20. SKARN DEPOSITS

INTRODUCTION

Skarn deposits are abundant, variable, and economically important. They are a principal global source of tungsten, a major source of copper, and an important source of iron, molybdenum, zinc, and gold.

Skarn is an assemblage of dominantly calcium and magnesium silicates typically formed in carbonate-bearing rocks as a result of regional and thermal metamorphism, and by metasomatic replacement. Regional and stratiform metamorphic skarn deposits include, for example, skarn iron deposits that were derived from iron-rich sedimentary and volcanic rocks by recrystallization, isochemical metamorphism, and bimetasomatism. Recrystallization, in particular, results in upgrading the quality of ore for concentration, beneficiation, and metallurgical recovery by increasing grain size of the ore minerals. The term "skarn" was first applied to the calc-silicate gangue associated with some Swedish iron ores of this type (Geijer and Magnusson, 1952). It is not normally used for skarn-type mineral assemblages produced by regional metamorphism of pre-existing deposits, for example highly metamorphosed lithofacies of iron-formation (Gross, 1968; "Skarn iron", subtype 20.4).

Thermal metamorphism of calcareous rocks by adjacent plutons causes a bimetasomatic exchange of ions between dissimilar lithologies, e.g., limestone and pelite, in addition to recrystallization of limestone. The resultant calc-silicate hornfels and marble is subsequently converted to anhydrous prograde skarn under the metasomatic influence of hot hydrothermal fluids emanating from the adjacent crystallizing pluton. Most economic concentrations of ore minerals occur during the cooling of the hydrothermal system, coincident with the onset of retrograde alteration. In rare instances, existing mineral deposits are converted to skarn deposits by metamorphism, as proposed by Sangster et al. (1990) for Meat Cove and Lime Hill, Nova Scotia; Johnson et al. (1990) for Franklin Furnace, New Jersey; Gemmell et al. (1992) for Aguilar, Argentina; and Hodgson (1975) for Broken Hill, Australia.

Most skarn deposits consist of metallic ore minerals and skarn silicates as gangue, and form as a result of magmatic hydrothermal processes, as inferred from their ubiquitous association with intrusive rocks. The skarn itself may be classified according to its calcic or magnesian mineral assemblage, derived from its limestone or dolostone host rock, respectively. Skarn deposits, i.e. skarns which contain economic concentrations of minerals, on the other hand, are most usefully classified according to the dominant contained economic metal. On this basis, the skarn subtypes zinc-lead-silver, copper, gold, iron, and tungsten can be distinguished and are described separately in the following accounts.

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20.1 SKARN ZINC-LEAD-SILVER

K.M. Dawson

IDENTIFICATION

Zinc-lead-silver skarn deposits are distinguished from other skarn deposits by their distinctive Mn- and Fe-rich mineralogy and their common occurrence along structural pathways and lithological contacts at some distance from intrusive contacts. Plutons may occur at distances of several kilometres from the deposit, or may not be exposed. The metamorphic aureole centred on the skarn is less extensively developed than in W and Cu skarn deposits. Related intrusions are variable in size, composition, and depth of emplacement. Johannsenitic (i.e., Mn- and Fe-rich) pyroxene is more abundant than andraditic garnet in prograde skarn, and manganiferous actinolite, epidote, ilvaite, and chlorite are common minerals in retrograde skarn.

Dawson, K.M.
1996: Skarn zinc-lead-silver; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 448-459 (also Geological Society of America, The Geology of North America, v. P-1).

A continuum is recognized that extends from endoskarn and reaction skarn at or near the intrusive contact, through exoskarn to more stratigraphically or structurally controlled manto and chimney deposits with progressively higher sulphide and lower calc-silicate gangue contents with increasing distance from the intrusion, passing ultimately to carbonate-hosted veins with manganese-rich silicate and carbonate gangue. Meinert (1992), in acknowledging some problems in Zn skarn classification, noted that most large skarn deposits contain both skarn-rich and skarn-poor ore in a variety of geometric settings, including mantos and chimneys. In this context, deposits identified in the literature as "replacements" with little or no calc-silicate gangue, e.g., Bluebell, British Columbia; Gilman, Colorado; and Tintic, Utah are recognized as genetically related to skarn Zn-Pb deposits and intrusions, even if neither are exposed.

Significant Canadian Zn-Pb skarns and mantos (Fig. 20.1-1) include the previously producing deposits Sa Dena Hes at Mount Hundere, Yukon Territory and Bluebell, Mineral King, and Jersey in southeastern British Columbia, and the developed manto deposits at Quartz Lake, Yukon Territory; Midway, British Columbia; and Prairie Creek, Northwest Territories. Small deposits occur adjacent to the Cassiar, Seagull, and Mount Billings batholiths and Flat River stock in the northern Canadian Cordillera, and on Vancouver Island, British Columbia.

Some large foreign Zn-Pb skarn deposits include Santa Eulalia, Naica, San Martin, and Velardeña, Mexico; the Central Mining district, New Mexico; the Central Colorado Mineral Belt, Colorado; Stantrg, Yugoslavia; El Mochito, Honduras; Nikolaevskoe, Primor'ye, Russia; Kamioka and Nakatatsu, Japan; Yeonhua, Korea; and Shuikoushan, China.

IMPORTANCE

Significant production of Ag, Pb, and Zn has been obtained from several skarn and replacement deposits in southeastern British Columbia. Production has taken place from only one of numerous base metal skarns in the northern Canadian Cordillera, but significant reserves have been developed in several others (Table 20.1-1). Skarn deposits of Zn, Pb, and Ag are common throughout the world, but statistics on production from skarn deposits relative to other base metal deposit types are not readily available. The more silver-rich deposits are important sources of the world's silver, with the bulk of such ore coming from replacement deposits in limestone peripheral to areas of skarn formation.

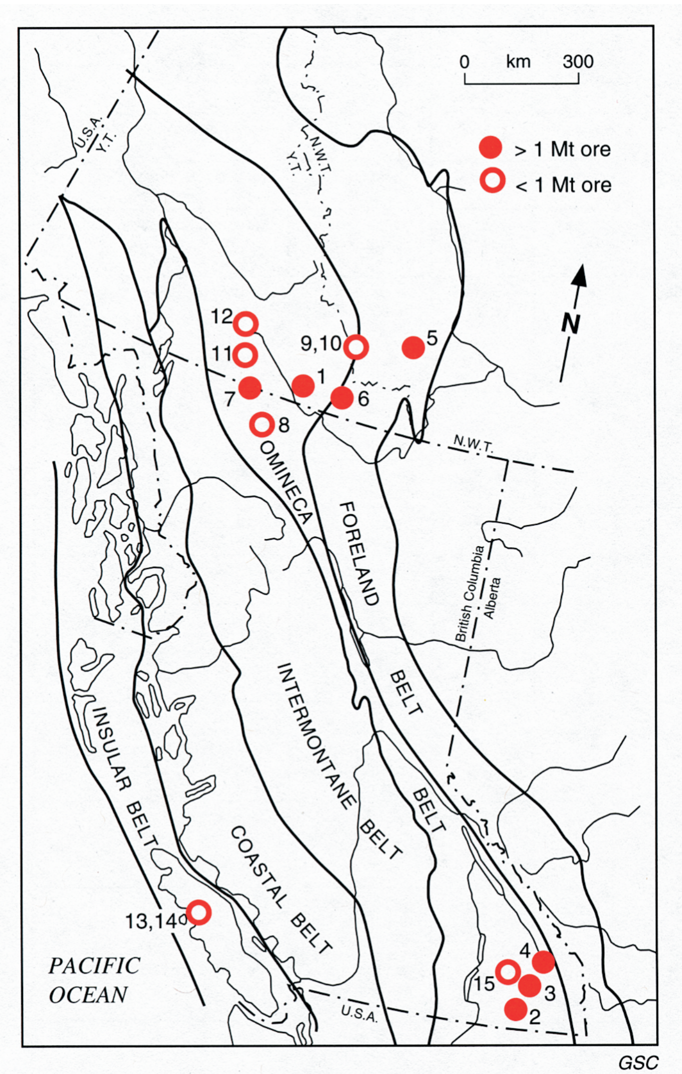


Figure 20.1-1. Significant Zn-Pb-Ag skarn and replacement deposits of the Canadian Cordillera. Numbered symbols correspond to deposits listed in Table 20.1-1.

SIZE OF DEPOSIT

On a global basis, most large skarn deposits mined underground for predominantly Zn and Pb contain 1 to 10 Mt of Zn+Pb metal in orebodies that range from 3 to 90 Mt at relatively high average grades of 10 to 15% Zn+Pb, with Zn usually dominant (Table 20.1-1, Fig. 20.1-2). The large Ag-rich skarn deposits of northern Mexico constitute a subgroup of deposits with greater than 10 Mt contained Zn+Pb metal. Most base metal skarns contain 30 to 300 g/t Ag, but Ag-rich deposits, whose average grade commonly exceeds 500 g/t Ag, are often mined for their Ag content alone. Copper may be recovered from base metal skarns, at grades averaging 0.2 to 2% Cu. Tungsten, gold, cadmium, and tin are present in small amounts in several Cordilleran deposits.

Skarn deposits and orebodies in British Columbia and Yukon Territory range from less than 1 t to about 8 Mt of ore. Tonnage and grade figures are not available for the numerous skarn occurrences in the northern Cordillera, but these occurrences are generally small. Size, grade, and other characteristics of Zn-Pb-Ag skarns worldwide have been tabulated by Einaudi et al. (1981).

GEOLOGICAL FEATURES

Geological setting

Base metal skarns in the North American Cordillera are hosted by the same Upper Proterozoic to mid-Paleozoic shelf sedimentary rocks that host W skarns, except on Vancouver Island where host rocks are Paleozoic and lower Mesozoic oceanic arc-type volcanic-carbonate sequences. Mexican and Central American deposits are hosted by a Jura-Cretaceous transgressive carbonate-clastic overlap assemblage. Asian, Australian, South American, European, and Russian deposits are hosted by dominantly Paleozoic limestones developed on continental margins. Host sedimentary strata in the North American Cordillera are underlain by basement lithologies dominated by thick, craton-derived clastic assemblages which, in the southern Cordillera, overlie crystalline Precambrian rocks. Associated granitoid rocks commonly are late orogenic to postorogenic, but may be synorogenic.

In the northern Canadian Cordillera, Zn-rich skarn deposits occur in belts in cratonal host rocks adjacent to the Mount Billings batholith in southeastern Yukon Territory and the Flat River and smaller stocks in southwestern Northwest Territories. A second belt of Ag-Pb-Zn manto and skarn deposits, e.g., Midway and Ketza River, occurs 100 km to the west within equivalents of North American shelf sedimentary rocks in the displaced Cassiar cratonal terrane, adjacent to the Cassiar and Seagull batholiths and small satellitic intrusions. In the southeastern Canadian Cordillera, skarn, replacement, and vein deposits of the Salmo, Riondel-Ainsworth and Slocan districts are adjacent to the synorogenic Nelson batholith and younger intrusions, but are hosted by carbonate strata of both Kootenay and Quesnellia terranes. The Mineral King deposit was formed along the margin of the North American craton, in dolostone of the Mount Nelson Formation in the

Contents

upper part of the Purcell Assemblage, and no associated intrusion is exposed (Fyles, 1960). In contrast to late orogenic to postorogenic deposits of the northern Cordillera, these deposits are more deformed and metamorphosed (Dawson et al., 1991).

Age of host rocks, associated rocks, and mineralization

Host rocks for Zn-Pb-Ag skarns are the metamorphosed equivalents of limestone and calcareous to carbonaceous pelites: skarn, calc-silicate hornfels, schist, and marble. On

Table 20.1-1. Significant Canadian and foreign Pb-Zn-Ag skarns and mantos.

