (C01, C02).

COMMENTS: Subdivision of porphyry copper deposits can be made on the basis of metal content, mainly ratios between Cu, Mo and Au. This is a purely arbitrary, economically based criterion, an artifact of mainly metal prices and metallurgy. There are few differences in the style of mineralization between deposits although the morphology of calcalkaline deposits does provide a basis for subdivision into three distinct subtypes - the 'volcanic, classic, and plutonic' types. A fundamental contrast can be made on the compositional differences between calcalkaline quartz-bearing porphyry copper deposits and the alkalic (silica undersaturated) class. The alkalic porphyry copper deposits are described in a separate model - L03.

PORPHYRY Cu ± Mo ± Au L04

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Calcalkalic systems can be zoned with a cupriferous (± Mo) ore zone having a 'barren', low-grade pyritic core and surrounded by a pyritic halo with peripheral base and precious metal-bearing veins. Central zones with Cu commonly have coincident Mo, Au and Ag with possibly Bi, W, B and Sr. Peripheral enrichment in Pb, Zn, Mn, V, Sb, As, Se, Te, Co, Ba, Rb and possibly Hg is documented. Overall the deposits are large-scale repositories of sulphur, mainly in the form of metal sulphides, chiefly pyrite.

GEOPHYSICAL SIGNATURE: Ore zones, particularly those with higher Au content, can be associated with magnetite-rich rocks and are indicated by magnetic surveys. Alternatively the more intensely hydrothermally altered rocks, particularly those with quartz-pyrite-sericite (phyllic) alteration produce magnetic and resistivity lows. Pyritic haloes surrounding cupriferous rocks respond well to induced polarization (I.P.) surveys but in sulphide-poor systems the ore itself provides the only significant IP response.

OTHER EXPLORATION GUIDES: Porphyry deposits are marked by large-scale, zoned metal and alteration assemblages. Ore zones can form within certain intrusive phases and breccias or are present as vertical 'shells' or mineralized cupolas around particular intrusive bodies. Weathering can produce a pronounced vertical zonation with an oxidized, limonitic leached zone at surface (leached capping), an underlying zone with copper enrichment (supergene zone with secondary copper minerals) and at depth a zone of primary mineralization (the hypogene zone).

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE:

- Worldwide according Cox and Singer (1988) based on their subdivision of 55 deposits into subtypes according to metal ratios, typical porphyry Cu deposits contain (median values):

  Porphyry Cu-Au: 160 Mt with 0.55 % Cu, 0.003 % Mo, 0.38 g/t Au and 1.7 g/t Ag.
  Porphyry Cu-Au-Mo: 390 Mt with 0.48 % Cu, 0.015 % Mo, 0.15 g/t Au and 1.6 g/t Ag.
  Porphyry Cu-Mo: 500 Mt with 0.41 % Cu, 0.016 % Mo, 0.012 g/t Au and 1.22 g/t Ag.

  A similar subdivision by Cox (1986) using a larger data base results in:

  Porphyry Cu: 140 Mt with 0.54 %Cu, <0.002 % Mo, <0.02g/t Au and <1 g/t Ag.
  Porphyry Cu-Au: 100 Mt with 0.5 %Cu, <0.002 % Mo, 0.38g/t Au and 1g/t Ag. (This includes deposits from the British Columbia alkalic porphyry class, B.C. model L03.)
  Porphyry Cu-Mo: 500 Mt with 0.42 % Cu, 0.016 % Mo, 0.012 g/t Au and 1.2 g/t Ag.

- British Columbia porphyry Cu ± Mo ± Au deposits range from <50 to >900 Mt with commonly 0.2 to 0.5 % Cu, <0.1 to 0.6 g/t Au, and 1 to 3 g/t Ag. Mo contents are variable from negligible to 0.04 % Mo. Median values for 40 B.C. deposits with reported reserves are: 115 Mt with 0.37 % Cu, ~0.01 % Mo, 0.3g /t Au and 1.3 g/t Ag.

ECONOMIC LIMITATIONS: Mine production in British Columbia is from primary (hypogene) ores. Rare exceptions are Afton mine where native copper was recovered from an oxide zone, and Gibraltar and Bell mines where incipient supergene enrichment has provided some economic benefits.

END USES: Porphyry copper deposits produce Cu and Mo concentrates, mainly for international export.

PORPHYRY Cu ± Mo ± Au L04

IMPORTANCE: Porphyry deposits contain the largest reserves of Cu, significant Mo resources and close to 50 % of Au reserves in British Columbia.

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PORPHYRY Mo (LOW-F-TYPE) L05

by W. David Sinclair[1]

IDENTIFICATION

SYNONYMS: Calcalkaline Mo stockwork; Granite-related Mo; Quartz-monzonite Mo.

COMMODITIES (*BYPRODUCTS*): Mo (*Cu, W*)

EXAMPLES (British Columbia - *Canada/International*): Endako (093K006), Boss Mountain (093A001), Kitsault (103P120), Adanac (104N052), Carmi (082ESW029), Bell Moly (103P234), Red Bird (093E026), Storie Moly (104P069), Trout Lake (082KNW087); *Red Mountain (Yukon, Canada), Quartz Hill (Alaska, USA), Cannivan (Montana, USA), Thompson Creek (Idaho, USA), Compaccha (Peru), East Kounrad (Russia), Jinduicheng (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockwork of molybdenite-bearing quartz veinlets and fractures in intermediate to felsic intrusive rocks and associated country rocks. Deposits are low grade but large and amenable to bulk mining methods.

TECTONIC SETTING(S): Subduction zones related to arc-continent or continent-continent collision.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres; multiple stages of intrusion are common.

AGE OF MINERALIZATION: Archean (e.g. Setting Net Lake, Ontario) to Tertiary; Mesozoic and Tertiary examples are more common.

HOST/ASSOCIATED ROCK TYPES: All kinds of rocks may be hostrocks. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusive rocks. Genetically related intrusive rocks range from granodiorite to granite and their fine-grained equivalents, with quartz monzonite most common: they are commonly porphyritic. The intrusive rocks are characterized by low F contents (generally <0.1 % F) compared to intrusive rocks associated with Climax-type porphyry Mo deposits.

DEPOSIT FORM: Deposits vary in shape from an inverted cup, to roughly cylindrical, to highly irregular. They are typically hundreds of metres across and range from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore is predominantly structurally controlled; mainly stockworks of crosscutting fractures and quartz veinlets, also veins, vein sets and breccias.

ORE MINERALOGY (Principal and *subordinate*): Molybdenite is the principal ore mineral*; chalcopyrite, scheelite, and galena are generally subordinate*.

Sinclair, W.D. (1995): Porphyry Mo (Low F- type); *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 93-95.

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

PORPHYRY Mo (LOW-F-TYPE) L05

GANGUE MINERALOGY: Quartz, pyrite, K-feldspar, biotite, sericite, clays, calcite and anhydrite.

ALTERATION MINERALOGY: Alteration mineralogy is similar to that of porphyry Cu deposits. A core zone of potassic and silicic alteration is characterized by hydrothermal K-feldspar, biotite, quartz and, in some cases, anhydrite. K-feldspar and biotite commonly occur as alteration selvages on mineralized quartz veinlets and fractures but may be pervasive in areas of intense fracturing and mineralization. Phyllic alteration typically surrounds and may be superimposed to various degrees on the potassic-silicic core; it consists mainly of quartz, sericite and carbonate. Phyllic alteration is commonly pervasive and may be extensive. Propylitic alteration consisting mainly of chlorite and epidote may extend for hundreds of metres beyond the zones of potassic-silicic and phyllic alteration. Zones of argillic alteration, where present, are characterized by clay minerals such as kaolinite and are typically overprinted on the other types of alteration; distribution of argillic alteration is typically irregular.

WEATHERING: Oxidation of pyrite produces limonitic gossans; oxidation of molybdenite produces yellow ferrimolybdite.

ORE CONTROLS: Quartz veinlet and fracture stockwork zones superimposed on intermediate to felsic intrusive rocks and surrounding country rocks; multiple stages of mineralization commonly present.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip Mo and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and in associated country rocks. Incursion of meteoric water during waning stages of the magmatic-hydrothermal system may result in late alteration of the hostrocks, but does not play a significant role in the ore-forming process.

ASSOCIATED DEPOSIT TYPES: Ag-Pb-Zn veins (I05), Mo-bearing skarns (K07) may be present.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mo, Cu, W and F may be anomalously high in hostrocks close to and overlying mineralized zones; anomalously high levels of Pb, Zn and Ag occur in peripheral zones as much as several kilometres distant. Mo, W, F, Cu, Pb, Zn and Ag may be anomalously high in stream sediments. Mo, W and Pb may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Magnetic anomalies may reflect presence of pyrrhotite or magnetite in hornfels zones. Radiometric surveys may be used to outline anomalous K in altered and mineralized zones. Induced polarization and resistivity surveys may be used to outline high-pyrite alteration zones.

OTHER EXPLORATION GUIDES: Limonitic alteration of pyrite can result in widespread gossan zones. Yellow ferrimolybdite may be present in oxidized zones. Ag-Pb-Zn veins may be present in peripheral zones.

ECONOMIC FACTORS

GRADE AND TONNAGE: Typical size is 100 Mt at 0.1 to 0.2 % Mo. The following figures are for production plus reserves.

Endako (B.C.): 336 Mt at 0.087 % Mo; Boss Mountain (B.C.): 63 Mt. at 0.074 % Mo;
Kitsault (B.C.): 108 Mt at 0.115 % Mo; Lucky Ship (B.C.): 14 Mt at 0.090 % Mo;
Adanac (B.C.): 94 Mt at 0.094 % Mo; Carmi (B.C.): 34 Mt at 0.091 % Mo;
Mount Haskin (B.C.): 12 Mt at 0.090 % Mo; Bell Moly (B.C.): 32 Mt at 0.066 % Mo;
Red Bird (B.C.): 34 Mt at 0.108 % Mo; Storie Moly (B.C.): 101 Mt at 0.078 % Mo;
Trout Lake (B.C.): 50 Mt at 0.138 % Mo; Glacier Gulch (B.C.): 125 Mt at 0.151 % Mo;
Red Mountain (Yukon): 187 Mt at 0.100 % Mo; Quartz Hill (Alaska): 793 Mt at 0.091 % Mo;
Thompson Creek (Idaho): 181 Mt at 0.110 % Mo; Compaccha (Peru): 100 Mt at 0.072 % Mo;
East Kounrad (Russia): 30 Mt at 0.150 % Mo.

PORPHYRY Mo (LOW-F-TYPE) L05

IMPORTANCE: Porphyry Mo deposits associated with low-F felsic intrusive rocks have been an important source of world molybdenum production. Virtually all of Canada's Mo production comes from these deposits and from porphyry Cu-Mo deposits.