No.	Deposit/ District/ Location	Type	Size (Mt)	Zn (%)	Pb (%)	Cu (%)	Ag (g/t)	Au (g/t)	Other	Skarn minerals	References
Canadian deposits											
1	Sa Dena Hes; Mount Hundere, Y.T.	skarn, manto	4.9 (R)	12.7	4	n.d.	60	n.d.	tet	gross, diop, act, qtz, fluor	Indian and Northern Affairs Canada, 1992
2	Jersey, Emerald; Salmo, B.C.	skarn, manto	7.7 (P)	3.5	1.65	n.d.	3.1	n.d.	W 0.23%, As	px, gar, dol, cal, trem, qtz, chl, wol, oliv, serp, musc	Höy, 1982; Whishaw, 1954
3	Bluebell; Riondel, B.C.	manto	4.8 (P)	6.3	5.2	minor	45	n.d.		sid, ank, minn, dic, cal, qtz, kneb	Ohmoto and Rye, 1970; Höy, 1980
4	Mineral King; B.C.	manto	2.1 (P)	4.12	1.76	n.d.	25	n.d.		dol, qtz, bar	Fyles, 1960
5	Prairie Creek, N.W.T.	manto	3.75 (R)	14.7	13	0.5	202	n.d.	Hg, W	si, cal	Northern Miner, 28/02/1994
6	Quartz Lake, Y.T.	manto	1.5 (R)	6.6	5.5	minor	102	n.d.	As, Sb	qtz, dol, sid, ank	Vaillancourt, 1982
7	Midway; B.C.	manto	1.2 (R)	9.6	7	minor	410	minor	Sn 0.1%, Sb,As,Bi	qtz, ser, cal, sid, rut, trem, ep	Bradford and Godwin, 1988
8	Magno, D; Cassiar district, B.C.	skarn, manto	0.5 (R)	4.4	5.3	minor	168	1.4	Sn to 1.5%	px, gar, act, rhodoc, chl	C. Bloomer, unpub. data, 1981
9	Lucky Lake, N.W.T.	skarn	0.36 (est.)	6.2	2.5	minor	14	n.d.	W	diop, gar, act	Aho, 1969
10	Roy, N.W.T.	manto	0.15 (R)	3.1	5.2	0.1	147	1.4	Sn 0.13% As, B	qtz, cal	V. Kukor, unpub. data, 1982
11	Silver Hart, Y.T.	skarn	0.1 (R)	3.8	1.4	minor	958	n.d.	Sb, As, W	gar, diop, ves, qtz, cal	E. Buhlmann, pers. comm., 1988; Abbott, 1983
12	Tintina Silver, Y.T.	skarn	0.1 (R)	10	6	minor	690	n.d.	Sb, As, W	diop, gar, qtz, ilv, trem	Northern Miner, 31/01/1980; Morin et al., 1977
13	Zip, B.C.	skarn	0.08 (est.)	12.5	3.7	1.7	64	n.d.		ep, px, gar, chl	Gunning, 1932
14	Caledonia, B.C.	skarn	0.07 (P)	7.45	0.6	6.04	704	0.01		ep, gar, act, ser	GCNL 221, 1981; Webster et al., 1992
15	Piedmont, B.C.	skarn, manto	0.005 (P)	13	4.7	0.1	124	tr	As, Bi, Cd, Sb	gar, px, cp, biot	Webster et al., 1992
Foreign deposits											
16	Santa Eulalia, Mexico	skarn, manto, chimney	50 (P+R)	3	2	0.1	125	tr	Sn, V, Hg, Sb, As, W	gar, joh-hed, ep, chl, qtz, fluor, mgt	Hewitt, 1968; Megaw et al., 1988
17	Providencia-Concepcion del Oro, Mexico	skarn, chimney, manto	25 (P+R)	0.6	1	2	30	0.6	Sb, As, Hg	gar, trem, wol, mgt, scap, diop	Buseck, 1966
18	Naica, Mexico	skarn, chimney	21 (P+R)	3.8	4.5	0.4	150	0.3	Mo, Hg, W to 0.12%	gar, wol, ves, diop, trem	Erwood et al., 1979; Ruiz et al., 1986
19	San Martin, Mexico	skarn, chimney	21 (P+R)	5.3	0.6	1.24	146	0.7	As, Mo	gar, hed, trem, act, wol, ves, ep, chl	Megaw et al., 1988; White, 1980
20	Charcas, Mexico	skarn	15 (P+R)	8	2.5	0.5	140	n.d.	Sb, As, Hg, Sn	gross, hed, wol, ep, diop, trem, ilv, qtz, dat, dan, axin, tourm	Megaw et al., 1988

a global basis, Upper Proterozoic to Cretaceous host rocks are intruded by Paleozoic to mid-Tertiary granitoid batholiths, stocks, and dykes. Most skarn deposits in the Canadian and American Cordillera have developed preferentially in limestone beds of Upper Proterozoic to Upper Paleozoic cratonal or pericratonic sedimentary sequences. Skarns on Vancouver Island occur in Upper Triassic, volcanic arc-related limestone of accreted Wrangellia. Zinc-lead skarns of the Central Mining district, New Mexico are hosted by Carboniferous shelf limestone (Meinert, 1987). Skarn deposits of northern Mexico developed in Lower Cretaceous limestones within a Jura-Cretaceous transgressive carbonate-clastic assemblage that overlaps Paleozoic cratonal sedimentary terranes (Campa and Coney, 1983). Zinc-lead-silver skarns in the northern Canadian Cordillera, like W skarns, have formed preferentially in

No.	Deposit/ District/ Location	Type	Size (Mt)	Zn (%)	Pb (%)	Cu (%)	Ag (g/t)	Au (g/t)	Other	Skarn minerals	References
21	Velardeña, Mexico	skarn, manto, chimney	15 (P+R)	5	4	2.5	175	0.5	As to 12%	grand, ves, wol, ep, diop-hed, spec	Gilmer et al., 1986; Megaw et al., 1988
22	Catorce, Mexico	skarn, chimney	10 (P+R)	6	10	minor	80	minor	Sb, As, Bi, Hg	gar, px, ep	Megaw et al., 1988
23	Zimapan district; La Negra, El Monte, Mexico	skarn	10 (P+R)	2.5	1.2	0.65	150	n.d.	W, Te, B, As, Sb	hed, and-gross, wol, bors	Dawson, 1985; Megaw et al., 1988
24	Central Mineral district; N. Mexico: Groundhog, Hanover, etc.	skarn	18 (P+R)	14	2	1	96	n.d.		joh-hed, and, bust, ilv, cum, amph, chl	Meinert, 1987
25	Gilman, Colorado	manto, chimney	11.7 (P)	8.5	1.5	0.9	228	1.7	Mo, As, Sb, Ba, F	mn-ank, sid, rhodoc, si, dol	Beaty et al., 1990
26	Leadville, Colorado	manto, skarn	23.8 (P)	3	4.2	0.2	320	3.7	Sb, Bi, W, Cd, Te	jasp, dol, sid, qtz, musc, bar, fluor	Beaty et al., 1990; Thompson and Arehart, 1990
27	Lark, Bingham Canyon, Utah	manto, skarn	39.2 (P)	1.9	4.7	0.93	106.2	1.85		wol, diop, qtz, cal	Atkinson and Einaudi, 1978
28	Tintic district, Utah	manto, chimney	17.2 (P)	1.2	5.9	0.9	485	4.86		si, mn-carb, ser, py, bar, dol	Morris, 1968
29	Park City, Utah	manto	13.1 (P)	4.5	8.7	0.38	556.3	2.3		qtz, rhodoc, hmt, cal, mn-cal, rhodon	Barnes and Simos, 1968
30	Mozumi, Maruyama, Tochibora: Kamioka district, Japan	skarn	90 (P+R)	5	0.7	n.d.	30	n.d.	Sn, Mo, W	hed, ep, gar, chl, ser, hmt, cal, qtz	Sakurai and Shimazaki, 1993
31	Nakayama, Hitokata, etc.; Nakatatsu district, Japan	skarn	16.2 (P)	5.5	0.4	0.1	31	n.d.	Sn, Bi, Te	hed-joh, and, wol, bust, qtz, rhodoc, act, chl, rhodon	Kano and Shimizu, 1992
32	El Mochito, Honduras	skarn, chimney	7.1 (P)	8	4.2	minor	128	n.d.		and, hed, bust, amph, ilv, chl, fluor	Shultz and Hamann, 1977
33	Stantrg, Yugoslavia	skarn	12.5 (P)	3.8	8.6	0.2	140	n.d.		hed, and, ilv, amph	Forgan, 1950
34	Yeonhua I & II, S. Korea	skarn	9.6 (P)	6.6	3	minor	minor	n.d.		hed, and, bust, rhodon, chl	Yun, 1979
35	Nikolaevskoe; Primor'ye, Russia	skarn	40 (P+R)	n.d.	n.d.	0.2-0.5%	30-50	n.d.	Sn, Bi, In	gar, hed, wol, axin, dat, fluor, act, ep	V.V. Ratkin, pers. comm., 1994
36	Shuikoushan, China	skarn	1.5 (P)	20	17	n.d.	224	n.d.		gar, px, ep, chl, zeol	Hsieh, 1950
37	Tienpaoshan, China	skarn	3 (P)	6	5	1.8	minor	n.d.		px, ep, fluor	Hsieh, 1950

Abbreviations:
Minerals: act = actinolite, amph = amphibole, and = andradite, ank = ankerite, axin = axinite, bar = barite, biot = biotite, bors = borospurrite, bust = bustamite, cal = calcite, carb = carbonate, chl = chlorite, cp = chalcopyrite, cum = cummingtonite, dan = danburite, dat = datolite, dic = dickite, diop = diopside, dol = dolomite, ep = epidote, fluor = fluorite, gar = garnet, grand = grossular-andradite, gross = grossularite, hed = hedenbergite, hmt = hematite, ilv = ilvaite, jasp =jasperoid, joh = johannssenite, kneb = knebelite, minn = minnesotaite, mgt = magnetite, mn = manganiferous, musc = muscovite, oliv = olivine, px = pyroxene, py = pyrite, qtz = quartz, rhodoc = rhodocrosite, rhodon = rhodonite, rut = rutile, scap = scapolite, ser = sericite, serp = serpentine, si = silica, sid = siderite, spec = specularite, tet = tetrahedrite, tourm = tourmaline, trem = tremolite, ves = vesuvianite, wol = wollastonite, zeol = zeolite.
Others: P = production, R = reserves, est. = estimate, n.d. = no data, GCNL = George Cross Newsletter Vancouver

Lower Cambrian shelf limestone, but have also developed in a broader age range of host rocks than W skarns, and, in addition, occur in some cases in regionally metamorphosed host rocks (Dawson and Dick, 1978).

Intrusive rocks associated with Zn-Pb-Ag skarns commonly are calc-alkaline felsic to intermediate batholiths, stocks, dykes, and sills, but also span a wide range of compositions from high-silica leucogranite and topaz granite, and also syenite plutons, through dioritic dykes. Small quartz monzonite stocks are most common. Intrusions show a broader compositional and morphological range and depth of emplacement than those associated with W and Cu skarns, from deep-seated batholiths to shallow dyke-sill intrusive complexes. In the Canadian Cordillera, both 'S-type' and 'I-type' granitoids of Chappell and White (1974) are associated with base metal skarns. Topaz-bearing peraluminous granite stocks and dykes are associated with some Zn-rich skarns in the northern Canadian Cordillera and Mexico. Stocks and dykes have in some cases been altered adjacent to mineralized exoskarn and endoskarn to assemblages containing sericite, epidote, clay, quartz, and fluorite. In almost all cases, zinc skarns occur distal to their associated igneous rocks.

Ore deposition was penecontemporaneous with associated intrusive rocks: mid-Cretaceous to Eocene in the North American Cordillera, except Jurassic in southern British Columbia and Eocene to Oligocene in northeastern Mexico; Mesozoic in eastern Asia; Permo-Triassic in Australia and Russia; and Tertiary in Europe.

Form of deposit and associated structures, zoning, and distribution of ore minerals

Zinc-lead-silver skarns are similar to the W skarns in that they commonly form in the thermal metamorphic aureole at the contact between granitoid intrusions and calcareous sedimentary rocks, but the contact metamorphic aureole is less extensive than that associated with deeper seated W skarns. Zinc-rich exoskarns have in many cases developed

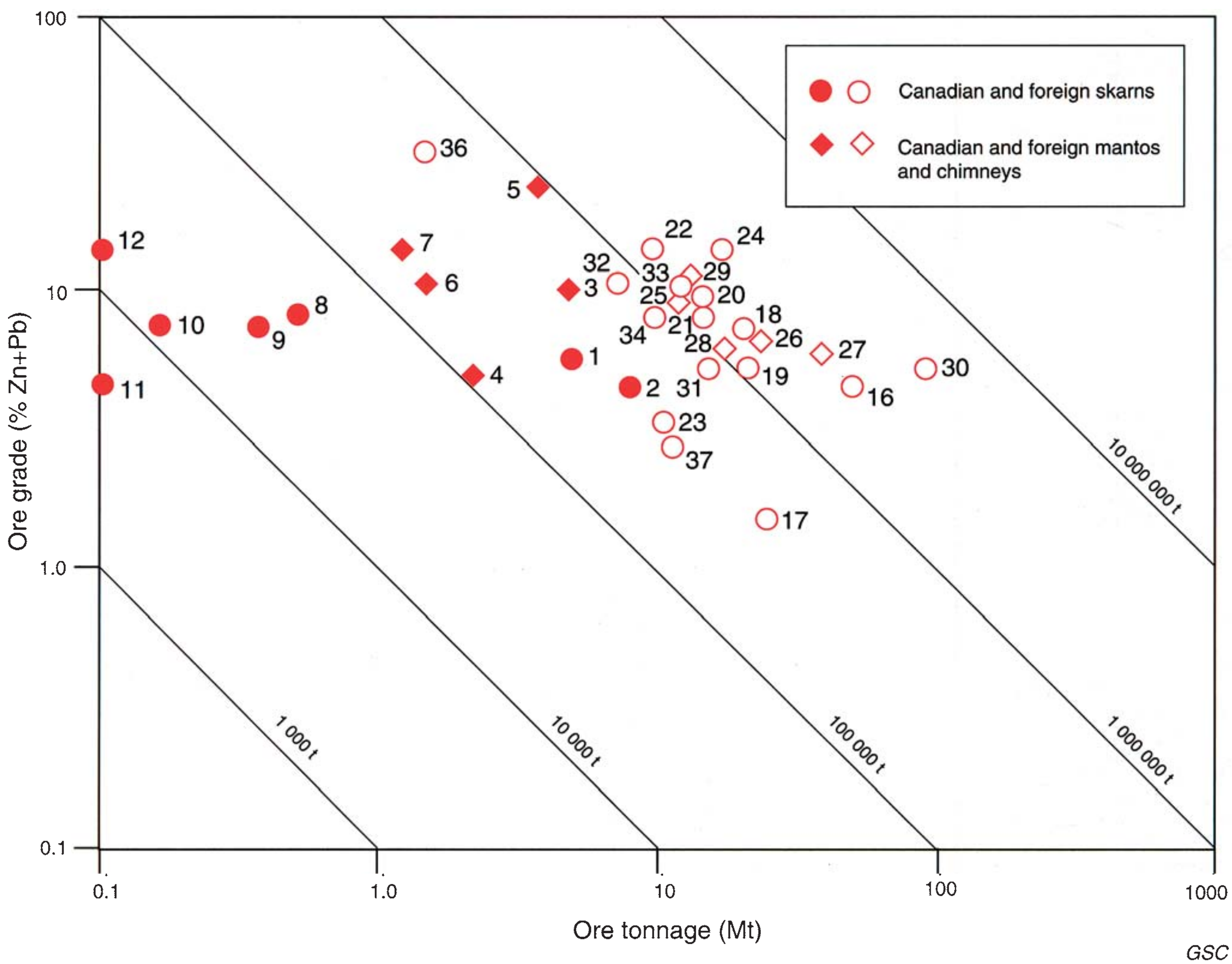


Figure 20.1-2. Tonnage versus grade of significant Canadian and foreign Zn-Pb-Ag skarn and replacement deposits. Numbered symbols correspond to deposits listed in Table 20.1-1.

along lithological contacts and structural pathways in unmetamorphosed rocks distant from the intrusive contact, and in places, e.g., Santa Eulalia (Hewitt, 1968), pass distally into essentially concordant mantos and discordant chimneys significantly higher in ore tonnage and grade than the skarn. The distinctive morphology, abrupt changes in ore grade and mineralogy, and paucity of calc-silicate gangue that characterize these distal members of the Zn-Pb skarn system have contributed to their classification as a distinct deposit type, i.e. "high temperature carbonate-hosted massive sulfide ores" of Titley (1993), "high-temperature carbonate-hosted Ag-Pb-Zn(Cu) deposits" of Megaw et al. (1988), and "carbonate-hosted sulfide deposits" of Beaty et al. (1990). Zinc-lead skarn deposits form a structurally zoned continuum that includes a) relatively small contact skarns adjacent to batholiths; b) endoskarns and extensive structurally and stratigraphically controlled exoskarns within, adjacent to, and at some distance from, stock contacts; c) skarn and replacement bodies following dykes and branching out along bedding and faults; d) 'rootless' exoskarn and replacement bodies in structural and stratigraphic traps distant from a probable or unknown igneous source; and e) most distal of all, carbonate-hosted vein deposits with calc-silicate and (or) manganese-silicate gangue (Einaudi et al., 1981).

Zinc-lead-silver skarns characteristically contain johannsenitic (manganiferous) pyroxene and subordinate amounts of andraditic garnet as prograde skarn minerals. Vesuvianite, bustamite, and wollastonite are present in some deposits. Iron-rich sphalerite predominates over galena in the ratio of about 3:2. Pyrrhotite or pyrite are common; magnetite, chalcopyrite, and arsenopyrite are less common. Retrograde minerals are Mn-rich actinolite, epidote, chlorite, ilvaite, calcite, and siderite; also rhodonite, fluorite, and quartz. The prograde mineral assemblage in Zn-rich skarns in Yukon Territory is distinctive in its abundant epidote, rare andradite, and common intergrowth of the two pyroxenes, Mn-hedenbergite and diopside (Dick, 1979).

Contact skarns and exoskarns close to the intrusive contact commonly are high in Fe, Cu, and W, and rarely, in Au. Zinc tends to occur inwards of Pb at intermediate distances from the intrusion. Skarns and replacements distant from the intrusive contact are rich in Mn, Ag, and Pb and, less commonly, in Sb and As. Zonal metal distribution patterns in some deposits have been modified and overprinted by retrograde mineral assemblages. In the large Zn-Pb-Ag(Cu, W, Au) skarn deposit at Naica, Chihuahua, Mexico, gold is concentrated with tungsten and copper in prograde skarn close to rhyolite dyke contacts (Clark et al., 1986). In the Midway and YP Ag-Pb-Zn (Au, Cu, Sn) manto deposits near the Yukon Territory-British Columbia border, Au is concentrated commonly with massive sulphide ores rich in Fe, Cu, and Zn, rather than with more distal Pb- and Ag-rich zones (K.M. Dawson, unpub. data, 1994). A similar trend is manifested as district-wide zonation at Ketza River, Yukon Territory where gold-rich pyrrhotite-chalcopyrite manto orebodies apparently grade outward over 1 to 3 km to Ag-Pb-Zn replacement deposits (Cathro, 1990). Both proximal Au-rich and distal Ag-rich zones probably are underlain by the same unexposed Cretaceous stock (Abbott, 1986).

The largest production from a Canadian Zn-Pb-Ag skarn deposit was attained from the Bluebell mine at Riondel, British Columbia between 1895 and 1971 (Fig. 20.1-1). A geological sketch map of the district is given in Figure 20.1-3, and a schematic block diagram of the orebodies in Figure 20.1-4. These enigmatic deposits have been described as 'vein replacements' by several authors, including Ohmoto and Rye (1970), Ransom (1977), Höy (1980), and Sangster (1986), and previously as 'syngenetic'

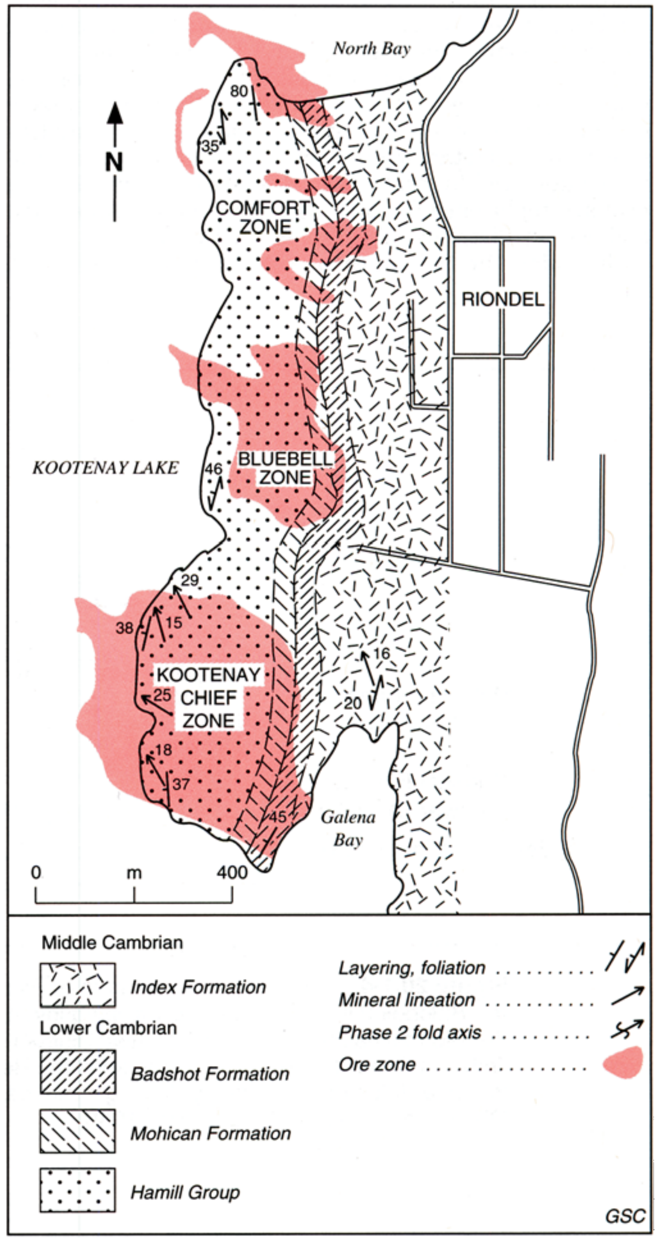


Figure 20.1-3. Sketch map of Riondel Peninsula showing distribution of formations and Bluebell mine orebodies, projected to surface (after Höy, 1980). Similar Zn-Pb-Ag replacement deposits of the Ainsworth district lie 4 km to the west, adjacent to the contact of the mid-Jurassic Nelson batholith.

by Sangster (1970). Features supporting relatively early mineralization include: essentially stratiform morphology and finely laminated texture of orebodies, consistent metal zoning with Pb stratigraphically higher than Zn, and apparent coincidence of some mineralization with predeformational brecciation and dolomitization. Features that argue more strongly for epigenesis include: alignment of ore shoots with steeply-dipping, crosscutting faults; lateral replacement of marble adjacent to these steep structures, including marble of the structurally overlying Mohican Formation; a distinctive skarn mineral assemblage that includes prograde knebelite (Fe, Mn-olivine) and retrograde minnesotaite (Fe-talc), Fe-, Mg-, and Mn-carbonates, chlorite, calcite, and quartz; fluid inclusion and stable isotopic data supporting a relatively high temperature, deeply seated origin (Ohmoto and Rye, 1970); and coarsely crystalline sulphide and gangue minerals in cavities formed after metamorphism and deformation. Lead isotopic data cited by Andrew et al. (1984) support either a primary replacement origin, as in the similar Ainsworth and Slocan districts, or a remobilized stratiform origin, both under the influence of the Nelson batholith. A younger, Eocene age of epigenetic mineralization (59 ± 3 Ma) is indicated by K-Ar data from vein muscovite cutting a gabbro dyke (Beaudoin et al., 1992).

Significant production was also obtained from two probable skarn orebodies, the Jersey and Emerald Zn-Pb mines in the Salmo district of southeastern British Columbia. These deposits are hosted by carbonate units of the lower Cambrian Laib Formation of the Kootenay Arc, and the Jersey has been grouped with the H.B., Remac, and Duncan Lake deposits as "concordant" (Fyles, 1966), "Remac type" (Sangster, 1970), and "sedimentary exhalative" (Sangster, 1986). The Jersey is adjacent to the Emerald, Feeney, and Dodger W skarn orebodies, within the same anticlinal structure and underlain by the same granitoid stock and related calc-silicate skarn horizon that hosts the W skarns. The geology of the Emerald Tungsten camp is given in Figure 20.1-5. The relationship of the Jersey to the Dodger in section, is shown in Figure 20.1-6. Both the ore mineral assemblage, which includes sphalerite with 6% Fe, pyrrhotite, arsenopyrite, and scheelite in addition to galena and pyrite, and the gangue assemblage of dolomite, calcite, quartz, muscovite, chlorite, tremolite, wollastonite, olivine,