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PORPHYRY Sn L06

by W. David Sinclair[1]

IDENTIFICATION

SYNONYM: Subvolcanic Sn

COMMODITIES (*BYPRODUCTS*): Sn (*Ag, W*)

EXAMPLES (British Columbia - *Canada/International*): *Mount Pleasant (New Brunswick, Canada), East Kemptville (Nova Scotia, Canada), Catavi, Chorolque and Cerro Rico stock (Bolivia), Ardlethan and Taronga (Australia), Kingan (Russia), Yinyan (China), Altenberg (Germany).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Fine-grained cassiterite in veinlet and fracture stockwork zones, breccia zones, and disseminated in porphyritic felsic intrusive rocks and associated country rocks.

TECTONIC SETTING: Zones of weak to moderate extension in cratons, particularly post orogenic zones underlain by thick crust, possibly cut by shallow-dipping subduction zones.

GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres in cratons; multiple stages of intrusion may be present.

AGE OF MINERALIZATION: Paleozoic to Tertiary.

HOST/ASSOCIATED ROCK TYPES: Predominantly genetically related intrusive rocks and associated breccias, but may also include related or unrelated sedimentary, volcanic, igneous and metamorphic rocks. Genetically related felsic intrusive rocks are F and/or B enriched and are commonly porphyritic. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusions.

DEPOSIT FORM: Deposits vary in shape from inverted cone, to roughly cylindrical, to highly irregular. They are typically large, generally hundreds of metres across and ranging from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore is predominantly structurally controlled in stockworks of crosscutting fractures and quartz veinlets, or disseminated in hydrothermal breccia zones. Veins, vein sets, replacement zones may also be present.

ORE MINERALOGY (Principal and subordinate): Cassiterite; *stannite, chalcopyrite, sphalerite and galena. Complex tin- and silver-bearing sulphosalts occur in late veins and replacement zones.*

GANGUE MINERALOGY: Pyrite, arsenopyrite, löllingite, topaz, fluorite, tourmaline, muscovite, zinnwaldite and lepidolite.

Sinclair, W.D. (1995): Porphyry Sn; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 97-99.

[1] Geological Survey of Canada, Ottawa

PORPHYRY Sn L06

ALTERATION MINERALOGY: In the Bolivian porphyry Sn deposits, sericite + pyrite ± tourmaline alteration is pervasive; in some deposits it surrounds a central zone of quartz + tourmaline. Sericitic alteration is typically bordered by weak propylitic alteration. In other deposits (*e.g.* , Ardlethan, Yinyan), central zones are characterized by greisen alteration consisting of quartz + topaz + sericite; these zones grade outward to quartz + sericite + chlorite alteration.

WEATHERING: Oxidation of pyrite produces limonitic gossans. Deep weathering and erosion can result in residual concentrations of cassiterite in situ or in placer deposits downslope or downstream.

ORE CONTROLS: Ore minerals occur in fracture stockworks, hydrothermal breccias and replacement zones centred on 1-2 km^2, genetically related felsic intrusions.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip Sn and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and associated country rocks. Mixing of magmatic with meteoric water during waning stages of the magmatic-hydrothermal system may result in deposition of some Sn and other metals, particularly in late-stage veins.

ASSOCIATED DEPOSIT TYPES: Sn veins (I13), Sn-polymetallic veins (H07).

COMMENTS: Some of the deposits listed (*e.g.* , Taronga, East Kemptville) are not "subvolcanic" but they are similar to some porphyry Cu deposits with regard to their large size, low grade, relationship to felsic intrusive rocks and dominant structural control (ie., mineralized veins, fractures and breccias).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Sn, Ag, W, Cu, Zn, As, Pb, Rb, Li, F, B may be anomalously high in hostrocks close to mineralized zones and in secondary dispersion halos in overburden. Anomalously high contents of Sn, W, F, Cu, Pb and Zn may occur in stream sediments and Sn, W, F (topaz) and B (tourmaline) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Genetically related intrusions may be magnetic lows (ilmenite- rather than magnetite-dominant); contact aureole may be magnetic high if pyrrhotite or magnetite are present in associated skarn or hornfels zones. Radiometric surveys may be used to outline anomalous U, Th or K in genetically related intrusive rocks or in associated altered and mineralized zones.

OTHER EXPLORATION GUIDES: Sn (-Ag) deposits may be zoned relative to base metals at both regional (district) and local (deposit) scales.

ECONOMIC FACTORS

GRADE AND TONNAGE: Tens of millions of tonnes at grades of 0.2 to 0.5% Sn.
Mount Pleasant (New Brunswick): 5.1 Mt @ 0.79% Sn; East Kemptville (Nova Scotia): 56 Mt @ 0.165% Sn; Catavi (Bolivia): 80 Mt @ 0.3% Sn; Cerro Rico stock, Bolivia: averages 0.3% Sn; Ardlethan (Australia): 9 Mt @ 0.5% Sn; Taronga (Australia): 46.8 Mt @ 0.145% Sn; Altenberg, (Germany): 60 Mt @ 0.3% Sn; Yinyan (China): "large" (50 - 100 Mt?) @ 0.46% Sn

ECONOMIC LIMITATIONS: Low grades require high volumes of production which may not be justified by demand.

IMPORTANCE: A minor source of tin on a world scale; when it was in production, East Kemptville was the major producer of tin in North America.

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PORPHYRY W L07

by W. David Sinclair[1]

IDENTIFICATION

SYNONYM: Stockwork W-Mo

COMMODITIES (*BYPRODUCTS*): W (*Mo, Sn, Ag*).

EXAMPLES (British Columbia - *Canada/International*): Boya; *Mount Pleasant (New Brunswick, Canada), Logtung (Yukon, Canada), Xingluokeng, Lianhuashan and Yanchuling (China).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockwork of W-bearing quartz veinlets and fractures in felsic intrusive rocks and associated country rocks. Deposits are low grade but large and amenable to bulk mining methods.

TECTONIC SETTING: Zones of weak to moderate extension in cratons, particularly post-collisional zones in areas of tectonically thickened crust.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres; multiple stages of intrusion are common.

AGE OF MINERALIZATION: Paleozoic to Tertiary, but Mesozoic and Tertiary examples are more common.

HOST/ASSOCIATED ROCK TYPES: Highly variable; mineralized rocks may be predominantly genetically related intrusive rocks, but may also be related or unrelated sedimentary, volcanic, igneous and metamorphic rocks. Genetically related felsic intrusive rocks are commonly F-rich (fluorite and/or topaz bearing) and porphyritic; unidirectional solidification features, particularly comb quartz layers, may also be present. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusions.

DEPOSIT FORM: Deposits vary in shape from inverted cup-shaped, to roughly cylindrical, to highly irregular. They are typically large, generally hundreds of metres across and ranging from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore minerals is structurally controlled; mainly stockworks of crosscutting fractures and quartz veinlets, also veins, vein sets, breccias, disseminations and replacements.

ORE MINERALOGY (Principal and *subordinate*): Main ore mineral is generally either scheelite or wolframite, although in some deposits both are present. *Subordinate ore minerals include molybdenite, bismuth, bismuthinite and cassiterite*.

Sinclair, W.D. (1995): Porphyry W; *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 101-104.

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

PORPHYRY W L07

GANGUE MINERALOGY: Pyrite, pyrrhotite, magnetite, arsenopyrite, löllingite, quartz, K-feldspar, biotite, muscovite, fluorite, topaz.

ALTERATION MINERALOGY: Hydrothermal alteration is pervasive to fracture controlled and, at deposit scale, is concentrically zoned. It is commonly characterized by the presence of greisen alteration minerals, including topaz, fluorite and Li- and F-rich micas. At Mount Pleasant, for example, pervasive greisen alteration consisting of quartz + topaz ± sericite ± chlorite associated with high-grade W zones and grades laterally into fracture-controlled quartz-biotite-chlorite-topaz alteration associated with lower grade W zones. Propylitic alteration, mainly chlorite and sericite, extends as far as 1500 m beyond the mineralized zones. Potassic alteration, dominated by K-feldspar, occurs locally within the central areas of pervasive greisen alteration. Other deposits such as Xingluokeng (China) are characterized more by central zones of silicic and potassic alteration (K-feldspar and biotite); zones of weak greisen alteration consisting of muscovite and fluorite may be present. Sericitic alteration forms a broad aureole around the central potassic zone; irregular zones of argillic alteration may be superimposed on both the potassic and sericitic zones. In detail, alteration patterns may be complex; at Logtung, for example, different stages of mineralized veins and fractures are characterized by different assemblages of ore and alteration minerals.

WEATHERING: Oxidation of pyrite produces limonitic gossans; oxidation of molybdenite, if present, may produce yellow ferrimolybdenite.

ORE CONTROLS: Quartz veinlet and fracture stockwork zones surround or are draped over and are superimposed to varying degrees on small stocks (<1 km^2); multiple stages of mineralization commonly present; felsic intrusions associated with the deposits are typically F-rich.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip W, Mo and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and associated country rocks. Incursion of meteoric water during waning stages of the magmatic-hydrothermal system may result in late alteration of the hostrocks, but does not play a significant role in the ore forming process.

ASSOCIATED DEPOSIT TYPES: Porphyry W deposits may be part of a spectrum of deposits that include Climax-type Mo deposits (L08) as one end-member and porphyry Sn deposits as the other (L06). Vein/replacement W, Sn, Ag deposits may be associated (I05, H07), *e.g.* Logjam Ag-Pb-Zn veins peripheral to the Logtung W-Mo deposit. Skarn (contact metamorphic) zones associated with genetically related felsic intrusions may be mineralized, but are not typical skarn W (i.e. contact metasomatic) deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: W, Mo and Sn are anomalous in hostrocks close to mineralized zones; anomalously high contents of F, Zn, Pb and Cu occur in wallrocks up to several kilometres from mineralized zones. W, Sn, Mo, F, Cu, Pb and Zn may be anomalously high in stream sediments and W, Sn and F (topaz) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Genetically related intrusions may be magnetic lows (ilmenite rather than magnetite dominant); contact aureole may be magnetic high if pyrrhotite or magnetite are present in associated skarn or hornfels zones. Radiometric surveys may be used to outline anomalous U, Th or K in genetically related intrusive rocks or in associated altered and mineralized zones.

OTHER EXPLORATION GUIDES: The presence of scheelite can be detected with an ultraviolet lamp

.

ECONOMIC FACTORS

GRADE AND TONNAGE: Tens to more than 100 Mt at grades of 0.2 to 0.3 % W (Lianhushan is exceptional at 0.8 % W). Boya (British Columbia): limited size due to thrust fault truncation, no published resource data. Mount Pleasant (New Brunswick): Fire Tower zone: 22.5 Mt @ 0.21 % W, 0.10 % Mo, 0.08 % Bi, (includes 9.4 Mt @ 0.31 % W, and 0.12 % Mo), North zone: 11 Mt @ 0.2 % W, 0.1 % Mo. Logtung (Yukon): 162 Mt @ 0.10 % W, 0.03 % Mo. Xingluokeng (China): 78 Mt @ 0.18 % W. Lianhuashan (China): ~40 Mt @ 0.8 % W.