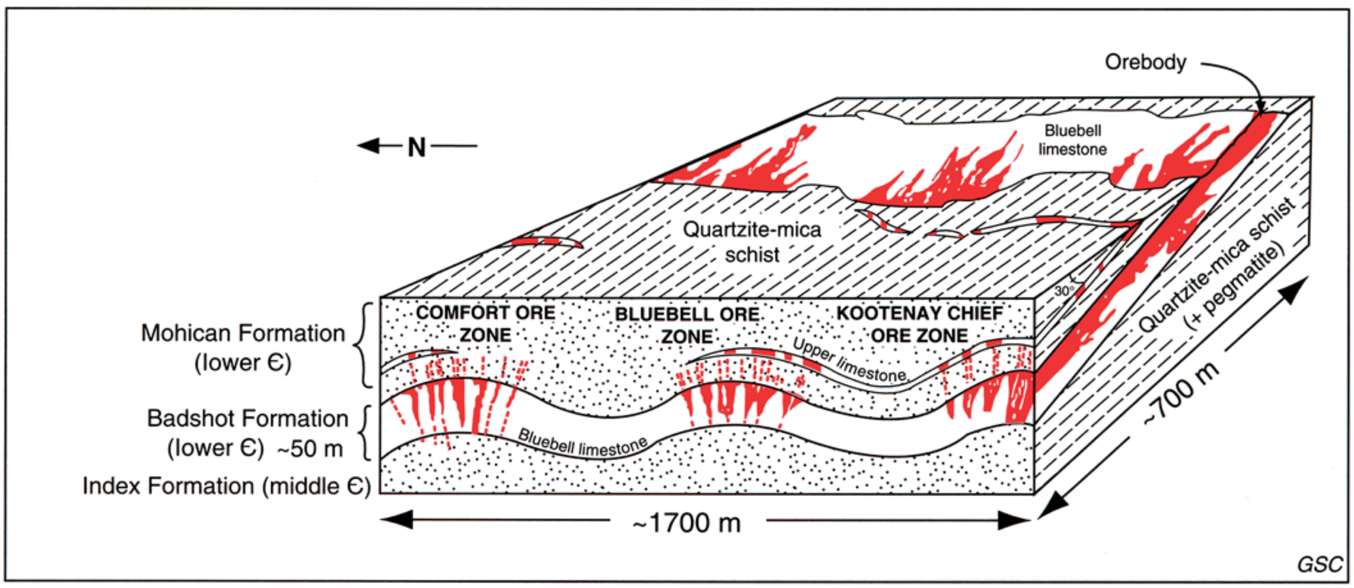
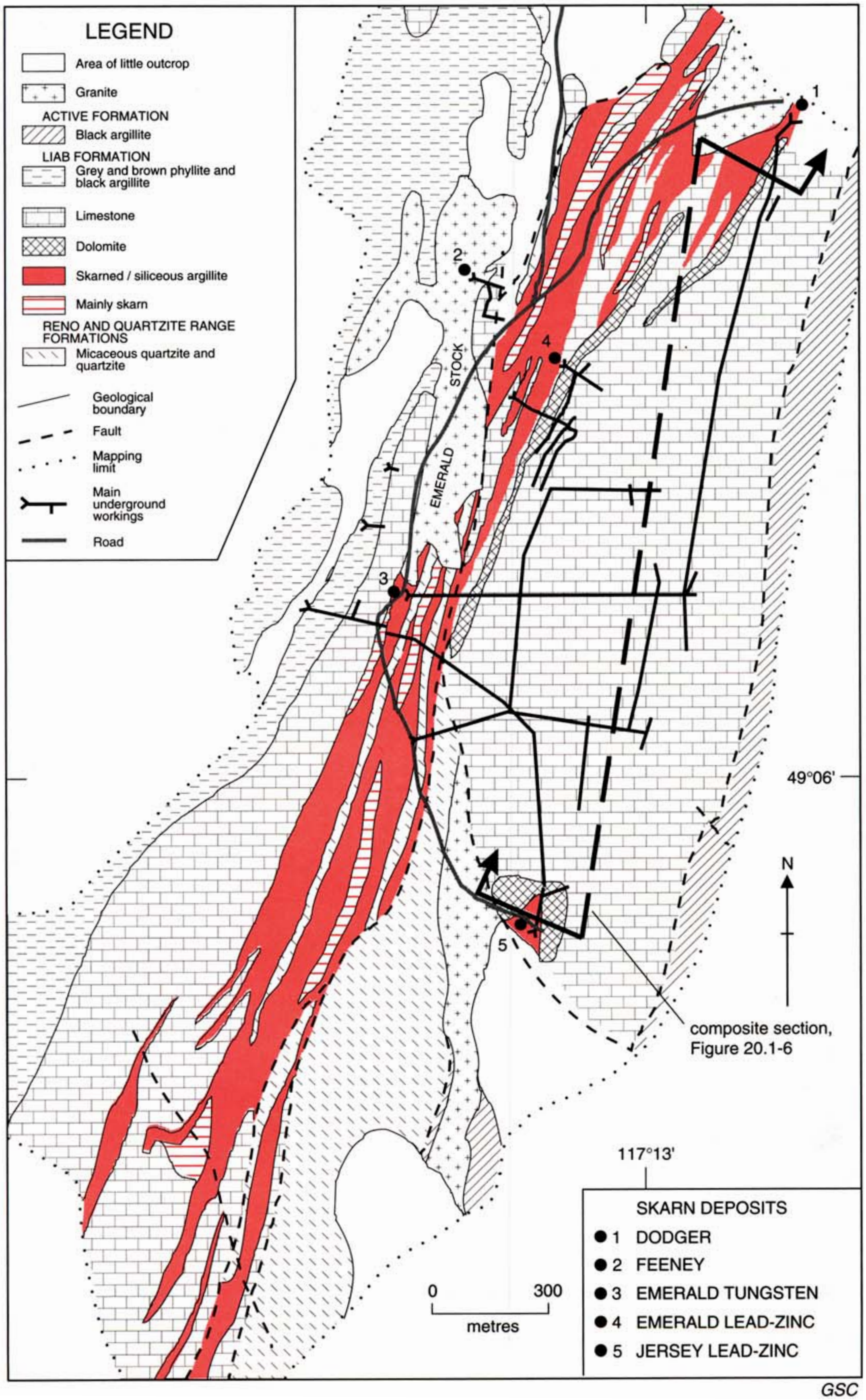


Figure 20.1-4. Schematic block diagram of Riondel Peninsula showing major Zn-Pb-Ag orebodies of the Bluebell mine. The westward-dipping inverted Cambrian succession lies within the lower limb of the Riondel nappe (Phase 1). The host Bluebell limestone (Badshot Formation) occupies the western limb of a Phase 2 northerly trending antiform. Replacement orebodies are localized by Phase 3 warps in earlier folds and by steeply dipping cross-fractures, both trending westerly to northwesterly. After Ohmoto and Rye (1970) and Höy (1980).

Figure 20.1-5. Geology of the Emerald Tungsten camp, Salmo, British Columbia, showing locations of skarn Zn-Pb and W deposits. Geology after Fyles and Hewlett, 1959 (modified after Webster et al., 1992, Fig. 2-2-5).


LEGEND
Area of little outcrop
Granite
ACTIVE FORMATION
Black argillite
LIAB FORMATION
Grey and brown phyllite and black argillite
Limestone
Dolomite
Skarned / siliceous argillite
Mainly skarn
RENO AND QUARTZITE RANGE FORMATIONS
Micaceous quartzite and quartzite
Geological boundary
Fault
Mapping limit
Main underground workings
Road
EMERALD STOCK
49°06'
117°13'
N
composite section, Figure 20.1-6
0
300
metres
SKARN DEPOSITS
1 DODGER
2 FEENEY
3 EMERALD TUNGSTEN
4 EMERALD LEAD-ZINC
5 JERSEY LEAD-ZINC
GSC

and serpentine (Whishaw, 1954; Bradley, 1970) are more representative of a Zn-Pb skarn deposit than is the simpler mineralogy of the Remac deposit to the south. The relationship of these probable Zn-Pb skarns to adjacent intrusions and consanguineous stratiform Zn-Pb deposits remains unclear. Production from the combined Jersey and Emerald Zn-Pb mines between 1914 and 1972 was 7.68 Mt of ore grading 3.49% Zn, 1.65% Pb, 3.08 g/t Ag, and 0.23% W (Höy, 1982).

The Sa Dena Hes mine at Mount Hundere, near Watson Lake, Yukon Territory is an example of a large Zn-Pb skarn without an exposed igneous source (Table 20.1-1). Several tabular skarn orebodies are concordant with bedding in a deformed Upper Proterozoic-Lower Cambrian limestone-phyllite sequence (Abbott, 1981). Distribution of abundant prograde actinolite-hedenbergite-grossularite and retrograde quartz-fluorite skarn assemblages is apparently unrelated to small aplite and diabase dykes, but may reflect the influence of a buried pluton (Dawson and Dick, 1978). Two additional large deposits, which formed at a distance from a probable or unknown igneous source, are Quartz Lake in southeastern Yukon Territory and Prairie Creek (Cadillac) near the South Nahanni River in Northwest Territories. The Quartz Lake deposit is a stratabound pyritic replacement of limestone in an Upper Proterozoic-Lower Cambrian conglomeratic quartzite-limestone-argillite shelf sequence (Gabrielse and Blusson, 1969; Morin, 1981). The ore mineral assemblage of pyrite, dark sphalerite, and galena, and lesser arsenopyrite, boulangerite, tetrahedrite, and chalcopyrite, and the gangue assemblage of quartz, dolomite, siderite, and ankerite, support an epigenetic origin as a skarn related to small, barely unroofed Cretaceous plutons in the district. Recent exploration drilling of the developed Prairie Creek prospect, an extensive Zn-Pb-Ag vein in a shear zone in dolostone and shale of the Middle Devonian Arnica Formation (Thorpe, 1972) has revealed a stratabound orebody at depth that more than doubled known reserves (Table 20.1-1). Consistently high Zn+Pb and elevated Cu values in ore, and lesser amounts of W and Hg (Jonasson and Sangster, 1975) support an igneous source, but the closest known plutons are exposed 80 km to the west.

Mineralogy

Principal ore minerals: sphalerite, galena (in part argentiferous), Ag sulphosalts.

Other opaque minerals: chalcopyrite, pyrrhotite, magnetite, arsenopyrite, pyrite, Pb sulphosalts, tetrahedrite, scheelite.

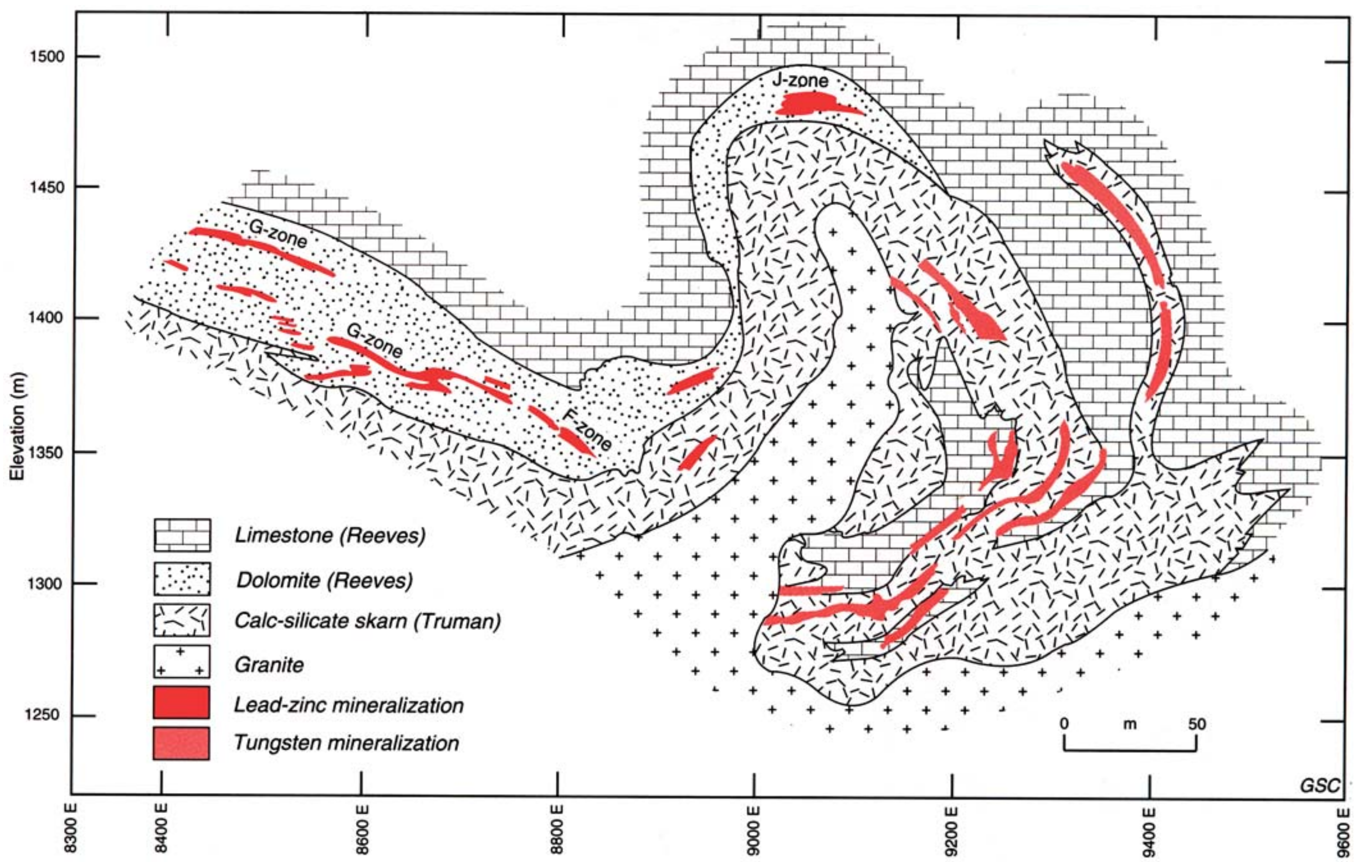


Figure 20.1-6. Composite section looking north of the East Dodger tungsten mine and Jersey lead-zinc mine, Salmo, British Columbia. Approximate line of composite section shown in Figure 20.1-5. Modified after Thompson (1973).

Prograde skarn minerals: Mn-rich pyroxene (johannsenitic hedenbergite), andraditic garnet, vesuvianite, wollastonite, bustamite, epidote, diopside, olivine (knebelite).

Retrograde skarn minerals: manganoan varieties of actinolite, epidote, chlorite, siderite, and ilvaite, and also calcite, quartz, fluorite, rhodonite, axinite, talc.