ECONOMIC LIMITATIONS: Low grades require high production volumes which may not be justified by current demand for tungsten.

IMPORTANCE: Not currently an important source of world W production; some W may be recovered from deposits in China (*e.g.* Lianhuashan), but none is recovered at present (1994) from deposits outside China. Mount Pleasant Tungsten in New Brunswick produced slightly more than 2000 t of concentrate grading 70 % WO_3 from 1 Mt of ore mined from 1983 to 1985.

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PORPHYRY Mo (Climax-type) L08

by W. David Sinclair[1]

IDENTIFICATION

SYNONYMS: Granite molybdenite; Climax Mo; granite-related Mo.

COMMODITIES (*BYPRODUCTS*): Mo (*W, Sn; pyrite and monazite have also been recovered from the Climax deposit*)

EXAMPLES (British Columbia - *Canada/International*): No unequivocal Climax-type porphyry Mo deposits occur in British Columbia or *other parts of Canada*; *Climax, Henderson, Mount Emmons and Silver Creek (Colorado, USA), Pine Grove (Utah, USA), Questa (New Mexico), Malmbjerg (Greenland), Nordli (Norway).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Stockworks of molybdenite-bearing quartz veinlets and fractures in highly evolved felsic intrusive rocks and associated country rocks. Deposits are low grade but large and amenable to bulk mining methods.

TECTONIC SETTING: Rift zones in areas of thick cratonic crust.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres; multiple stages of intrusion are common.

AGE OF MINERALIZATION: Paleozoic to Tertiary, but mainly Tertiary.

HOST/ASSOCIATED ROCK TYPES: Genetically related felsic intrusive rocks are high-silica (>75% SiO_2), F-rich (>0.1% F) granite/rhyolite; they are commonly porphyritic and contain unidirectional solidification textures (USTs), particularly comb quartz layers. Contents of Rb, Y and Nb are high; Ba, Sr and Zr are low. Mineralized country rocks may include sedimentary, metamorphic, volcanic, and older intrusive rocks. Tuffs or other extrusive volcanic rocks may be associated with deposits related to subvolcanic intrusions.

DEPOSIT FORM: Deposits typically form an inverted cup or hemispherical shell; shapes may be modified by regional or local structures. They are typically large, generally hundreds of metres across and ranging from tens to hundreds of metres in vertical extent.

TEXTURE/STRUCTURE: Ore is structurally controlled; mainly stockworks of crosscutting fractures and quartz veinlets, also veins, vein sets and breccias; disseminations and replacements are less common.

ORE MINERALOGY (Principal and *subordinate)*: Molybdenite; *wolframite, cassiterite, sphalerite, galena, monazite*.

Sinclair, W.D. (1995): Porphyry Mo (Climax-type); *in* Selected British Columbia Mineral Deposit Profiles, Volume 1, D.V. Lefebure and G.E. Ray, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 105-108.

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

PORPHYRY Mo (Climax-type) L08

GANGUE MINERALOGY: Quartz, pyrite, topaz, fluorite and rhodochrosite.

ALTERATION MINERALOGY: Potassic alteration (K-feldspar ± biotite) is directly associated with high-grade Mo (>0.2% Mo); pervasive silicic alteration (quartz ± magnetite) may occur locally in the lower parts of high-grade Mo zones. Quartz-sericite-pyrite alteration may extend hundreds of metres vertically above orebodies; argillic alteration may extend hundreds of metres beyond quartz-sericite-pyrite alteration, both vertically and laterally. Spessartine garnet occurs locally within quartz-sericite-pyrite and argillic alteration zones. Greisen alteration consisting of quartz-muscovite-topaz occurs as alteration envelopes around quartz-molybdenite veins below high-grade Mo zones. Propylitic alteration is widespread and may extend for several km.

WEATHERING: Oxidation of pyrite produces limonitic gossans; oxidation of molybdenite produces yellow ferrimolybdite.

ORE CONTROLS: Quartz veinlet and fracture stockwork zones surround or are draped over, and are superimposed to varying degrees on small, genetically related stocks (area <1 km^2); multiple stages of mineralization are commonly present; abundant comb quartz layers and other USTs characterize productive intrusions.

GENETIC MODEL: Magmatic-hydrothermal. Large volumes of magmatic, highly saline aqueous fluids under pressure strip Mo and other ore metals from temporally and genetically related magma. Multiple stages of brecciation related to explosive fluid pressure release from the upper parts of small intrusions result in deposition of ore and gangue minerals in crosscutting fractures, veinlets and breccias in the outer carapace of the intrusions and associated country rocks. Incursion of meteoric water during waning stages of the magmatic-hydrothermal system may result in late alteration of the hostrocks, but does not play a significant role in the ore-forming process.

ASSOCIATED DEPOSIT TYPES: Ag-base metal veins (I05), fluorspar deposits. Some porphyry W-Mo deposits (*e.g.* Mount Pleasant) may be W-rich Climax-type deposits. Mo may also be present in adjacent skarn deposits (K07). Climax-type porphyry Mo deposits may be related to rhyolite-hosted Sn deposits (H07, USGS model 25h).

COMMENTS: This model is based mainly on descriptions of Climax and Climax-type deposits in Colorado. These deposits tend to have more complex igneous-hydrothermal systems and higher average Mo grades than low-F-type porphyry Mo deposits.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Mo, Sn, W, Rb, Mn and F may be anomalously high in hostrocks close to and overlying mineralized zones; Pb, Zn, F and U may be anomalous in wallrocks as much as several kilometres distant. Mo, Sn, W, F, Cu, Pb, Zn may be anomalous in stream sediments and Mo, Sn, W, and F (topaz) may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Genetically related intrusions may be magnetic lows (ilmenite rather than magnetite dominant). Radiometric surveys may be used to outline anomalous U, Th or K in genetically related intrusive rocks or in associated altered and mineralized zones.

OTHER EXPLORATION GUIDES: Deposits occur in extensional tectonic settings in areas of thick continental crust. Genetically related felsic intrusive rocks generally have high contents of Nb (>75 ppm). Ag-Pb-Zn veins, topaz, fluorite and Mn-garnet may be present in peripheral zones. Yellow ferrimolybdite may be present in oxidized zones.

PORPHYRY Mo (Climax-type) L08

ECONOMIC FACTORS

GRADE AND TONNAGE: Deposits typically contain hundreds of millions of tonnes at 0.1 to 0.3 % Mo. Following figures are production plus reserves (from Carten et al., 1993): Climax, Colorado: 769 Mt @ 0.216% Mo (mineable), Henderson, Colorado: 727 Mt @ 0.171% Mo (geological), Mount Emmons, Colorado: 141 Mt @ 0.264% Mo (mineable), Silver Creek, Colorado: 40 Mt @ 0.310% Mo (geological), Pine Grove, Utah: 125 Mt @ 0.170% Mo (geological), Questa, New Mexico: 277 Mt @ 0.144% Mo (mineable), Malmbjerg, Greenland: 136 Mt @ 0.138% Mo (geological), Nordli, Norway: 181 Mt @ 0.084% Mo (geological)

ECONOMIC LIMITATIONS: Economic viability of these deposits is affected by Mo production from other types of deposits such as porphyry Cu-Mo deposits, which produce Mo as a coproduct or byproduct.

IMPORTANCE: Porphyry Mo deposits of the Climax type have been a major source of world Mo production and contain substantial reserves.

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PODIFORM CHROMITE M03

by Chris Ash[1]

IDENTIFICATION

SYNONYMS: Alpine type; ophiolite hosted chromite.

COMMODITIES (*BYPRODUCTS*): Chromite (may contain platinum group elements Os, Ir and Ru).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Castle Mountain Nickel (082ESE091) and Scottie Creek (092INW001); *Guleman ore field (Turkey); Kalimash - Kukes-Tropoje district, Bulquize and Todo Manco - Bater-Martanesh district (Mirdita ophiolite, Albania); Tiébaghi ophiolite and Massif du Sud (New Caledonia), Acoje and Masinloc-Coto (Zambales range/ophiolite, Luzon, Phillipines); Batamshinsk, Stepninsk, Tagashaisai and Main SE ore fields (Kempirsai massif, Southern Urals, Russia); Xeraivado and Skoumtsa mines (Vourinos ophiolite, Greece); Semail ophiolite (Oman); Luobusa, Donqiao, Sartohay, Yushi, Solun, Wudu and Hegenshan deposits (China) all > 1.5 Mt.*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits of massive chromitite occur as pods, lenses or layers within ophiolitic ultramafic rocks.

TECTONIC SETTING: Obducted fragments of oceanic, lower crustal and upper mantle ultramafic rocks within accreted oceanic terranes.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Formed as a primary magmatic differentiate during early olivine and chrome-spinel crystal fractionation of basaltic liquid at an oceanic spreading centre; (1) as massive to disseminated pods and lenses of chrome-spinel surrounded by a dunite envelope within depleted mantle harzburgite; or (2) as massive to disseminated cumulate layers in dunite at the base of the crustal plutonic section.

AGE OF MINERALIZATION: Mesozoic and younger.

HOST/ASSOCIATED ROCK TYPES: Variably serpentinized peridotite; residual mantle harzburgite; cumulate dunite.

DEPOSIT FORM: Podiform, tabular lenses, irregular masses, cumulate layers. Pods and lenses typically occur in clusters of variable size.

TEXTURE/STRUCTURE: Massive to disseminated, nodular (*syn*. leopard, grape, bean or shot ore), chromite net, occluded silicate, orbicular.

ORE MINERALOGY: Chromite.

GANGUE MINERALOGY [Principal and *subordinate*]: Variably serpentinized olivine and orthopyroxene, magnetite, *iddingsite*.

WEATHERING: Black, no noticeable affects resulting from surface oxidation.

Ash, C. (1996): Podiform Chromite; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 109-111.

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PODIFORM CHROMITE M03

ORE CONTROLS: Proximity to the crust-mantle transition zone. Restricted to dunite bodies in tectonized harzburgite below this transition, or lower dunitic portions of ultramafic cumulate section above it.

GENETIC MODEL: Early fractional crystallization of chromite from a basaltic liquid either (1) just below the crust-mantle transition (syn. petrological MOHO) in small magma pockets or possibly conduits within the residual mantle harzburgite; or (2) immediately above the crust-mantle transition as cumulate layers within dunite at the base of the axial magma chamber. Pods and lenses in harzburgite obtain their diagonistic shape as a result subsolidus to hypersolidus ductile deformation due to mantle convection.

COMMENTS: Ophiolites of suprasubduction zone affinity with harzburgite mantle sections appear to be the only ophiolite type to host economic deposits of podiform chromite. A lack of any sizable chromite occurrence in British Columbia may reflect the fact that most ophiolitic complexes in the province are of mid-ocean ridge affinity. Occurrences of podiform chromite are found in ophiolitic ultramafic rocks in the Slide Mountain, Cache Creek and Bridge River terranes. Most of these known occurrences have been reviewed by Hancock (1990).

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Cr

GEOPHYSICAL SIGNATURE: Gravity anomaly.

OTHER EXPLORATION GUIDES: Found in rocks formed near or within the ophiolitic crust-mantle transition zone.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Grades range from 20 to 60% Cr_2O_3 and are a function of the texture of the chromite; *i.e.* amount of chromite relative to gangue serpentinite. Tonnages are variable, ranging from several thousand tonnes to several million tonnes.

ECONOMIC LIMITATIONS: The complex structure and irregular distribution make exploration and development difficult.

END USES: Chromium has a wide range of uses in the iron and steel industry which accounts for over 75% of its use. Chromite is also used in making refractory bricks for furnace linings.

IMPORTANCE: An important source of metallurgical-type chromite ores (45-60% Cr_2O_3: Cr/Fe = 2.8-4.3). Podiform chromite is the only source of refractory-type ore (min. 25% Al_2O_3: min. 60% $Cr_2O_3 + Al_2O_3$: max. 15% FeO). Historically podiform-type ore fields account for 57% of all chromite produced.

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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.

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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-Ti±V oxide deposits. In California in the San Gabriel Range occurrences of the ilmenite-subtype are hosted by anorthosite and ferrodiorite intrusions within a metamorphic complex composed of gneisses.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Ti, Fe, V, Cr, Ni, Cu, Co geochemical anomalies.

GEOPHYSICAL SIGNATURE: Magnetic or EM response, although if the deposit is particularly ilmenite-rich it may exhibit either a subdued or a strong negative anomaly. Sometimes the subdued response displays characteristic irregular patterns of negative and positive anomalies that show broad smooth profiles or patterns.

OTHER EXPLORATION GUIDES: Heavy mineral concentrations of ilmenite and titaniferous magnetite in placer deposits. Abundant apatite in some deposits. Association with anorthosite and gabbro intrusive complexes along deep fracture and fault zones.

ECONOMIC FACTORS

GRADE AND TONNAGE: Both grade and tonnage vary considerably. The ilmenite deposits are up to several hundreds of millions of tonnes with from 10 to 75% TiO_2, 32 to 45% Fe and less than 0.2% V. The Tellnes deposit comprises 300 Mt averaging 18% TiO_2. The Lac Tio deposit, largest of 6 deposits at Allard Lake, contains more than 125 Mt of ore averaging 32% TiO_2 and 36% FeO. Titaniferous magnetite deposits can be considerably larger, ranging up to a billion tonnes with grades between 20 to 45% Fe, 2 to 20% TiO_2 and less than 7% apatite with V contents averaging 0.25%.

ECONOMIC LIMITATIONS: The economic deposits are typically coarse, equigranular aggregates which are amenable to processing depending on the composition and kinds of exsolution textures of the Fe-Ti-oxide minerals.

USES: Titanium dioxide is a non-toxic, powdered white pigment used in paint, plastics, rubber, and paper. Titanium metal is resistant to corrosion and has a high strength-to-weight ratio and is used in the manufacturing of aircraft, marine and spacecraft equipment.

IMPORTANCE: Apart from placers, this type of deposit is the major source of TiO_2. These deposits were an important source of iron (pig iron) in the former Soviet Union. They have been mined for Fe in Canada, however, the grades are generally lower than those in iron formations and iron laterites. The only current iron production is as a co-product with TiO_2 in pyrometallurgial processing of ilmenite ore.

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ALASKAN-TYPE Pt±Os±Rh±Ir M05

by Graham T. Nixon[1]

IDENTIFICATION

SYNONYMS: Zoned ultramafic, Uralian-type, Alaskan-type.

COMMODITIES (*BYPRODUCTS*): Pt (*Ir, Os, Rh, magnetite*).

EXAMPLES (British Columbia - *Canada/International*): Tulameen Complex and associated placers; magnetite plus trace platinum group elements (PGE) -Lodestone Mountain (092HSE034), Tanglewood Hill (092HSE035); chromite - Grasshopper Mountain (092HNE011); olivine - Grasshopper Mountain Olivine (092HNE189); *Red Mountain, Goodnews Bay (Alaska, USA), Tin Cup Peak (Oregon, USA), Ural Mountains and Aldan Shield (Russia), Fifield district (NSW, Australia).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Ultramafic intrusive complexes, commonly zoned, forming sills, stocks or intrusive bodies with poorly known external geometry. Subeconomic platinum group elements in lode occurrences are associated with:

1) thin (centimetre-scale), disrupted chromitite layers ,
2) thick (metre-scale) concentrations of cumulus magnetite or
3) clinopyroxenite.

Economic placer deposits appear to be derived predominantly from chromitite-hosted PGE occurrences.

TECTONIC SETTINGS: Traditionally subdivided into orogenic (unstable) and platformal (stable) environments. In British Columbia, Alaskan-type complexes were emplaced during an episode of Cordillera-wide, subduction-related arc magmatism followed by an episode of orogenic compression.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Zoned to crudely layered ultramafic-mafic intrusive complexes with rarely preserved (or poorly documented) metamorphic aureoles. Intrusive margins are commonly faulted. Traditionally viewed as deep-seated cumulates diapirically re-emplaced at high levels in the crust. In British Columbia, at least, most intrusions appear to represent cumulate deposition in upper crustal (subvolcanic?) magma chambers and the diapiric re-emplacement model lacks definitive supporting evidence.

AGE OF MINERALIZATION: Precambrian to late Mesozoic; most Alaskan-type complexes in British Columbia appear to be mid-Triassic to late Early Jurassic in age.

HOST/ASSOCIATED ROCK TYPES: Predominantly dunite, wehrlite, olivine clinopyroxenite, clinopyroxenite, hornblende clinopyroxenite, clinopyroxene hornblendite, hornblende- and/or clinopyroxene-bearing gabbro/diorite. Minor lithologies include chromitite, magnetitite, olivine-hornblende clinopyroxenite, and hornblendite. Associated feldspar-bearing lithologies include gabbro/diorite, monzonite, monzodiorite and minor alkali-feldspar syenite and hornblende-feldspar ± quartz ± biotite pegmatite.

Nixon, G.T. (1996): Alaskan-type Pt±Os±Rh±Ir; *in* Selected British Columbia Mineral Deposit Profiles, Volume 2, D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy, Mines and Petroleum Resources*, pages 113-116.

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ALASKAN-TYPE Pt±Os±Rh±Ir M05

DEPOSIT FORM: Lode occurrences of PGEs are primarily controlled by magmatic cumulate stratigraphy: 1) chromitites are restricted to dunites where they form thin discontinuous layers or schlieren, pods and nodular masses seldom more than a metre in length; 2) magnetitites and concentrations of cumulus magnetite form well bedded, locally continuous layers up to six m thick intercalated with hornblende clinopyroxenite; 3) lenses and vein-like bodies of relatively coarse-grained or "pegmatoid", biotite and magnetite-poor, PGE-bearing clinopyroxenites are enclosed by finer grained, biotite and magnetite-rich, PGE-poor clinopyroxenites.

TEXTURE/STRUCTURE: Cumulus and intercumulus textures are most common; poikilitic textures may predominate locally, especially in hornblende-bearing lithologies. Comparatively rare macroscopic layering. Euhedral to subhedral chromite concentrations form networks around olivine or discrete wispy or thin layers in dunite. Chromitites typically form schlieren and nodular masses due to syndepositional remobilization. Magnetite-rich accumulations usually form thin to thick bedded layers in hornblende clinopyroxenite. Tectonic deformation, commonly in the form of ductile shear fabrics, is locally superimposed on magmatic textures, and is especially prevalent at intrusive contacts.

ORE MINERALOGY (Principal and *subordinate*): Three types of PGE mineral (PGM) associations are recognized in lode occurrences: 1) chromitite-PGM association, principally chromite and Pt-Fe(-Cu-Ni) alloys (e.g. tetraferroplatinum, isoferroplatinum, rare *native platinum, tulameenite*) and minor *Os-Ir* and *Pt-Ir alloys, Rh-Ir sulpharsenides (hollingworthite-irarsite* series), *sperrylite* ($PtAs_2$), *geversite* ($PtSb_2$), and *laurite* (RuS_2); 2) magnetitite-PGM association (not well documented), principally magnetite (Ti-V-rich in certain cases) and Pt-Fe and Os-Ir alloys, and rare *cooperite* (PtS); 3) clinopyroxenite-PGM association (known from a single locality - Fifield, NSW, Australia), principally Pt-Fe alloys (isoferroplatinum-tetraferroplatinum), erlichmanite (OsS_2), cooperite, and sperrylite-geversite. Minor amounts of *base metal sulphides (chalcopyrite, pentlandite, pyrrhotite, pyrite, bornite, violarite, bravoite, millerite, heazlewoodite*) generally accompany the PGM in all three associations.

GANGUE MINERALOGY (Principal and *subordinate*): The principal gangue minerals include olivine, chrome spinel, clinopyroxene, and hornblende in ultramafic rocks; hornblende, clinopyroxene and plagioclase in gabbroic/dioritic rocks; and hornblende, quartz (rare) and alkali feldspar in leucocratic differentiates. Orthopyroxene is characteristically absent as a cumulus phase but may form very rare intercumulus grains. Accessory magnetite and apatite are generally common, and locally abundant in hornblende clinopyroxenite; sphene and zircon occur in felsic differentiates; phlogopite-biotite is particularly widespread as an accessory phase in British Columbia.

ALTERATION MINERALOGY: Secondary PGM are minor and closely associated with the primary PGM alloys. Remobilization of PGE is believed to be extremely limited and may be commonly related to postmagmatic serpentinizaton processes acting during regional metamorphism and deformation.

WEATHERING: It has been argued by some that the PGE found in placer occurrences may owe their origin to the hydromorphic dispersion and precipitation of PGE during normal weathering processes. The debate continues, but it is clear from a variety of textural, mineralogical and isotopic (Re-Os) data that the common placer PGE occurrences are the products of mechanical degradation of magmatic lode occurrences and not surficial remobilization processes.

ORE CONTROLS: The PGM appear to be restricted to chromitite, magnetite-rich or clinopyroxenite layers which formed by primary magmatic crystallization processes. The chromite is typically associated with dunite whereas the magnetite is found with clinopyroxenite.

GENETIC MODEL: The origin of the PGE in Alaskan-type deposits is magmatic with very limited low-temperature remobilization. A low sulphidation, relatively high oxidation magmatic environment (subduction-related?) appears to be an important genetic control. The chromitites in dunite and, to a much lesser extent, the magnetite-rich layers in clinopyroxenite, appear to be the ultimate source of the placer PGE.

ALASKAN-TYPE Pt±Os±Rh±Ir M05

ASSOCIATED DEPOSIT TYPES: Placer deposits (C01, C02) are extremely important since they have been the only significant economically recoverable source of PGE associated with Alaskan-type complexes. Some lode deposits have been worked in Russia but their documentation is extremely poor.