DEFINITIVE CHARACTERISTICS

1. Manganese- and iron-rich mineralogy.
2. Occurrence along stratigraphic contacts and structural pathways, including dyke contacts.
3. Occurrence at a distance from intrusive contacts.
4. Limited size of metamorphic aureole in comparison with other skarn types.
5. Abundant sulphide deposition beyond metamorphic aureole, as replacement of carbonate rock.
6. Pyroxene dominant over garnet in prograde skarn.
7. Pronounced structurally-controlled zoning of deposit morphology and metal zoning, with proximal skarns rich in Cu and W, and distal skarns, mantos, and veins rich in Mn, Ag, and Pb.

GENETIC MODEL

In the genetic model for Pb-Zn-Ag skarns, limestone and calcareous pelite adjacent to a cooling and crystallizing batholith, stock, or dyke-sill complex undergoes isochemical thermal metamorphism to marble and calc-silicate hornfels. Metasomatism is initiated by the separation of a magmatic-hydrothermal fluid released by crystallization and hydrofracturing of the pluton, and this aqueous fluid may combine with metamorphic waters to transport Fe, Mg, Si, Al, and base metal cations and sulphur. Metasomatic fluids pass along pluton and dyke contacts, stratigraphic contacts, fold hinges, fractures, and other permeable pathways and infiltrate the surrounding wall rocks. Marble and calc-silicate hornfels are replaced by prograde exoskarn, but some exoskarn and most sulphide replacements extend along structural pathways beyond the limits of the metamorphic aureole into limestone. Simultaneously, epidote-rich endoskarns form in the pluton and in pelitic hornfels by introduction of calcium from the host rock, and wollastonite forms in marble.

Skarn close to the pluton is rich in andraditic garnet, but clinopyroxene is the dominant prograde mineral. More distal assemblages include pyroxenoids, i.e., rhodonite, wollastonite, and bustamite, and prograde hydrous minerals, i.e., epidote and chlorite. Johannsenitic pyroxene becomes depleted successively in Mg, then Fe, and enriched in Mn along the strike of structural conduits away from the intrusion, towards the marble front away from fluid channelways, and at higher elevations in the system. Calc-silicate compositions are controlled mainly by the composition of the host rocks, the oxidation state, and the temperature of the system. Exoskarns may pass continuously beyond the thermal aureole into sulphide-rich and calc-silicate-poor concordant to discordant skarn bodies termed mantos and chimneys, respectively, and most distally to Ag-Pb-Zn vein deposits that contain quartz, carbonate, and minor calc-silicate gangue.

Late in the prograde stage of skarn formation, the evolving ore fluid is enriched in sulphur, manganese, and ferric iron, and sulphide and magnetite deposition commences. Copper- and zinc-rich skarn assemblages form closest to the intrusive contact, together with W and Au, if present. Greater deposition of Pb, Ag, and Mn occurs at a distance from the intrusion, in conjunction with Pb- and Ag-sulphosalt minerals. The main period of sulphide deposition follows skarn formation and is accompanied by hydrous alteration of early skarn minerals and hydrolytic alteration of intrusions. Early calcium-rich silicates are altered to calcium-depleted, Fe- and Mn-enriched silicates, carbonates, and iron oxides. Distal skarns and replacements are affected less by hydrous alteration than proximal skarns. Some peripheral mantos, chimneys, and veins are formed at this late stage.

Most skarn minerals can be enriched in manganese, including pyroxene, garnet, amphibole, pyroxenoid, olivine, ilvaite, chlorite, and serpentine. Meinert (1987) described a systematic increase in the pyroxene:garnet ratio and the manganese content of pyroxene along the path of hydrothermal fluid flow at the Groundhog deposit, New Mexico. Evolutionary stages for skarns in general are outlined in "Skarn tungsten" (deposit subtype 20.5; Fig. 20.5-3) and "Skarn copper" (deposit subtype 20.2; Fig. 20.2-7).

RELATED DEPOSIT TYPES

Massive sulphide bodies with little or no accompanying calc-silicate gangue minerals, in addition to the mantos, chimneys, and carbonate-hosted veins described above, are commonly termed "replacement deposits" and not widely recognized as distal members of a base metal skarn system, particularly if no related intrusion is recognized. In discussing the skarn deposits of northern Mexico, Megaw et al. (1988) made the important point that many zinc skarn districts grade outward from intrusion-associated to intrusion-free ores, therefore those districts lacking known intrusion relationships may not have been traced to their ends. The important Gilman and Leadville deposits of the Colorado Mineral Belt are recognized by Beaty et al. (1990) and Titley (1993) as mantos similar to the manto and skarn orebodies of northern Mexico, as described by Megaw et al. (1988). Similar mantos that occur at Pioche and Eureka, Nevada; Tombstone, Arizona; Tintic and Park City, Utah; U.S. and Lark mines, Bingham, Utah; and Magdalena, New Mexico are described by Titley (1993).

Incompletely explored Zn-Pb skarn districts may have only one or a few of the characteristic skarn and manto zones exposed, in addition to an unexposed intrusion. The presence of skarn minerals anywhere in the system, such as garnet- and manganese-rich pyroxene and amphibole, will definitively distinguish these deposits from other types of Zn-Pb-Ag deposits such as Mississippi Valley-type deposits, which they may resemble.

Zinc-rich skarns that have formed as peripheral parts of some W-Cu skarns in the northern Canadian Cordillera are relatively rich in W, but deficient in Pb and Ag (Dick, 1979). Base metal skarns adjacent to the Seagull batholith, a F- and B-rich leucogranite pluton in south-central Yukon Territory, are enriched in Sn, B, Be, and F to the extent that several are predominantly Sn skarns.

EXPLORATION GUIDES

The recognition of any of the following features within a prospective terrain may lead to the discovery of a Zn-Pb-Ag skarn deposit.

1. Relatively thick pure and impure limestone beds, interbedded with shale or pelite, and intruded by granitoid plutons of generally small dimensions, e.g., dykes and sills.
2. Stockwork fractures, faults, and porphyry dykes along and adjacent to a pluton/limestone contact.
3. Structural traps in carbonate host rock, particularly the intersection of anticlines and domes by structural conduits such as dykes, faults, and fault intersections.
4. Presence of calc-silicate skarn minerals, particularly garnet, pyroxene, and amphibole in association with base metal assemblages. Purplish-black Mn-rich gossan developed over calc-silicate and carbonate gangue minerals rich in Mn and Fe.
5. Pyroxene:garnet ratios and manganese contents of pyroxene decrease, and magnesium content of pyroxene increases, systematically towards the intrusive contact and hydrothermal conduit, enabling one to identify proximal and distal zones of large systems (Meinert, 1987).
6. Small base metal sulphide occurrences lacking apparent skarn affinity may be part of a major magmatic-hydrothermal system. Such deposits may be hosted by carbonate-pelite rocks distant from an intrusive source which may not be exposed and which may lack a thermal metamorphic aureole; consequently, these deposits may have little or no associated calc-silicate gangue. These deposits may, in places, include Ag-rich Zn-Pb veins and 'rootless' conformable and discordant Fe-Zn-Pb replacement bodies.
7. Metal zoning in the skarn assemblage shows enrichment away from an intrusive contact or hydrothermal conduit in the general order Fe-Cu-Zn-Pb-Ag-Sb-As.

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Contents

20.2 SKARN COPPER

20.2a Copper skarns not associated with porphyry copper deposits
20.2b Copper skarns associated with porphyry copper deposits

K.M. Dawson and R.V. Kirkham

INTRODUCTION

Skarn copper deposits are characterized by their large size relative to tungsten, lead-zinc, and gold skarns; association with both porphyry copper- and nonporphyry copper-related intrusions; and relatively oxidized, gold-rich mineral assemblages developed close to intrusive contacts with carbonate rocks. Principal commodities are Cu and Mo, but Fe, Au, and Ag are common byproducts, and Zn, Pb, W, and Bi are common minor constituents. Two principal divisions of copper skarns are recognized, i.e., those not associated with porphyry copper deposits (subtype 20.2a) and those associated with porphyry copper deposits (subtype 20.2b). Two additional subdivisions are recognized, based on the composition of the plutons, i.e. calc-alkaline and alkaline (Table 20.2-1). Significant Canadian and foreign examples of the above are: non-porphyry-associated: Phoenix, British Columbia; Whitehorse Copper Belt, Yukon Territory; Sayak I, Kazakhstan, Concepcion del Oro, Mexico; and Tongling, Lower Yangtze, China; porphyry-associated calc-alkaline: Gaspé Copper, Quebec; Twin Buttes, Arizona, U.S.A.; and Gold Coast, Ok Tedi district, Papua New Guinea; and porphyry-associated alkaline: Ingerbelle and Galore Creek, British Columbia and Larap, Philippines. Distribution of principal skarn copper deposits in Canada is shown in Figure 20.2-1.

IMPORTANCE

Skarn copper deposits account for approximately 5% of Canada's copper production and less than 5% of its reserves. Copper skarns are perhaps the world's most abundant skarn type. Significant deposits are mined around the world; in the porphyry copper province of southwestern United States, in the Ural Mountains of Russia, Kazakhstan, and in the Lower Yangtze River area, China, skarn deposits are a major source of copper.

Dawson, K.M. and Kirkham, R.V.
1996: Skarn copper; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 460-476 (also Geological Society of America, The Geology of North America, v. P-1).

SIZE AND GRADE OF DEPOSIT

Tonnages and grades of significant Canadian and foreign skarn copper deposits are given in Table 20.2-2. Size, grade, and some geological characteristics of global skarn copper deposits were tabulated by Einaudi et al. (1981), and of porphyry copper-related skarns by Einaudi (1982). Copper-bearing skarns associated with, and forming part of, porphyry copper deposits, which include some of the world's largest skarn deposits, range in size from 50 to greater than 320 Mt of skarn ore. They average about 100 Mt at a grade of 1% Cu. In addition to skarn copper ore, variable amounts of porphyry-type stockwork and disseminated copper ore are hosted within adjacent intrusions and other rocks. Canadian porphyry deposit-related copper skarn deposits average about 90 Mt of ore grading between 0.4 and 1.0% Cu. Large porphyry deposit-related copper skarns, shown as circles on Figure 20.2-2, contain more than 1 Mt of Cu metal. Copper skarns developed adjacent to intrusions with no related porphyry copper deposits, shown as square symbols on Figure 20.2-2, are smaller, i.e. generally between 2 and 30 Mt of ore, but higher in copper grade, i.e., in the 1.5% to 2.5% Cu range. Canadian examples of this skarn type, such as Phoenix, British Columbia and Whitehorse Copper Belt, Yukon Territory have produced significant copper. Limited production and reserve data indicate that the Tongling and adjacent skarn districts in the Lower Yangtze River area in China combined contain greater than 10 Gt of ore grading about 1% Cu.

GEOLOGICAL FEATURES

Geological setting

Porphyry deposit-related copper skarns commonly occur in continental marginal belts, where miogeoclinal calcareous sediments have been intruded by epizonal calc-alkaline granodioritic to quartz monzonitic magnetite-bearing, I-type plutons. Large deposits in the southwestern United States occur in such a setting, in association with subduction-related magmatic arcs. Deposits in similar settings are located in Mexico, Peru, Russia, China, and Japan. Many of these deposits occur within evolved magmatic arcs which developed on continental crust. Timing of skarn-related intrusion is commonly postorogenic.

Table 20.2-1. Mineralogy of three skarn copper subtypes.

Plutonic asociation of skarn Cu	Prograde skarn minerals	Retrograde skarn minerals
Mineralized calc-alkaline porphyry Cu stocks	andraditic garnet, diopsidic pyroxene, wollastonite	actinolite, tremolite, chlorite, montmorillonite, quartz, calcite
Unmineralized stocks, unrelated to porphyry Cu	grandite garnet, diopsidic pyroxene, wollastonite, magnetite, epidote	epidote, actinolite, tremolite, hornblende, chlorite, quartz, calcite
Mineralized alkaline porphyry Cu-Au stocks	andraditic garnet, diopsidic pyroxene, orthoclase, biotite, albite, epidote, sphene, vesuvianite	chlorite, actinolite, epidote, calcite, albite, scapolite, zeolite, hematite

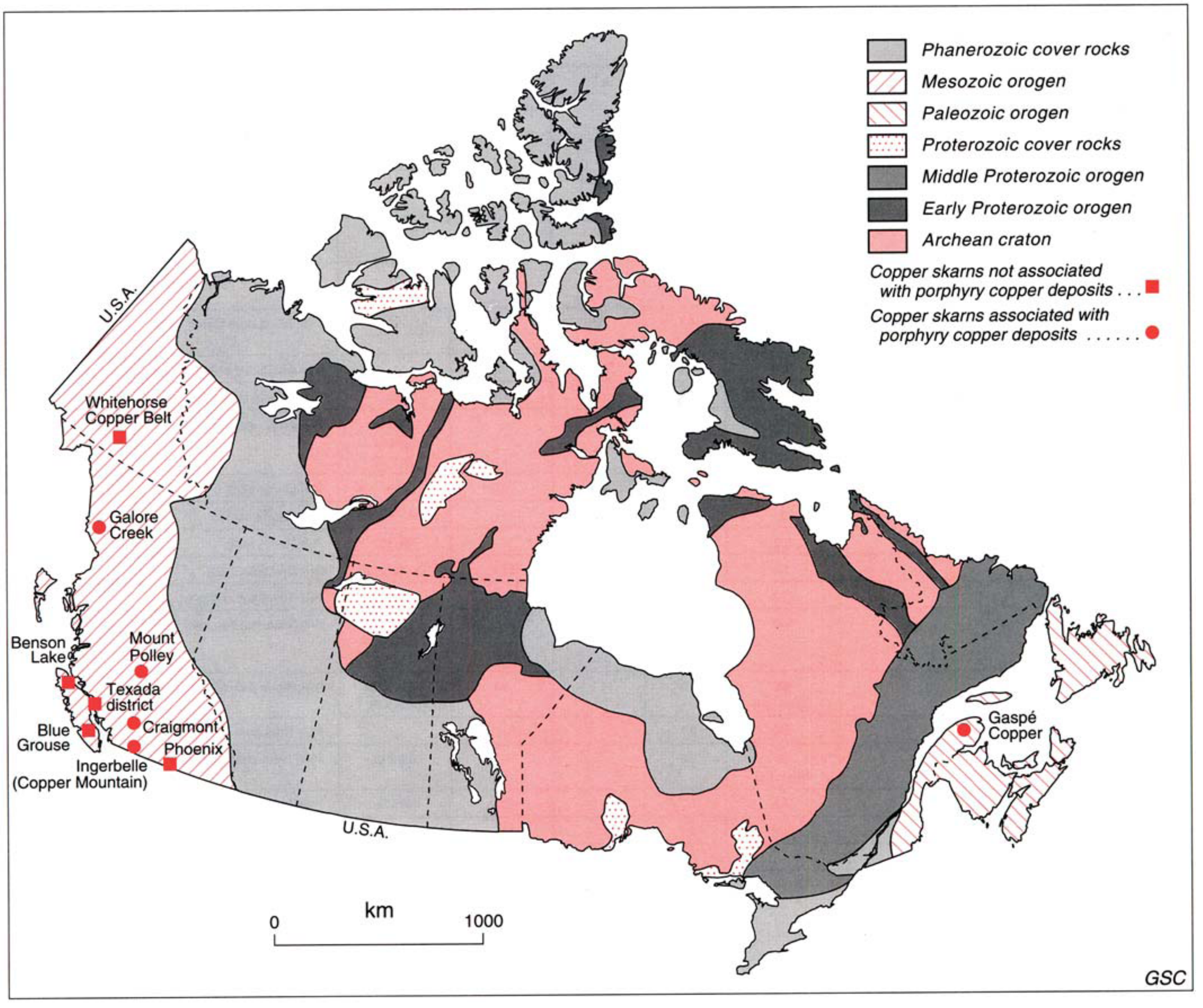


Figure 20.2-1. Distribution of principal skarn copper deposits in Canada.

Table 20.2-2. Tonnages and grades of significant Canadian and foreign skarn copper deposits.

Deposit, location	Size (million tonnes)	Average Grade %Cu	g/t Au	g/t Ag	other	Comments P = production R = reserves
Canadian deposits						
1. Ingerbelle (Copper Mountain), Princeton, British Columbia	240 (skarn 216)	0.40	0.16	0.63		about 90% is skarn P (1972-1988) + R (Similco, Mines Ltd., internal publication, 1989)
2. Stikine Copper, Galore Creek, British Columbia	113 (skarn 90)	1.06	0.4	7.7		about 80% is skarn R (Allen et al., 1976)
3. Craigmont, Merritt, British Columbia	35	1.13	tr.	tr.	19.6% Fe 0.12% Mo	P (1961-1982)+ R (BC MINFILE, 1988; Morrison, 1980)
4. Phoenix, Greenwood, British Columbia	34	0.8	1.1	15	Fe, Pb, Zn	P (1893-1976) + R (Church, 1986)
5. Mount Polley, British Columbia (Cariboo Bell)	48 (skarn 10)	0.38	0.55	4.5	Fe	about 20% is skarn. R (Imperial Metals Corp., internal publication, 1991)
6. Whitehorse Copper Belt, Yukon Territory	10.1	1.4	1.0	8.8	Mo	P (1898-1982) + R (Watson, 1984; Meinert, 1986)
7. Prescott, Marble Bay, etc., Texada Island, British Columbia	21.2	0.2	0.1	1.9	Fe	P (1885-1976) + R (Ettlinger and Ray, 1988)
8. Old Sport, Coast Copper, Benson Lake, British Columbia	2.7	1.5	1.4	4.0	33% Fe	P (1962-1971) + R (Meinert, 1986)
9. Blue Grouse, Cowichan Lake, British Columbia	0.25	3.0	tr.*	11	Fe, Zn	P (1917-1960), Fyles (1955), Ray and Webster (1991)
10. Gaspé Copper (Mines Gaspé), Murdochville, Quebec	67	1.45	--	10 (E zone)	Mo, Zn, W, Bi	A,B,C,E, skarn zones) P+R (Allcock, 1982; Wares and Williams-Jones, 1993)
Foreign deposits						
11. Carr Fork, Utah, U.S.A.	400 (skarn 80)	2.2	0.6	12		P+R; 20% is skarn (Cameron and Garmoe, 1987)
12. Twin Buttes, Arizona, U.S.A.	400 (skarn 320)	0.7	--	6.0	0.03% Mo	P+R; 80% is skarn (Barter and Kelly, 1982)
13. Santa Rita, New Mexico, U.S.A.	350 (skarn 70)	0.9	0.2	--		P+R; 20% is skarn (Nielson, 1970)
14. Ely District, Nevada, U.S.A.	339 (skarn 68)	0.7	0.3	0.9		P+R; 20% is skarn (James, 1976)
15. Ertsberg, Irian Jaya, Indonesia	52.6	2.4	0.8	8.0		P+R (MacDonald and Arnold, 1993; Meinert, 1987)
16. Gold Coast, Ok Tedi district, Papua-New Guinea	54	1.53	1.6	--	Mo	R; Gold Coast skarn (Hewitt et al., 1980)
17. Larap, Philippines	17	0.42	0.3	--	0.09% Mo 22% Fe W, U, Bi	P+R (Sillitoe and Gappe, 1984)
18. Rosita, Honduras	4	1.6	0.9	6.0	Fe	P+R (Bevan, 1973)
19. Concepcion del Oro, Mexico	2	2.0	1.6	--	Fe, Zn, Pb	P+R (Buseck, 1966)
20. Memé, Haiti	1.2	2.5	--	--	Fe, Mo	P+R (Kesler, 1968)
21. Yaguki, Japan	1.2	0.8	3.0	156	Fe, W, Co, Bi	P+R (Shimazaki, 1969)
22. Red Dome, Australia	13.8	0.46	2.0	4.6	1% Zn	P+R (Torrey et al., 1986)
23. Morococha, Peru	>10	2.4	--	123.5	1.5% Zn 0.5% Pb 20% Fe	P+R (estimated) (Petersen, 1965)
24. Mission Arizona, U.S.A.	400 (skarn 320)	0.8	--	9.6	0.019% Mo 0.024% Pb	P+R; 80% is skarn (Einaudi et al., 1981)
25. Christmas Arizona, U.S.A.	100	0.7	--	--		P+R; 100% skarn (Perry, 1968)
26. El Tiro (Silver Bell), Arizona, U.S.A.	50 (skarn 7.5)	0.8	--	--	0.8% Zn	P+R; 15% is skarn (Graybeal, 1982)
27. Kasaan Peninsula, Alaska, U.S.A.	4.3	2	--	440	50% Fe	P+R (Green et al., 1989)
28. Zackly, Alaska, U.S.A.	1.25	2.7	6.0	30		P+R (Nokleberg et al., 1988)

*tr. = trace

Porphyry deposit-related copper skarns in the Canadian Cordillera differ from the deposits cited above in several ways: their accreted oceanic-volcanic arc setting, i.e. Quesnellia and Stikinia, is in contrast to craton marginal settings in southwestern United States, Mexico, and Russia; limestone host rocks are scarce, resulting in less abundant calc-silicate gangue; and they are associated with alkaline, mainly monzonitic intrusions, rather than intermediate to felsic calc-alkaline plutons (Table 20.2-1). Other porphyry deposit-related copper skarns are found in similar oceanic-island arc settings in the Philippines, Papua New Guinea, Honduras, and Haiti (Table 20.2-2). Craigmont mine at Merritt, British Columbia is a copper-magnetite skarn associated with the border phase of the calc-alkaline Guichon Creek batholith, whose younger intrusive phases host the large Highland Valley (Valley Copper, Lornex) porphyry district. Although the border phase is unmineralized, Craigmont is classified in this paper as a porphyry-associated skarn copper deposit.

Copper skarns not associated with porphyry copper deposits occur typically in oceanic-island arc settings, within interstratified limestone-volcanic flow-volcaniclastic sequences (e.g., Phoenix, Greenwood district), but also occur in continental marginal carbonate strata (e.g., Concepcion del Oro, Zacatecas, Mexico). Associated intrusions are generally intermediate to mafic in composition. The skarn mineral assemblages tend to be iron-rich and to share characteristics, including accreted arc and rifted continental marginal settings, with calcic iron skarns (Einaudi et al., 1981).

Age of host rocks and mineralization

Host rocks in which skarn copper deposits have been preferentially formed include pure and impure limestone, dolostone, calcareous sedimentary rocks, thermally metamorphosed equivalents of these lithologies, and also calcic metavolcanic and meta-intrusive rocks. Host rocks range from Precambrian to Cenozoic in age, and are predominantly Phanerozoic. The host rocks of North American skarn copper deposits are predominantly Paleozoic cratonic carbonate strata in the western United States and the Appalachian Orogen, Late Triassic oceanic-island arc volcano-sedimentary sequences in the northern Cordillera, and Cretaceous shelf carbonate strata in Mexico and Central America. Skarn host rocks are dominantly Late Paleozoic to Tertiary oceanic-arc assemblages in Japan, Philippines, and Papua New Guinea, and Paleozoic craton marginal beds in Australia and Russia.

Age of skarn mineralization is mainly Mesozoic or younger, and penecontemporaneous with the associated intrusion. Mineralization age is dominantly early Tertiary in the western United States, Mexico, and Central and South America; Early to mid-Jurassic in British Columbia; Late Jurassic and Cretaceous in Alaska, Yukon Territory, and China; Paleozoic in the Appalachians, Australia, and Russia; and Tertiary in Japan, Philippines, and Papua New Guinea.

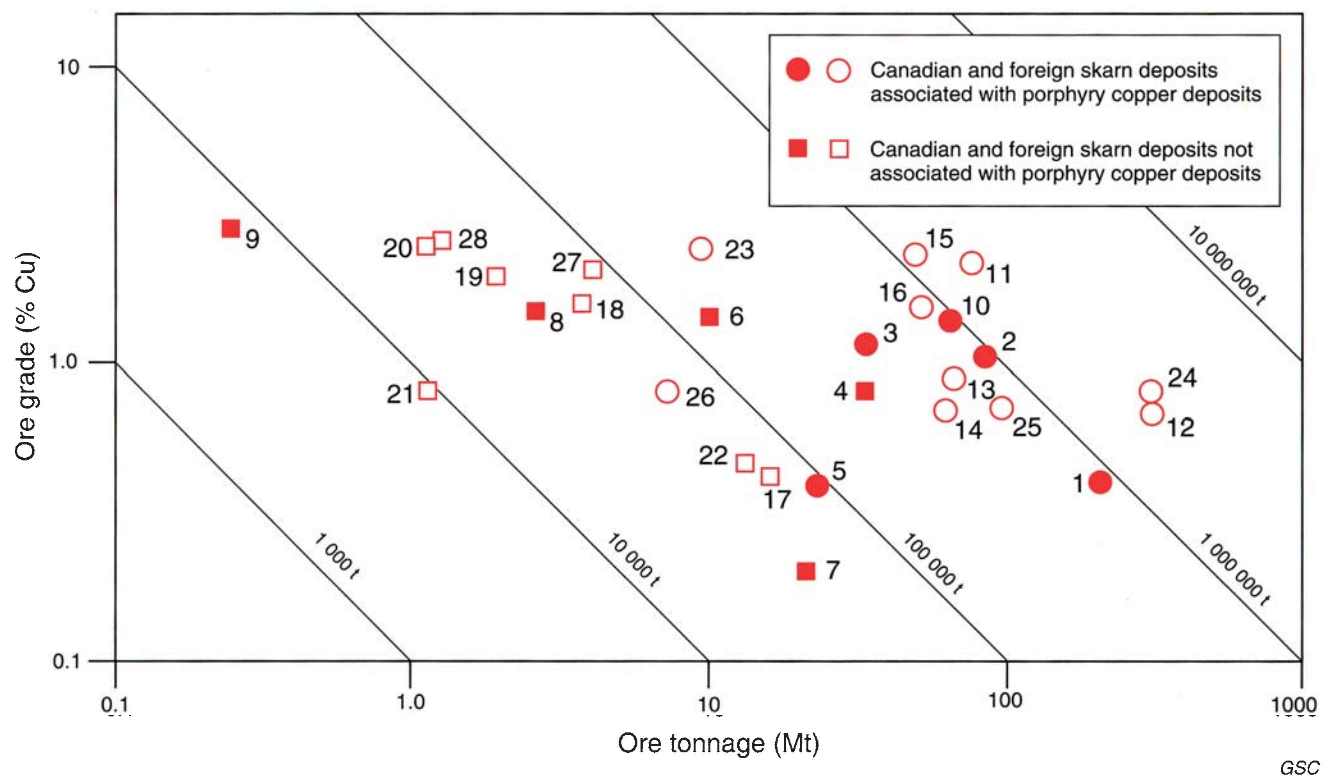


Figure 20.2-2. Grade versus tonnage of significant Canadian and foreign copper skarn deposits. Numbers correspond to deposits listed in Table 20.2-1.