COMMENTS: All of the world's most important Alaskan-derived placers appear to be related to concentrations of PGE in chromitites. Gold in these placers appears to have been derived from a separate source. Magnetite accumulations in clinopyroxenites of the Tulameen Complex have been explored for magnetite.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Primarily Pt, with subsidiary Os, Rh and Ir; other elements such as Cu, Ni, and Cr may be locally important. Geochemical pathfinder elements for PGE, such as As and Sb, may also be important.

GEOPHYSICAL SIGNATURE: Primarily magnetic; gravity may be important.

OTHER EXPLORATION GUIDES: Stream sediment sampling of heavy mineral concentrates for PGE is a key exploration tool; in favourable circumstances PGE geochemistry and platinum nugget mineralogy can uniquely distinguish an Alaskan-type heritage from all other common PGE environments.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: PGE concentrations in grab samples from lode deposits are extremely spotty such that reliable tonnages and grades are not available. The associated placer deposits are likewise extremely variable. Maximum grade of Pt from the Goodnews Mining Company records, Alaska (1957) was approximately "$37 per cubic yard" at February 1993 prices. Placers in the Tulameen district reportedly yielded some 620 kg of impure platinum between 1889 and 1936. Some of the placer deposits in the former Soviet Union have yielded exceptional platinum nuggets of up to 11.3 kg.

ECONOMIC LIMITATIONS: The chromitite-PGE association appears to be the most important in British Columbia; without exception, all of these chromitite occurrences are small, dispersed throughout a dunite host, and all have been remobilized soon after deposition within the high-temperature magmatic environment. A small open pit operation appears to be the only potentially economic method of PGE extraction. The occurrence of the PGE as small micrometre-size inclusions in refractory chromite poses problems for processing.

END USES: PGE are primarily used as high-temperature catalysts in a variety of industries, perhaps the most familiar being platinum for automobile catalytic converters. Other uses include medical and electronic (fuel cells, thermocouples), and platinum is used in jewelry.

IMPORTANCE: PGE are classed as a strategic commodity. The most important producers are South Africa and Russia.

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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.

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

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ULTRAMAFIC-HOSTED CHRYSOTILE ASBESTOS M06

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.

TYPICAL GRADE AND TONNAGE (continued): 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 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.*

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[2] Omya Inc., Proctor, Vermont, USA.

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*.

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.

ULTRAMAFIC-HOSTED TALC-MAGNESITE

M07

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: The grade and size of these deposits is highly variable. The Deloro deposit consists of 54% magnesite and 28% talc. It is about 1800 metres in length, 300 metres wide and has been drilled to the depth of 120 metres. An underground talc mine of Cyprus Minerals Co., located at Windham, Vermont consists of lenses exceeding 230 metres in length and 100 metres in width. The Lahnaslampi orebody in Finland contains over 30 million tonnes exceeding 50% talc and 0.1 to 0.2% Ni. Nickel concentrate is produced from the tailings at Lahnaslampi. There is the opportunity that talc could be a by-product from listwanite-hosted gold mines. The metallurgical tests suggest that in some cases, it is technically possible to produce a magnesite concentrate as talc by-product. However, economics of the process and exact technical specifications of the potential product are not well documented.

ECONOMIC LIMITATIONS: Steatite contains more than 90% talc. Flotation is required for most deposits to produce high-quality fillers for paint and plastic applications, the ceramic and pharmaceutical industries, and crayons. Underground mining is economically feasible to depths exceeding 300 metres. FeO content of magnesite from these deposits varies from 0.5 to 7%. Research is underway to chemically reduce iron content of magnesite, in order to achieve refractory grade magnesia products. Current restrictions placed on asbestos-bearing materials makes the ores from asbestos-free deposits easier to market.

END USES: Talc from these deposits is commonly used in paper, ceramic, paint, plastic, roofing and electrical applications. Massive talc and soapstone are used in electric insulation, refractory applications, as carving stone or as raw material for laboratory sinks.

IMPORTANCE: Ultramafic-hosted talc-magnesite deposits are important source of talc.

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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*.

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VERMICULITE M08

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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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.

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CARBONATITE-ASSOCIATED DEPOSITS N01

HOST/ASSOCIATED ROCK TYPES: Host rocks are varied, including calcite carbonatite (sovite), dolomite carbonatite (beforsite), ferroan or ankeritic calcite-rich carbonatite (ferrocarbonatite), magnetite-olivine-apatite ± phlogopite rock, nephelinite, syenite, pyroxenite, peridotite and phonolite. Carbonatite lava flows and pyroclastic rocks are not known to contain economic mineralization. Country rocks are of various types and metamorphic grades.

DEPOSIT FORM: Carbonatites are small, pipe-like bodies, dikes, sills, small plugs or irregular masses. The typical pipe-like bodies have subcircular or elliptical cross sections and are up to 3-4 km in diameter. Magmatic mineralization within pipe-like carbonatites is commonly found in crescent-shaped and steeply-dipping zones. Metasomatic mineralization occurs as irregular forms or veins. Residual and other weathering-related deposits are controlled by topography, depth of weathering and drainage development.

TEXTURE/STRUCTURE: REE minerals form pockets and fill fractures within ferrocarbonatite bodies. Pyrochlore is disseminated; apatite can be disseminated to semi-massive; bastnaesite occurs as disseminated to patchy accumulations; fluorite forms as veins and masses; hematite is semi-massive disseminations; and chalcopyrite and bornite are found in veinlets.

ORE MINERALOGY [Principal and *subordinate*]:

Magmatic: bastnaesite, pyrochlore, apatite, anatase, *zircon, baddeleyite, magnetite, monazite, parisite, fersmite*.

Replacement/Veins: fluorite, vermiculite, bornite, chalcopyrite and other sulphides, hematite.

Residual: anatase, pyrochlore and apatite, locally crandallite-group minerals containing REE.

GANGUE MINERALOGY [Principal and *subordinate*]: Calcite, dolomite, siderite, ferroan calcite, ankerite, hematite, biotite, titanite, olivine, *quartz*.

ALTERATION MINERALOGY: A fenitization halo (alkali metasomatized country rocks) commonly surrounds carbonatite intrusions; alteration mineralogy depends largely on the composition of the host rock. Typical minerals are sodic amphibole, wollastonite, nepheline, mesoperthite, antiperthite, aegerine-augite, pale brown biotite, phlogopite and albite. Most fenites are zones of desilicification with addition of Fe^{3+}, Na and K.

WEATHERING: Carbonatites weather relatively easily and are commonly associated with topographic lows. Weathering is an important factor for concentrating residual pyrochlore or phosphate mineralization.

ORE CONTROLS: Intrusive form and cooling history control primary igneous deposits (fractional crystallization). Tectonic and local structural controls influence the forms of metasomatic mineralization. The depth of weathering and drainage patterns control residual pyrochlore and apatite deposits, and vermiculite deposits.

GENETIC MODELS: Worldwide, mineralization within carbonatites is syn- to post-intrusion and commonly occurs in several types or stages:

1) REE-rich carbonatite and ferrocarbonatite, magmatic magnetite, pyrochlore
2) Fluorite along fractures
3) Barite veins
4) U-Th minerals + silicification
5) calcite veining and reprecipitation of Fe oxides (hematite)
6) Intense weathering may take place at any later time.

Magmatic mineralization may be linked either to fractional crystallization or immiscibility of magmatic fluids. Metasomatism and replacement are important Not all mineralization types are associated with any individual carbonatite intrusion. In general, it is believed that economic Nb, REE and primary magnetite deposits are associated with transgressive (late) igneous phases, but understanding of the majority of deposits is not advanced enough to propose any general relationship of timing. mineralization at St. Honoré, for example, is probably relatively early-formed.

CARBONATITE-ASSOCIATED DEPOSITS N01

ASSOCIATED DEPOSIT TYPES: Nepheline syenite (R13) and nepheline syenite-related corundum deposits and sodalite. REE and zircon placer deposits (C01, C02) deposits can be derived from carbonatites. Wollastonite occurrences are in some cases reported in association with carbonatites. Fluorite deposits are known from the roof zones of carbonatite complexes (I11). Kimberlites and lamproites (common host-rocks for diamonds) may be along the same tectonic features as carbonatites, but are not related to the same magmatic event.

COMMENTS: Carbonatites should be evaluated for a variety of the mineral substances as exemplified by the exceptional Palabora carbonatite which provides phosphate (primary and possibly hydrothermal), Cu (hydrothermal), vermiculite (weathering) and also Zr, U and Th as byproducts. While extrusive carbonatite rocks are known to contain anomalous REE values, for example the Mount Grace pyroclastic carbonatite in British Columbia, they are not known to host REE in economic concentrations.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Resistant niobium or phosphate minerals in soils and stream sediments; F, Th and U in waters.

GEOPHYSICAL SIGNATURE: Magnetic and radiometric expressions and sometimes anomalous radon gas concentrations furnish primary targets.

OTHER EXPLORATION GUIDES: Carbonatites are commonly found over broad provinces, but individual intrusions may be isolated. Fenitization increases the size of target in regional exploration for carbonatite-hosted deposits. U-Th (radioactivity) associated with fluorite and barite within carbonatites are considered as indirect REE indicators. Annular topographic features can coincide with carbonatites.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Araxa deposit contains 300 million tonnes grading 3% Nb_2O_5; Cargill deposit consists of 60 million tonnes at 20% P_2O_5; Niobec deposit hosts 19 million tonnes grading 0.66 % Nb_2O_5; Alley has extensive zones exceeding 0.66% Nb_2O_5 and locally exceeding 2%.

ECONOMIC LIMITATIONS: Competitive markets are established for most of the commodities associated with carbonatites. In 1996, the world consumption was estimated at 22 700 tonnes of Nb_2O_5. Araxa mine, the largest single source of Nb_2O_5 in 1996, produced 18 300 tonnes of concentrate which was largely reduced into standard ferro-niobium. Brazil's second largest producer, Catalao, produced 3 600 tonnes of ferroniobium The largest North American producer is Niobec Mine which produced 3 322 tonnes of Nb_2O_5 which was also reduced to ferro-niobium. At the end of 1996 standard grade ferro-niobium sold at $US 15.2/kg, vacuum grade at $US 37.5/kg, nickel-niobium at US$ 39.7 - 55.1/kg of contained niobium. Demand for REE in 1996 was estimated at 65,000 tonnes/year contained rare earth oxides or US$ 650 million. Currently China accounts for nearly half of the world production due largely to heavy discounting, USA is the second largest producer. Separated rare earths account for 30% of the market by volume but 75% by value. Tantalum primary production for 1996 was estimated at 100.1 tonnes of Ta_2O_5 contained in tantalum-bearing tin slags (principally from smelters in Brazil, Thailand and Malaysia) and 426.0 tonnes of Ta_2O_5 in tantalite or other minerals.