Form of deposit and associated structures, zoning, and distribution of ore minerals

The morphology of calc-alkaline porphyry copper-related skarn copper deposits reflects the relatively high level of emplacement of associated felsic porphyry stocks, with resultant less extensive development and lower metamorphic grade of thermal aureoles compared with those surrounding deeper seated batholiths with associated tungsten-rich skarns. Multiple intrusive events contributed to the characteristically intense fracturing, brecciation, and breccia pipe formation. The relatively great extent and thickness of the skarns reflects the high fracture porosity and low pressure of the shallow porphyry system. Skarn has been formed close to intrusive contacts as irregular, tabular, vein-like to peneconcordant contact skarns or exoskarns with patchy, massive, and disseminated ore mineral assemblages.

Alteration in calc-alkaline porphyry stocks that evolved from early potassium silicate to late sericite assemblages parallels skarn alteration in carbonate wall rocks: in limestone an oxidized prograde assemblage of ferric iron-rich andradite garnet and ferrous iron-poor clinopyroxene is developed; pyroxene hornfels is altered to actinolite and biotite along sulphide-magnetite veinlets; pyrite-chalcopyrite-magnetite near plutonic contacts passes gradationally to bornite-chalcopyrite-wollastonite near marble contacts, reflecting the trend with time, and towards the periphery of the system, to a decrease in total iron and an increase in oxidation-sulphidation states (Burt, 1972; Einaudi et al., 1981). Sphalerite, pyrrhotite, tennantite, and galena are enriched in peripheral parts of the skarn system. Voluminous hydrous silicate-carbonate alteration of skarn and silica-pyrite alteration of limestone develops contemporaneously with late sericite-clay alteration of the stock. Retrograde skarn assemblages include actinolite, carbonates, clay, silica, iron oxides, and sulphides, and lesser amounts of chlorite, epidote, and talc. Low vein temperatures (<350°C, Roedder, 1971), influx of oxidized groundwater (Sheppard and Taylor, 1974), and peripheral deposition of base and precious metals represent the final stages of a long-lived sulphur-rich hydrothermal system. Zonation of sulphide and calc-silicate skarn assemblages in a large porphyry copper skarn system is exemplified by the Carr Fork deposit, Bingham mining district, Utah (Fig. 20.2-3A, B).

The Mines Gaspé copper deposits at Murdochville, Quebec are hosted by a folded, carbonate-rich Lower Paleozoic sequence of the Gaspé-Connecticut Valley synclinorium and are associated with porphyritic epizonal intrusions of a more deeply seated Devonian plutonic complex (Procyshyn et al., 1989). Several skarn and stockwork vein deposits occur within a broad aureole of calc-silicate hornfels enclosing the Copper Mountain porphyritic biotite granodiorite plug and the Porphyry Mountain diatreme breccia pipe and dyke-sill swarm (Wares and Williams-Jones, 1993). A map of the Mines Gaspé area and a cross-section are given in Figures 20.2-4A and 20.2-4B.

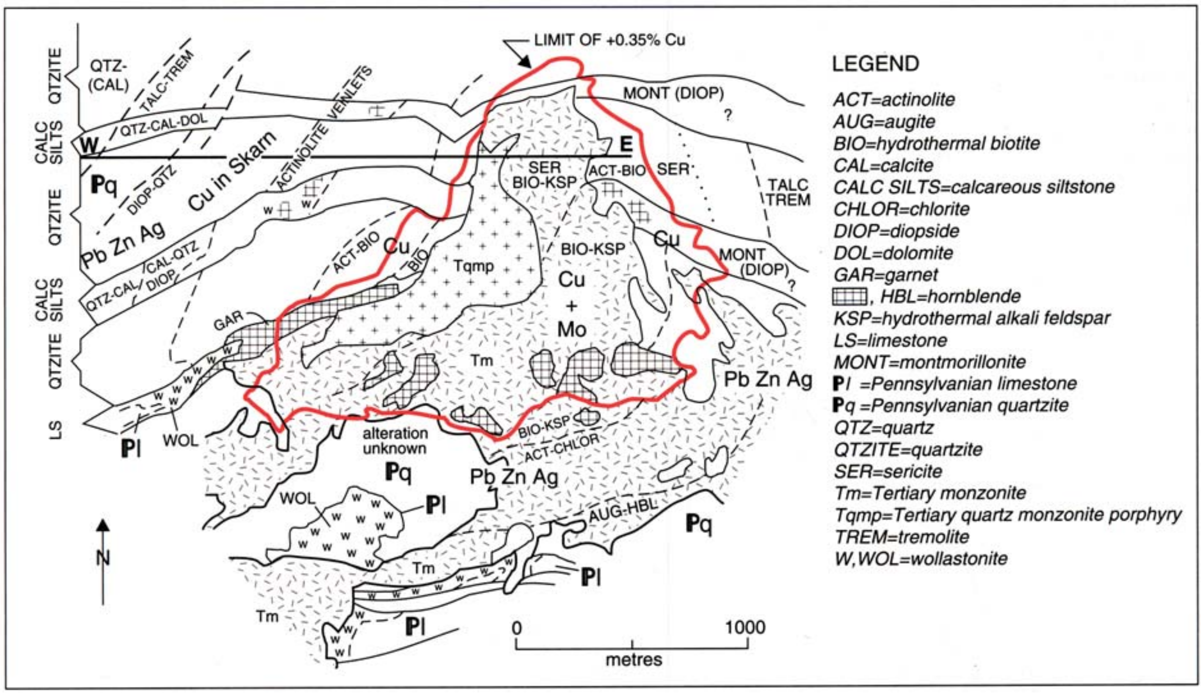
Thermal metamorphism preceded development of skarn and stockwork ores of four types: 1) the most economically significant deposits are the relatively early massive to disseminated pyrrhotite-chalcopyrite-cubanite replacements of discrete limestone beds enveloped, in part, by actinolite-rich skarn assemblages, that include the E-zone deposits with aggregate mining reserves of 6.7 Mt grading 2.8% Cu and 10 g/t Ag (Wares and Williams-Jones, 1993); 2) tabular skarn orebodies of disseminated to semi-massive sulphides that replaced limestone; deposits of this type in the B and C horizons at Needle Mountain contained a premining reserve of 47 Mt grading 1.48% Cu (Wares and Williams-Jones, 1993). The skarn assemblage of andradite, salite, quartz, actinolite, calcite, epidote, and K-feldspar replaced earlier-formed metamorphic minerals (Allcock, 1982). Garnet/pyroxene ratios and Fe-contents of garnets decrease away from the Copper Mountain and Porphyry Mountain plutons (Murphy, 1986), supporting an intrusive source of metasomatic fluids; 3) coevally with skarn, porphyry-style disseminated and stockwork Cu- and Mo-bearing veinlets were deposited in fractured potassic calc-silicate hornfels, adjacent to the Copper Mountain plug (i.e., Copper Mountain zone) and in the Needle Mountain "A" zone; these two zones combined total 222 Mt grading 0.42% Cu and 0.02% Mo (Wares and Williams-Jones, 1993); and 4) retrograde sulphide-quartz-actinolite-fluorite-anhydrite veins formed in potassic hornfels as the final stage of mineralization in the Copper Mountain zone.

Skarn copper deposits not associated with porphyry copper deposits are distinguished from porphyry copper-related skarns mainly by lack of stockwork and disseminated Cu and Mo sulphides in the intrusion and other rocks, and also by smaller size, more massive nature, and higher Cu grade. They are associated with calcic iron skarns with which they have several features in common, including tectonic setting, composition of intrusions, skarn morphology, and mineralogy. Prograde skarn minerals include garnet intermediate in composition between grossularite and andradite, diopsidic pyroxene, wollastonite, magnetite, and epidote. Examples of coexisting calcic copper and iron skarns are found in the Texada Island, Benson Lake, and Greenwood districts of British Columbia (Tables 20.2-1 and 20.2-2). This type of skarn copper deposit lacks the intense stockwork fracturing typical of porphyry deposits, resulting in the restriction of retrograde mineral assemblages to vug fillings, contact zones, and widely spaced, structurally controlled fluid conduits. Retrograde skarn assemblages commonly include actinolite, tremolite, epidote, chlorite, quartz, and calcite; significant concentrations of base metals and precious metals are associated with the retrograde skarn assemblages.

In the Whitehorse Copper Belt, Yukon Territory, thirty-two Cu, Fe (Mo, Au, Ag) skarn deposits occur in both calcareous and dolomitic units of the upper Triassic Lewes River Group, a back-arc succession of arkosic clastic and carbonate rocks. Skarns are localized mainly along the irregular western contact of the Whitehorse batholith (Fig. 20.2-5A), a composite calc-alkaline granodioritic pluton with a dioritic margin (Morrison, 1981) that postorogenically intruded accreted Stikinia in mid-Cretaceous time (Dawson et al., 1991). The silicate mineralogy of individual skarn deposits is largely a function of the skarn protolith (Morrison, 1981). Skarns formed from a limestone protolith (e.g., War Eagle, Fig. 20.2-5B) contain abundant andraditic garnet, less abundant iron-rich (up to Hd_{37}; Meinert, 1986) pyroxene, wollastonite, and vesuvianite, and variable amounts of the retrograde alteration products actinolite, epidote, and chlorite. Skarns with a dolomitic

Contents

A



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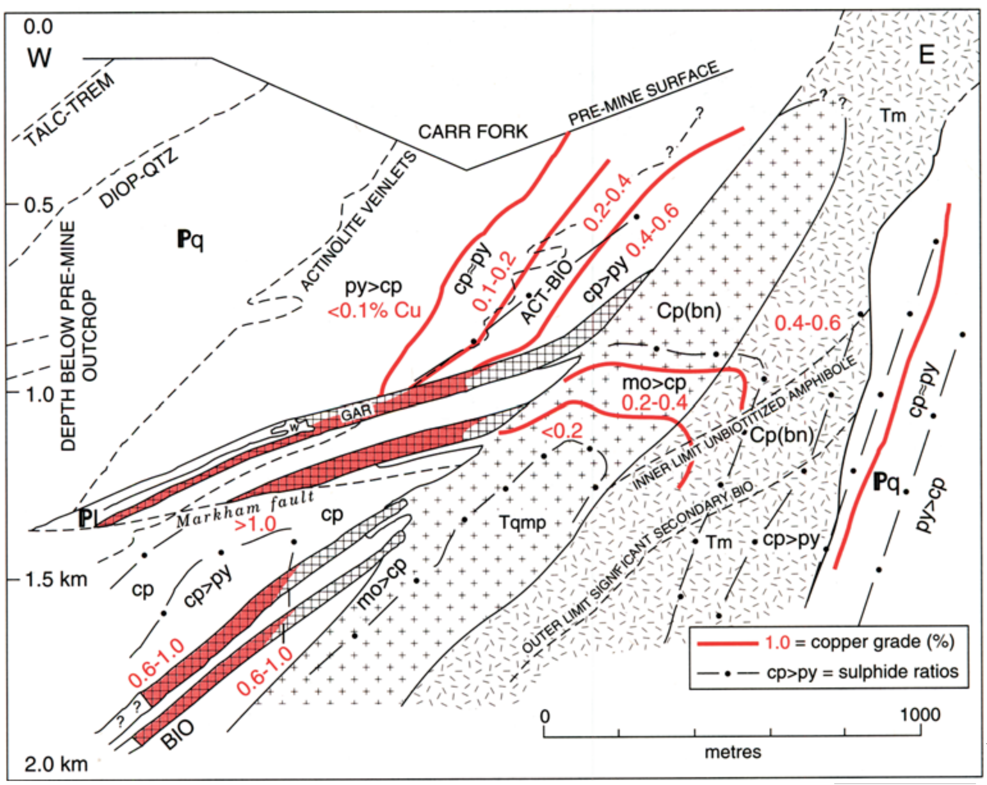

Figure 20.2-3. Mineral zoning and alteration in the Bingham mining district, Utah, U.S.A. After Atkinson and Einaudi (1978) and Einaudi (1982, Fig. 7.14, 7.15). **A)** Alteration in igneous and sedimentary rocks at surface, and metal zonation relative to central quartz monzonite porphyry stock. **B)** Cross-section W-E (looking north) of the Carr Fork skarn copper deposit, western contact zone of the Bingham stock, illustrating alteration, copper grades, and sulphide mineral ratios.

protolith (e.g., Arctic Chief, Fig. 20.2-5C) contain abundant prograde magnesian minerals such as diopside and forsteritic olivine, less abundant andradite, and retrograde phlogopite, brucite, serpentine, and talc. The sulphide minerals are associated mainly with retrograde alteration assemblages: chalcopyrite and pyrite preferentially with actinolite and chlorite; and bornite and chalcocite with epidote. The rare micaceous copper mineral valleriite ($4(Fe,Cu)S \cdot 3(Mg,Al)(OH)_2$) is restricted to retrograde alteration assemblages in magnesian, i.e. dolomitic, rocks. The highest average Au and Ag grades occur where massive sulphide and retrograde alteration assemblages coexist in skarn (Meinert, 1986).