END USES: Rare Earths - mainly as a catalyst in oil refining, catalytic converters, glass industry, coloring agents, fiber optics, TV tubes, permanent magnets, high strength alloys and synthetic minerals for laser applications. Phosphate: fertilizers, phosphorus, and phosphoric acid. Sr: Color TV screens, pyrotechnics and magnets. Nb: carbon stabilizer in stainless steel, niobium carbide used in cutting tools, Nb-containing temperature-resistant steel used in turbines, Nb-base alloys in reactors, super alloys for military and aerospace applications. Tantalum: in corrosion-resistant alloys; implanted prosthesis; nuclear reactors and electronic industry. Carbonates may be used in local portland cement industries. Vermiculite is exfoliated and used in agriculture, insulation, as lightweight aggregate, and other construction materials.

CARBONATITE-ASSOCIATED DEPOSITS N01

IMPORTANCE: Carbonatites are the main source of niobium and important sources of rare earth elements, but have to compete for the market with placer deposits and offshore placer deposits (Brazil, Australia, India, Sri-Lanka). They compete with sedimentary phosphate deposits for a portion of the phosphate market.

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KIMBERLITE-HOSTED DIAMONDS N02

by Jennifer Pell[1]

IDENTIFICATION

SYNONYMS: Diamond-bearing kimberlite pipes, diamond pipes, group 1 kimberlites.

COMMODITIES (*BYPRODUCTS*): Diamonds (some gemstones produced in Russia from pyrope garnets and olivine*).*

EXAMPLES (British Columbia - *Canada/International*): No B.C. deposits, see comments below for prospects; *Koala, Panda, Sable, Fox and Misery (Northwest Territories, Canada), Mir, International, Udachnaya, Aikhal and Yubilenaya (Sakha, Russia), Kimberly, Premier and Venetia (South Africa), Orapa and Jwaneng (Botswana), River Ranch (Zimbabwe).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Diamonds in kimberlites occur as sparse xenocrysts and within diamondiferous xenoliths hosted by intrusives emplaced as subvertical pipes or resedimented volcaniclastic and pyroclastic rocks deposited in craters. Kimberlites are volatile-rich, potassic ultrabasic rocks with macrocrysts (and sometimes megacrysts and xenoliths) set in a fine grained matrix. Economic concentrations of diamonds occur in approximately 1% of the kimberlites throughout the world.

TECTONIC SETTING: Predominantly regions underlain by stable Archean cratons.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: The kimberlites rise quickly from the mantle and are emplaced as multi-stage, high-level diatremes, tuff-cones and rings, hypabyssal dikes and sills.

AGE OF MINERALIZATION: Any age except Archean for host intrusions. Economic deposits occur in kimberlites from Proterozoic to Tertiary in age. The diamonds vary from early Archean to as young as 990 Ma.

HOST/ASSOCIATED ROCK TYPES: The kimberlite host rocks are small hypabyssal intrusions which grade upwards into diatreme breccias near surface and pyroclastic rocks in the crater facies at surface. Kimberlites are volatile-rich, potassic ultrabasic rocks that commonly exhibit a distinctive inequigranular texture resulting from the presence of macrocrysts (and sometimes megacrysts and xenoliths) set in a fine grained matrix. The megacryst and macrocryst assemblage in kimberlites includes anhedral crystals of olivine, magnesian ilmenite, pyrope garnet, phlogopite, Ti-poor chromite, diopside and enstatite. Some of these phases may be xenocrystic in origin. Matrix minerals include microphenocrysts of olivine and one or more of: monticellite, perovskite, spinel, phlogopite, apatite, and primary carbonate and serpentine. Kimberlites crosscut all types of rocks.

DEPOSIT FORM: Kimberlites commonly occur in steep-sided, downward tapering, cone-shaped diatremes which may have complex root zones with multiple dikes and “blows”. Diatreme contacts are sharp. Surface exposures of diamond-bearing pipes range from less than 2 up to 146 hectares (Mwadui). In some diatremes the associated crater and tuff ring may be preserved. Kimberlite craters and tuff cones may also form without associated diatremes (e.g. Saskatchewan); the bedded units can be shallowly-dipping. Hypabyssal kimberlites commonly form dikes and sills.

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

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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.

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

SYNONYMS: None.

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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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 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 (BY PRODUCTS): 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 may cover the whole spectrum from granitic to gabbroic composition. 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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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 s*ubordinate*): Andalusite, *staurolite, garnet*.

GANGUE MINERALOGY (Principle and *subordinate*): Fine grained hornfels matrix - usually cordierite, biotite, muscovite, chlorite and quartz.

ALTERATION MINERALOGY: Retrograde metamorphism results in andalusite being altered to mica and staurolite or mica and chlorite. Such alteration (even partial) may render the andalusite unusable for industrial applications.

WEATHERING: Andalusite is not highly susceptible to chemical weathering and as such, may accumulate in alluvial sediments or as a residual deposit.

ORE CONTROLS: Andalusite development is a factor of the composition of the protolith and the high temperature/low pressure conditions adjacent to an igneous intrusion. The chemical nature and thickness of the original sedimentary layers and their respective distance from the intrusive contact are the main controls on the formation of andalusite hornfels orebodies. Although the metamorphic aureole may extend a large distance, typically only a few areas within the aureole satisfy the conditions necessary to produce economic accumulations of andalusite.

GENETIC MODELS: Andalusite deposits develop in pelitic rocks with high alumina and low calcium contents at temperatures of 550° to 600°C and low pressures of about two kilobars. Such conditions usually develop within the contact aureole of an intrusive. At higher temperatures, sillimanite or corundum and spinel would form at the expense of andalusite.

ASSOCIATED DEPOSIT TYPES: Wollastonite (K09) and garnet (K08) skarns form under similar circumstances from calcium-rich protoliths. Andalusite hornfels deposits can be the source for placer andalusite (C01, C02). Microcrystalline graphite (P03) and gem corundum (Q09) are also found in contact aureoles of igneous rocks.

COMMENTS: Under special conditions, regional, low pressure metamorphism can result in crystallization of sufficient andalusite to be a commercial grade. Some contact aureoles of large intrusive complexes, like the Bushveld Complex, are so extensive that they have features similar to regional low-pressure metamorphism.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: None.

GEOPHYSICAL SIGNATURE: None.

OTHER EXPLORATION GUIDES: Andalusite, corundum and spinel in alluvial deposits; geological contacts of pelitic sediments with plutonic rocks; sedimentary roof pendants in large plutonic complexes. Most deposits are found within one km of the related igneous intrusion. Economic deposits are more likely in prospective regions with well developed weathering profiles.

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. Paradis[2], 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, USA
[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, and ± rutile.*

ALTERATION MINERALOGY: Pyrophyllite, muscovite and sericite are common alteration products of kyanite.

WEATHERING: In general intense weathering facilitates separation of kyanite family minerals from gangue minerals.

ORE CONTROLS: Stratigraphy, chemical composition of the protolith and degree of metamorphism. High-grade zones within the mineralized units are commonly located in crests of folds, sheer zones and sweat-outs that were open to fluids at the time of the crystallization of anhydrous, aluminous silicates.

GENETIC MODEL Kyanite, sillimanite, garnet and muscovite are metamorphic minerals. Kyanite deposits are hosted by quartzites, schists and paragneisses of high pressure metamorphic terrains. Sillimanite occurs mainly in schists and gneisses affected by high-temperature, high-pressure metamorphism.

ASSOCIATED DEPOSIT TYPES: Garnet-bearing paragneiss, some of the abyssal pegmatites (O04), crystalline flake graphite (P04) deposits. Secondary (C01) and primary (P06) sapphires, placer kyanite, sillimanite, andalusite and garnet or staurolite deposits (C02, C03) and corundum in aluminous metasediments occur in similar geological environments.

COMMENTS: In North America, kyanite is the most widely used Al_2SiO_3 polymorph. Sister polymorphs are andalusite and sillimanite. When calcined these minerals are converted to mullite, a highly refractory phase. Kyanite converts to mullite at 1370°C. This conversion is accompanied by a non reversible volume expansion of 18%. Because of this volume change, calcination of kyanite is required before it can be used in refractory shapes. For discussion on the andalusite see deposit model P01.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: N/A.

GEOPHYSICAL SIGNATURE: Regional geophysical data, such as EM, radiometric methods, etc. may be used as indirect tools to trace favourable metasedimentary units if marker horizons or igneous intrusions have distinctive signatures.

OTHER EXPLORATION GUIDES: Delimit areas where metamorphic conditions required to form anhydrous aluminum silicates were reached. Identify favorable lithologies and pay special attention to crests of folds and metasediment-intrusive rocks contacts. Panning along stream beds for heavy minerals is an effective exploration tool, since the density of aluminum silicates varies from 3.1 to 3.7 g/cm^3.

KYANITE, MUSCOVITE, GARNET IN METASEDIMENTS P02

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Graves Mountain has possible reserves of 30 Mt at 25% kyanite and Willis Mountain reports indicated reserves of 65 Mt at 25% kyanite.

ECONOMIC LIMITATIONS: Anhydrous aluminum silicate polymorphs are relatively low priced products. Transportation distance and processing required for specific end uses may limit the market area. Processing to mullite or precalcination does increase the market area for kyanite, assuming favourable energy costs near the mine site. Kyanite concentrates should contain a minimum of 56% Al_2O_3 and 42% SiO_2, with less than 1% Fe_2O_3, 1.2% TiO_2, 0.1% MgO and 0.1% CaO. In general, the coarse-grained concentrates command the highest prices; therefore, ores containing larger kyanite crystals with minor amounts of unwanted mineral inclusions are particularly attractive. Several large, high-grade deposits are not exploited because the kyanite incorporates deleterious mineral inclusions. Co-production of mica and garnet as part of hard-rock kyanite operations should be considered in modern feasibility studies.
Sillimanite concentrates are derived mainly as a byproduct of heavy mineral sand operations. The well-known sillimanite-corundum sources from Assam, India are nearly exhausted. Similar product was also mined in the Pella District, Republic of South Africa. Fibrolite sillimanite is not mined from gneisses because of processing difficulties. Occurrences with “matchstick”-sized crystals were mined in the past and are more amenable to upgrading.

END USES: These deposits represent low-cost raw materials for mullite-based, high-performance refractories characterized by high hot strength and resistance to chemically corrosive environments. Kyanite has applications in high-performance refractory products used in both brick and monolitic applications. Also utilized in steel and glass industries, cement kilns, heat treatment furnaces, ceramic and petrochemical industries. Kyanite has new applications in non-slip flooring, glazes and abrasives. Sillimanite-corundum boulders are cut directly into refractory shapes. Assuming comparable grades, sillimanite concentrate could compete with andalusite, both of these minerals are characterized by a relatively low volume increase during mullitization if compared to kyanite. However, currently there is a very limited market incentive to produce sillimanite concentrate.

IMPORTANCE: Kyanite derived from quartzites and schists is the most commonly used anhydrous aluminum silicate in North America. In Europe and in Japan, andalusite is the most preferred polymorph, because it does not require precalcination.

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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.

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Asbury Graphite Mills Inc., Asbury, New Jersey, USA

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 invaded by igneous rocks or 2) coal seams traced across regional metamorphic isograds into low to medium-grade metamorphic areas.

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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.

MICROCRYSTALLINE GRAPHITE P03

END USES: Microcrystalline graphite is used in brake linings, foundry applications, lubricants, pencils, refractories, and steel making. The graphite may contain several percent volatile material. In fact, some meta-anthracite from South Korea is marketed as microcrystalline graphite, but it may be due largely to export restrictions on energy exports from Korea.

IMPORTANCE: Metamorphosed coal beds are the main source of microcrystalline graphite. For most applications, synthetic graphite and crystalline graphite may be substituted for amorphous graphite but at increased cost.

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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.

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Asbury Graphite Mills Inc., Asbury, New Jersey, USA

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), wollastonite skarn (K09) and abyssal (ceramic) pegmatite (Q04) deposits.

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 coarse flakes, which can be easily liberated, may 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. Sillimanite, graphite-sillimanite or graphite-tourmaline alteration is reported adjacent to the veins in Sri Lanka and New Hampshire.

[1] British Columbia Geological Survey, Victoria, B.C., Canada
[2] Asbury Graphite Mills Inc., Asbury, New Jersey, USA

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. British Columbia has no documented vein graphite occurrences.

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 Star (082FNW259); *Elk Creek, Bozeman and Bear Trap deposits (Montana, USA), Gangoda and Tannahena occurrences (Sri Lanka),*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Corundum occurs as porphyroblasts or idiomorphic, xenomorphic or skeletal crystals within high grade, regionally metamorphosed belts. It is confined to specific metamorphic layers and concordant lenses of alumina-rich gneisses and schists. It is rarely of gem quality. Emery is a fine-grained, black, granular rock composed of intergrowths of corundum, magnetite, hercinite or hematite that commonly forms in medium to high grade metamorphic environments.

TECTONIC SETTINGS: Corundum in gneisses occurs mostly in fold belts or deep cratonic (catazonal) environments exhumed in thrust belts or by erosion. Emery and related meta-bauxites may be found in wide variety of tectonic environments.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: Most of these deposits form in high-grade, mainly granulite facies, dynamothermal metamorphic (catazonal) environments. Metasedimentary belts containing aluminous strata or lenses, in some cases intruded by igneous rocks, are particularly favourable. Emery deposits are also known to occur in similar and lower grade metamorphic environments.

AGE OF MINERALIZATION: Corundum is considered syn-metamorphic. The protolith may be Precambrian or younger. Rocks that were exposed at the surface during periods of extreme chemical weathering are particularly favourable

HOST/ASSOCIATED ROCK TYPES: Corundum-bearing gneisses and schists are associated with sillimanite-garnet-biotite gneisses, kyanite-mica schists, quartzites, clinopyroxenites, pegmatites, syenites or alkaline intrusions, anorthosites, charnockites, migmatites, granitic and intermediate intrusive rocks, quartz-mica schists, granulites, aplites, marbles, cordierite-bearing gneisses, amphibolites and wollastonite-scapolite rocks. The lithologies hosting metasedimentary emery lenses are commonly lower metamorphic grade equivalents of above listed rocks.

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

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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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[2] Geological Survey of Canada, Pacific Geoscience Centre, Sydney, B.C., Canada
[3] SOQUEM, Quebec City, Quebec, Canada

COLOMBIA-TYPE EMERALDS Q06

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.

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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).

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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 environment.

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.

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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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SEDIMENTARY ROCK-HOSTED OPAL
Q08

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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 have 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 by some 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 basements 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.

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[4]. In places opal seems to follow cross bedding. In unusual cases opal pieces eroded from the original host are incorporated

into younger sediments. In silicified sandstones precious opal may form the cement around detrital quartz grains, in other areas, the opal may be cut by gypsum or alunite-filled fractures. The lithologies above the opal may contain characteristic red-brown, gypsiferous silt-filled tubules.

[4] 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.

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 found 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.

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 $Aus. 10 000.00 per carat in cut form and Mintabie opal varied from $Aus. 50.00 to 10 000.00 per ounce of rough. Most of the white to milky colored opal from Coober Pedy was worth $Aus. 10.00 to 100.00 per ounce of rough, but the prices of top quality precious black and crystal opals exceeded $Aus. 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: In Australia mining 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 these 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. Doublets are produced where the precious opal is too thin, needs reinforcement or enhancement; plastic cement, a slice of common opal or other support is added to the back of the opal.

IMPORTANCE: Australian sedimentary-hosted opal deposits account for most of the opal produced today. The 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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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 (coarse grained rock consisting of anhedral corundum crystals in an oligoclase matrix), marundite (corundum in margarite matrix), syenite, pegmatite, aplite or hornfels. Associated rocks are ultramafics, a variety of mafic lithologies including gabbro, amphibolite, anorthosite, serpentinite, anthophyllite-chlorite-talc schist, peridotite and dunite and peraluminous orthogneisses or paragneisses.

Simandl, G.J. and Paradis, S. (1999): Ultramafic-related Corundum (Contact Metamorphic/Metasomatic); *in* Selected British Columbia Mineral Deposit Profiles, Volume 3, G.J. Simandl, Z.D. Hora and D.V. Lefebure and T. Höy, Editors, *British Columbia Ministry of Energy and Mines*, Open File 1999-10.

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ULTRAMAFIC-RELATED CORUNDUM Q09

DEPOSIT FORM: Most of the dyke-associated or fracture-controlled deposits that crosscut ultramafic and mafic rocks are planar or lens-shaped; rarely forming vertical plugs. They are less than a metre to 10 metres in thickness and may extend from few metres to several tens of metres along strike. These deposits exhibit several types of mineralogical zoning from the center of the deposit outwards:

a) Corundum-chlorite > spinel - chlorite > enstatite > talcose rock > friable dunite > dunite;
b) plumasite > biotitite > pegmatite > serpentinite;
c) aplite> plumasite>spinel-magnetite rock > vermiculite and/or chlorite > actinolite > talc>serpentinite;
d) barren pegmatite> marundite > talc-chlorite zone>amphibolite (pegmatite may not be present).

Lenticular or irregularly shaped, corundum-bearing pockets may be also present along the tectonic contacts between gneiss and serpentinite. Some of the gem-quality and most of the industrial grade corundum and emery deposits occur near the contacts of mafic and ultramafic intrusions with country rocks. Emery may form veins, layers and irregular or lens-shaped masses within both endo- and exometamorphic reaction zones. Most of the corundum is typically found in metapelites adjacent to such intrusions.

TEXTURE/STRUCTURE: Sapphire and ruby may form rhombohedral or hexagonal prisms or they may occur as clear portions of large, poikilitic corundum crystals that may exceptionally reach over a metre in length. In South African plumasites the corundum crystals commonly vary from 3 millimetres to 10 centimetres. In marundite, corundum occurs as coarse hexagonal crystals embedded in scaly or rosette-shaped aggregates of margarite. Emery rock is typically equigranular, fine-grained (<1mm). It may form layers, veinlets or lenses and irregular zones of massive ore in intrusive and country rock.

ORE MINERALOGY [Principal and *subordinate*]: <u>In plumasite and marundite:</u> sapphires, rubies, specimen- quality or industrial grade corundum.
<u>Within contact metamorphic zones of mafic and ultramafic intrusions:</u> mostly emery or silimanite-corundum rock or coarse industrial-grade corundum.
<u>Along tectonic contacts:</u> rubies, sapphires, specimen and industrial grade corundum.

GANGUE MINERALOGY [Principal and *subordinate*]: <u>In plumasites:</u> 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.
<u>In marundites:</u> margarite, ± feldspar, ± *biotite*, ± *apatite*, ± *garnet*, ± *tourmaline*, ± *fuchsite*, ± *kyenite* (?), ± *talcose material and possibly anthophyllite.*
<u>In metasomatic zones cross-cutting ultramafic rocks without plumasite core:</u> vermiculite, ± chlorite. The main solid inclusion in gem corundum is vermiculite.
<u>In contact metamorphic deposits:</u> a) In emery ores: Hercinite, pleonaste, magnetite, hematite/ *ilmenite, ilmenohematite. hypersthene, sapphirine, sillimanite, cordierite, garnet, biotite, feldspar, staurolite, gahnite. Some of the minor constituents in emery ore may be due to hostrock inclusions.* b) In sillimanite-corundum rock: *rutile and ilmenite are trace constituents.*

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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.

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.

ULTRAMAFIC-RELATED CORUNDUM Q09

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.

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.

ULTRAMAFIC-RELATED CORUNDUM Q09

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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); Y*ogo 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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ALKALI BASALT AND LAMPROPHYRE- HOSTED SAPPHIRE and RUBY Q10

TEXTURE/STRUCTURE: In extrusive rocks, sapphire and ruby occur as megacrysts that are typically bi-pyramidal, stepped and tapering or barrel shaped. The corundum crystals can be corroded and etched. Some crystals are zoned, contain a variety of solid inclusions and can be intergrown with other minerals. They may have spinel reaction rims. In New South Wales they are typically less than 1 carat in weight (about 5 mm or less). In Thailand the typical size of sapphires from alluvial sediments is 3-6 mm, but crystals up to 9.5 x 6 x 5.5 cm are also reported. Rubies of about 1-1.5 cm in diametre were found in some localities. In Yogo lamprophyre dykes, most of the sapphire occurs as subhedral to anhedral grains. The most common shape is a wafer with etched surfaces and a thin spinel crust. The host lithologies may contain numerous mantle or crust xenoliths, some of them corundum-bearing gneisses.

ORE MINERALOGY[Principal and *subordinate*]: Sapphire, ruby; ± *zircon.*

GANGUE MINERALOGY[Principal and *subordinate*]: In alkali volcanic rocks the gangue minerals are feldspar (mainly anorthoclase), pyroxene, ± analcime, ± olivine, amphiboles, such as kaersutite, ilmenite, ± magnetite, ± spinel, ± garnet, with minor biotite/phlogopite, *spinel and chrome diopside and zircon* ± rutile. Vesicles may contain amorphous silica, andesine and zeolites.
In lamprophyre hypabyssal rocks, pyroxene, phlogopite, ± calcite (mainly in veins), ± olivine, ± analcime are major constituents. Minor constituents are *magnetite, apatite, chlorite, serpentine, amphibole, brucite and feldspar*.
The main solid inclusions reported within the corundum in volcanic rocks are: spinels (hercynite, gahnite), ilmenite, rutile, ilmeno-rutiles, columbite, uranopyrochlore-betafite, zircon, akali feldspar, plagioclase, mica, thorite, sulphides and glass.

ALTERATION MINERALOGY: Volcaniclastic rocks that host gem corundum are commonly clay-altered and ferruginized due to combination of alteration and weathering.

WEATHERING: Palagonitic clasts and “clast in clast” structures are visible in weathered volcaniclastic rocks that host gem corundum. Weathering can greatly enhance the gem corundum grade and transform a low grade occurrence into a deposit of economic interest. The near surface portion of Yogo dike was weathered to a yellowish clay. Ore from the Yogo Gulch deposit was left on surface to weather for few months to reduce the need for crushing.

ORE CONTROLS: Primary controls are sapphire and ruby-bearing alkali basalt, lamprophyre, nephelinite, basanite or phonolite dikes, flows, pyroclastics or possibly diatremes. Unconformities, paleoregoliths or current 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).

ALKALI BASALT AND LAMPROPHYRE- HOSTED SAPPHIRE and RUBY Q10

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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.*

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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 is not suitable for gems because they crack too easily; however, the opal from many other volcanic-hosted occurrences is as stable as that from the Australian sedimentary-hosted deposits. Deposits located in intensely weathered terrains are easier to mine than deposits in unaltered rocks. Prices of the best quality opal have risen steadily since 1991. There is a relatively good market for precious opal, nevertheless strong marketing and value-added processing are considered essential parts of successful opal mining operations.

END USES: Precious opal is highly priced gemstone; “fire opal” may be faceted, opalized wood is a speciality ornamental stone commonly used for book ends.

IMPORTANCE: Volcanic rock-hosted opal deposits are numerous, but most of today's high quality opal production comes from Australian sedimentary-hosted deposits.

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BROKEN HILL-TYPE Pb-Zn-Ag±Cu S01

By Trygve Höy[1]

IDENTIFICATION

SYNONYMS: Shuswap-type, Ammeburg-type Zn-Pb, Jervois-type.

COMMODITIES (*BY-PRODUCTS)*: Pb, Zn, Ag, *(Cu, Au, barite*).

EXAMPLES (British Columbia (MINFILE #) - *Canada/International*): Cottonbelt (082M086), River Jordan (082M001), Ruddock Creek (082M082-084), Big Ledge? (082LSE012), Colby? (082ESW062); *Broken Hill and Pinnacles (New South Wales, Australia); Broken Hill and Black Mountain, Aggeneys district and Gammsberg area (South Africa), Knalla and Nygruvan, Bergslaggen district (Sweden).*

GEOLOGICAL CHARACTERISTICS

CAPSULE DESCRIPTION: Deposits comprise massive to semimassive galena, sphalerite, pyrrhotite and pyrite and/or magnetite layers or stacked lenses hosted by thin-bedded, commonly calcareous paragneiss successions. A complex gangue mineralogy includes a variety of calcsilicate minerals. These stratabound deposits are typically thin, but laterally extensive and were deformed and metamorphosed together with their hostrocks.

TECTONIC SETTING: In strongly deformed and metamorphosed supracrustal rocks commonly referred to as 'mobile belts' which probably originated in an intracratonic rift or possibly continental margin setting.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: Marine sediments and associated minor bimodal (?) volcanics (often felsic, possibly alkalic) reflect active extensional tectonics. Host successions include inferred evaporites and are generally interpreted as shallow marine. Underlying gneissic successions suggest some deposits formed on or along margins of tectonic highs. However, intense deformation and metamorphism have commonly masked relationships.

AGE OF MINERALIZATION: Commonly Lower and Middle Proterozoic; some British Columbia deposits may be hosted by Late Proterozoic to Cambrian rocks.

HOST/ASSOCIATED ROCK TYPES: Hosted by thin-bedded calcareous schists, impure marble, quartzites and, less commonly, graphitic schists. A common and important host rock is garnet quartzite which occurs as envelopes to the sulphide bodies; associated with well layered and heterogenous successions of quartzite, crystalline marble, quartzo-feldspathic gneiss, hornblende gneiss, and abundant pelitic and calcareous schist and gneiss; locally associated carbonatite and amphibolite. Banded iron formations, chert, gahnite quartzites and tourmalinites are common in the host stratigraphic succession as distal facies or in the footwall successions. Scapolite-rich units and sulphur isotopes suggest associated evaporites. Metamorphic grades vary from amphibolite to granulite.

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BROKEN HILL-TYPE Pb-Zn-Ag±Cu S01

DEPOSIT FORM: Stacked sulphide or sulphide/magnetite lenses are common; they are thin, irregular, discontinuous, strongly deformed massive sulphide bodies. Thickening in fold hinges is often critical to make economic thicknesses. Individual lenses vary from less than a metre to tens of metres and may extend hundreds of metres often grading laterally into quartzite, quartz gahnite, garnet quartzite or pyrite/pyrrhotite disseminated units that may persist for tens of kilometres.

TEXTURE/STRUCTURE: Mineralization occurs as discontinuous massive to semimassive sulphide lenses or as disseminated stratabound sulphides. Sulphides are massive to irregular banded, with locally coarse "skarn" textures; locally well layered or laminated sulphides and silicates occur. They are commonly medium to coarse grained and intimately intergrown with gangue calcsilicate minerals, quartz or magnetite; as well, there are occasional thin monomineralic sulphide layers. Disseminated sulphides are common in granular marble. Pegmatitic zones are present in some ore zones.

ORE MINERALOGY (Principal and *subordinate*): Galena, sphalerite, magnetite, pyrrhotite, pyrite; *chalcopyrite, tetrahedrite, molybdenite, arsenopyrite, löllingite*. In some deposits magnetite makes up more than 40% of the ore. Some deposits display zoning from siliceous Zn-rich to distal carbonate-silicate Pb-Ag rich ore.

GANGUE MINERALOGY (Principal and *subordinate*): Quartz, garnet, calcite, rhodonite, magnetite, siderite, pyroxenes and amphiboles, commonly manganiferous, fluorite; *Mn olivine, apatite, gahnite, plagioclase, biotite, chlorite, ankerite, epidote, graphite, barite, hematite, wollastonite, sillimanite, staurolite, vesuvianite*. The complex gangue mineralogy is a characteristic of Broken Hill-type deposits.

ALTERATION MINERALOGY: Original alteration assemblages are replaced by a complex variety of metamorphic minerals. Alteration envelopes and deposit zoning are common in larger deposits, but are generally not recognized in smaller ones. Footwall alteration pipes are generally not recognized, except for some of the Cu-rich deposits, which complicates their interpretation**.** Typically the alteration reflects enrichment of Fe, Si, Mn, Ca, P, F, K and CO_3 and includes metamorphic silicates including amphiboles, olivine, biotite, phlogopite, sillimanite, orthoclase and clinozoisite as well as carbonates, fluorite and a variety of other minerals. Spessartine-quartz halos surround many deposits, with more regional silicification (quartz) and K (sillimanite) enrichment. In the Broken Hill area, Australia, with increasing intensity of mineralization, Fe-Si-Mn systems (typical of metamorphosed iron formations) are overprinted by extreme Ca-Mn-F enrichment with calcsilicate assemblages.

WEATHERING: Large gossans are not common; however, pyrrhotite and pyrite in some deposits locally produce rusted outcrops. Some Australian deposits have deep weathered zones: gossanous quartz-garnet-gahnite rocks, with abundant Mn and Fe oxides at surface, and secondary Ag enrichment at depths associated with oxides (goethite and coronadite) and carbonates (dolomite, cerussite and smithsonite). Leached sulphides mark the transition into underlying sulphide ore.

ORE CONTROLS: Not well understood; deposits appear to be restricted to Proterozoic "mobile belts", generally interpreted to be intracratonic rifts. Oxidized shallow-marine basins, possibly developed due to extensional faulting above basement highs, and associated bimodal (?) volcanism are local controls.

GENETIC MODEL: Difficult to interpret due to high metamorphic grades. A sedimentary exhalite origin, with sulphide deposition in rapidly deepening rifts, is preferred because the deposits are associated with iron formations, chert and Mn-rich iron oxide facies. This environment, dominated by oxidized facies, contrasts with reduced, anoxic basins that commonly host sedex deposits. However, associated bimodal volcanics, ore and gangue chemistry and sulphide textures suggest similarities with volcanogenic massive sulphide deposition. Some workers have supported replacement models for the mineralization.

ASSOCIATED DEPOSIT TYPES: Sedimentary exhalative Pb-Zn deposits (E14), carbonatites (N01), nepheline syenites, polymetallic veins (I05) and W-Mo veins.

BROKEN HILL-TYPE Pb-Zn-Ag±Cu S01

COMMENTS: Broken Hill-type deposits are a difficult exploration target due to their setting in strongly metamorphosed and deformed rocks.

EXPLORATION GUIDES

GEOCHEMICAL SIGNATURE: Anomalous enrichments of Mn, Cu, Au, Bi, Sb, W, Co and As in the ore and some proximal exhalative units; high Ag:Pb ratios, Mn and K enrichment (with muscovite, K-feldspars and sillimanite) in alteration halos; elevated base metal values (particularly Zn) and Mn in more regional iron formations. In silt samples expect anomalous Pb, Zn, Ag, Mn and Ba.

GEOPHYSICAL SIGNATURE: Deposits with associated magnetite produce strong magnetic anomalies. Electromagnetic and induced polarization surveys may detect those deposits with pyrrhotite and pyrite massive sulphides lenses. Associated graphite in some (*e.g.*, Big Ledge) may provide local targets.

OTHER EXPLORATION GUIDES: Main exploration guide is appropriate sedimentary/tectonic environment - thin-bedded succession of paragneisses with abundant carbonate. The mineralization may occur at, or near, the transition from quartzo-feldspathic basement rocks to fine-grained clastic metasediments. Rapid lithologic facies changes in the vicinity of deposits may indicate local hydrothermal systems. Associated volcanism is indicative of extension or rifting. In closer proximity to deposits, unusual mineral assemblages include garnet quartzites, gahnite quartzites and Mn-rich calcsilicates with skarn textures.

ECONOMIC FACTORS

TYPICAL GRADE AND TONNAGE: Deposits frequently occur in clusters with numerous small, uneconomic deposits. Broken Hill-type targets average less than 5 to 20 Mt, but may be in excess of 100 Mt (Broken Hill, Australia: 280 Mt containing 10.0% Pb, 8.5% Zn and 148 g/t Ag, including approximately 150 Mt of more that 20% Pb+Zn). Grades are variable, commonly with 2 to 10 % Pb, 2 to 8% Zn and 10 to 150 g/t Ag. Some deposits contain no byproduct copper, others have 0.1 to 1% Cu. In British Columbia, known deposits range in size from less than one million to 6.5 Mt; geological reserves may be considerably larger. Grades range from approximately 2 to 5 % Zn and 2.5 to 6.5 % Pb with up to 50 g/t Ag. Ruddock Creek contains 5 Mt with 7.5% Zn, 2.5% Pb and Jordan River, 2.6 Mt with 5.6% Zn, 5.1% Pb and 35 g/t Ag.

ECONOMIC LIMITATIONS: Structural thickening is often critical to the genesis of economic deposits. Broken Hill-type deposits have not been mined in British Columbia, due mainly to their form - thin, though laterally persistent layers - and their location in remote, mountainous terrains.

IMPORTANCE: These deposit are an important source for lead, zinc and silver, and remain an attractive exploration target in British Columbia.

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