In British Columbia, some porphyritic members of the distinctive Copper Mountain alkaline plutonic suite, which are associated with porphyry Cu-Au deposits, also developed a distinctive type of skarn copper deposit. Synvolcanic syenite, monzonite, and diorite porphyry plutons intruded

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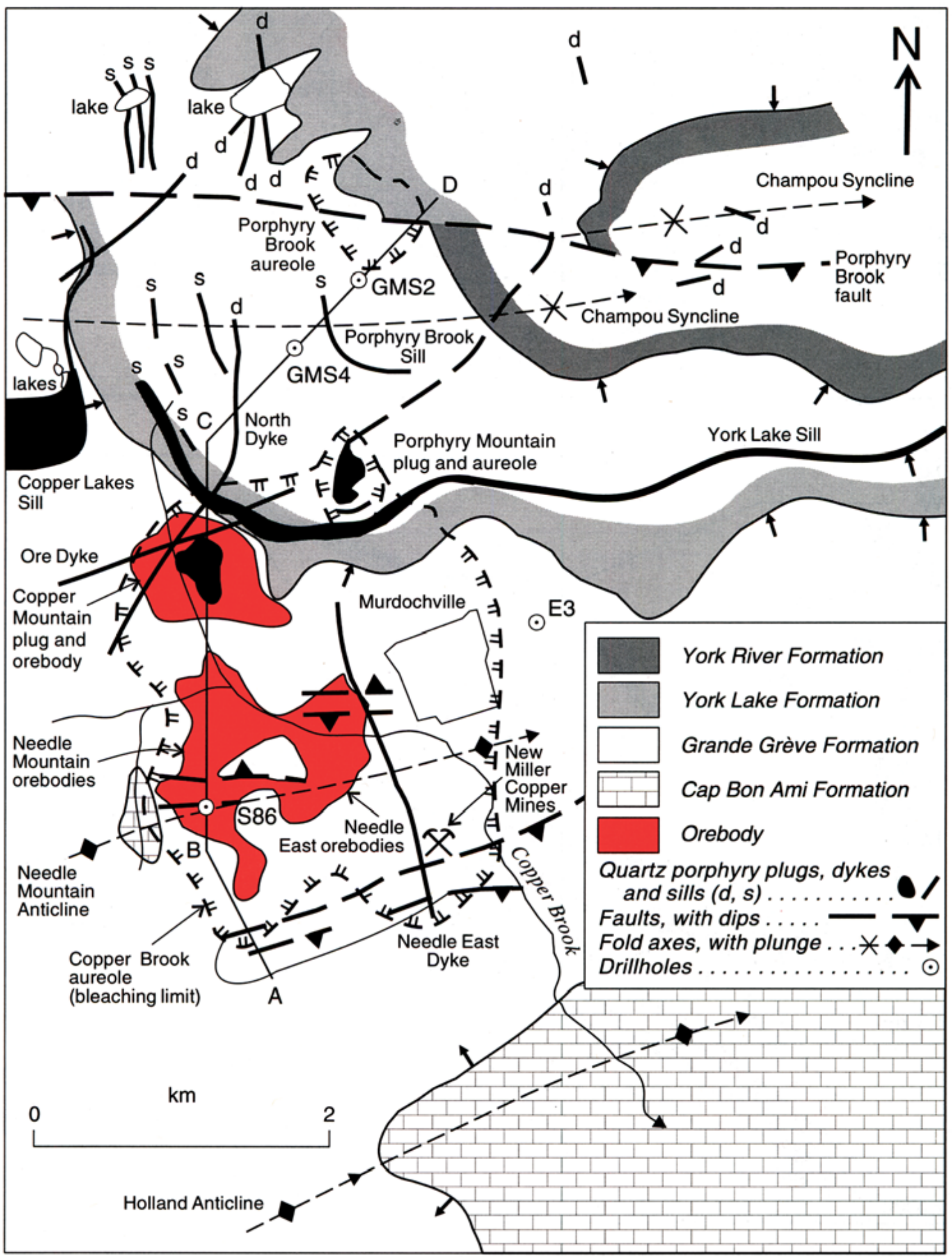

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Figure 20.2-4. A) Simplified geological map of Mines Gaspé in the Murdochville, Quebec area, after Allcock (1982, Fig. 2). The 150 m contour of the Copper Mountain plug is included to show its shape. Section ABCD is shown in Figure 4B. **B)** Section along line ABCD in Figure 4A, after Allcock (1982, Fig. 3). Deep drillholes are numbered. Distributions of minerals are given.

andesitic volcanic rocks, calcareous volcaniclastic rocks, and minor carbonate strata of the Quesnellia and Stikinia terranes prior to their accretion to North America in middle Jurassic time (Dawson et al., 1991). Similarities between the alkaline Copper Mountain plutonic suite and their host volcanic rocks of the eastern Nicola Assemblage suggest that they are subvolcanic equivalents (Woodsworth et al., 1991). The genetic relationship of alkaline to coeval calc-alkaline plutonic suites, and the relationship of both to the Early Jurassic tectonic regime, is not well understood. Skarn ore, which constitutes 20% (Mount Polley) to 80% (Galore Creek) of total reserves (Table 20.2-2), consists mainly of porphyry-style disseminations, vein stockworks, and breccia fillings of chalcopyrite, bornite, pyrite, and magnetite plus massive sulphide-magnetite replacements of calcareous volcanic and sedimentary units.

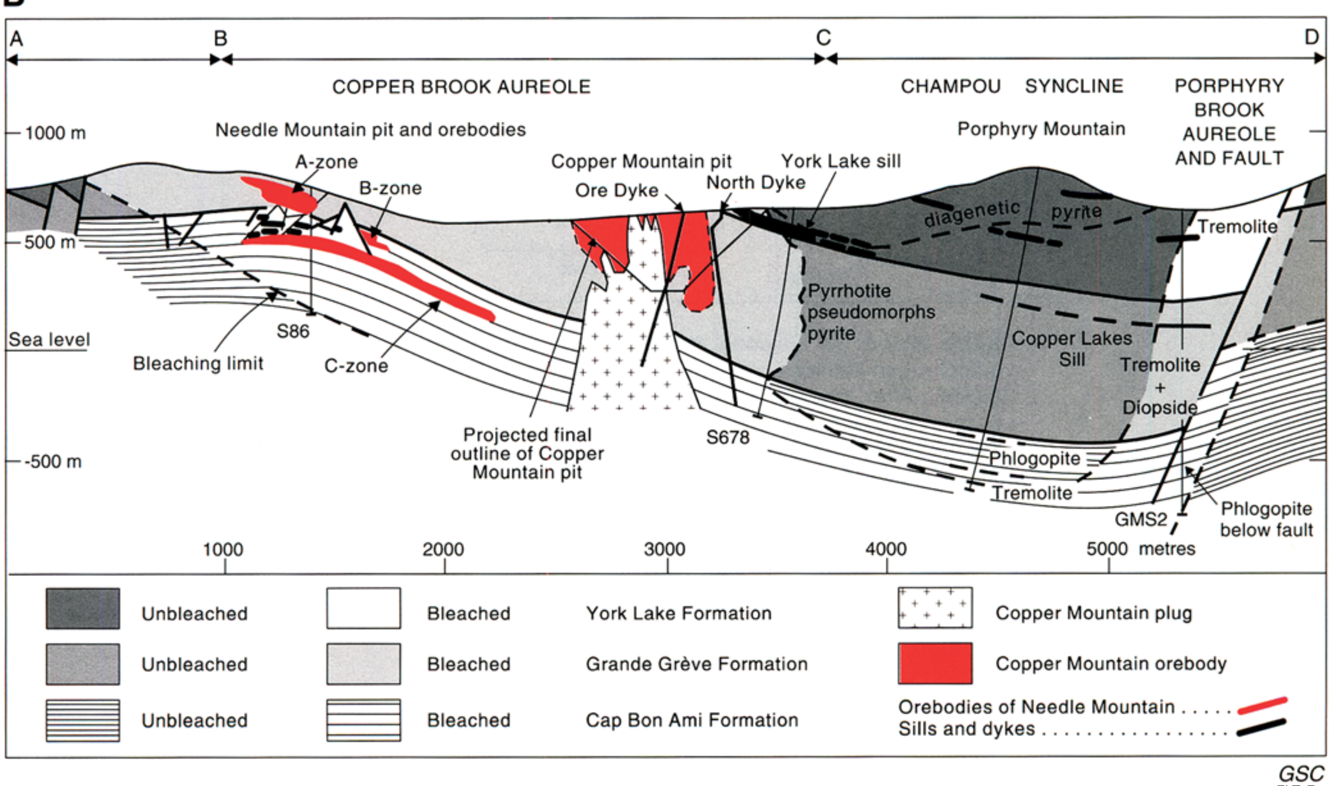
At the Ingerbelle mine, Princeton, British Columbia, Sutherland Brown et al. (1971), Preto (1972), Macauley (1973), and Fahrni et al. (1976) recognized skarn-like ore and gangue mineral zonation relative to the contact of the composite Lost Horse diorite-monzonite-syenite stock with agglomerate, tuff, tuff breccia, and sedimentary rocks of the Upper Triassic Nicola Group. Early biotite hornfels was overprinted by prograde albite-epidote-chlorite±andradite±diopsidic pyroxene±sphene; both stock and prograde skarn have been flooded by retrograde albite, K-feldspar, scapolite, calcite, and hematite. Chalcopyrite-bornite ore, about 90% of which is located in andesitic volcanic rocks, follows contacts, apophyses, and dykes of the Lost Horse intrusion. Elevated contents of Pt (about 0.15 ppm) and Pd (about 3.0 ppm) are present in sulphide concentrates from the adjacent Copper Mountain porphyry Cu-Au deposit (L.J. Hulbert, pers. comm., 1991).

At Galore Creek in northwestern British Columbia, prograde skarn copper ore, which was developed in calcareous pyroclastic, volcaniclastic, and shoshonitic (high K) volcanic rocks adjacent to contacts of pseudoleucite-phyric syenite dykes, constitutes about 80% of total ore reserves (Allen et al., 1976). Pervasive alteration assemblages of orthoclase and biotite in, or adjacent to, potassic rocks give way to calcic assemblages of zoned, anisotropic andradite, diopside, Fe-rich epidote, and vesuvianite plus chalcopyrite, bornite, pyrite, and magnetite and minor amounts of chalcocite, sphalerite, and galena, in calcareous host rocks (Fig. 20.2-6A-C). Retrograde assemblages include anhydrite, chlorite, sericite, calcite, gypsum, and fluorite.

About 20% of ore reserves at Mount Polley, in the Cariboo region of south-central British Columbia, are in copper skarn (Table 20.2-2) that developed in calcareous crystal and lapilli tuff of the Upper Triassic Takla Group adjacent to diorite, monzodiorite, and monzonite porphyry intrusions (Hodgson et al., 1976). Most of the ore is contained within several types of hydrothermal breccias (Fraser, 1994). Potassic alteration assemblages of orthoclase and biotite in, and adjacent to, the intrusions grade outward from the contacts of these intrusions and breccia contacts to prograde skarn assemblages of diopside-andradite-magnetite and peripheral propylitic assemblages of epidote-pyrite-albite. The bulk of the sulphide ore, i.e. chalcopyrite, bornite, and lesser amounts of pyrite, is associated with the retrograde assemblage carbonate, chlorite, zeolite, prehnite, epidote, and hematite.

Alkaline porphyry copper-related skarn deposits, like many calc-alkaline ones, are associated with small stocks emplaced at high levels in comagmatic volcanic sequences, with resultant intense fracturing, brecciation, and breccia pipe formation. Like calcic magnetite skarns, they are characterized by epidote-diopside-garnet endoskarn

B



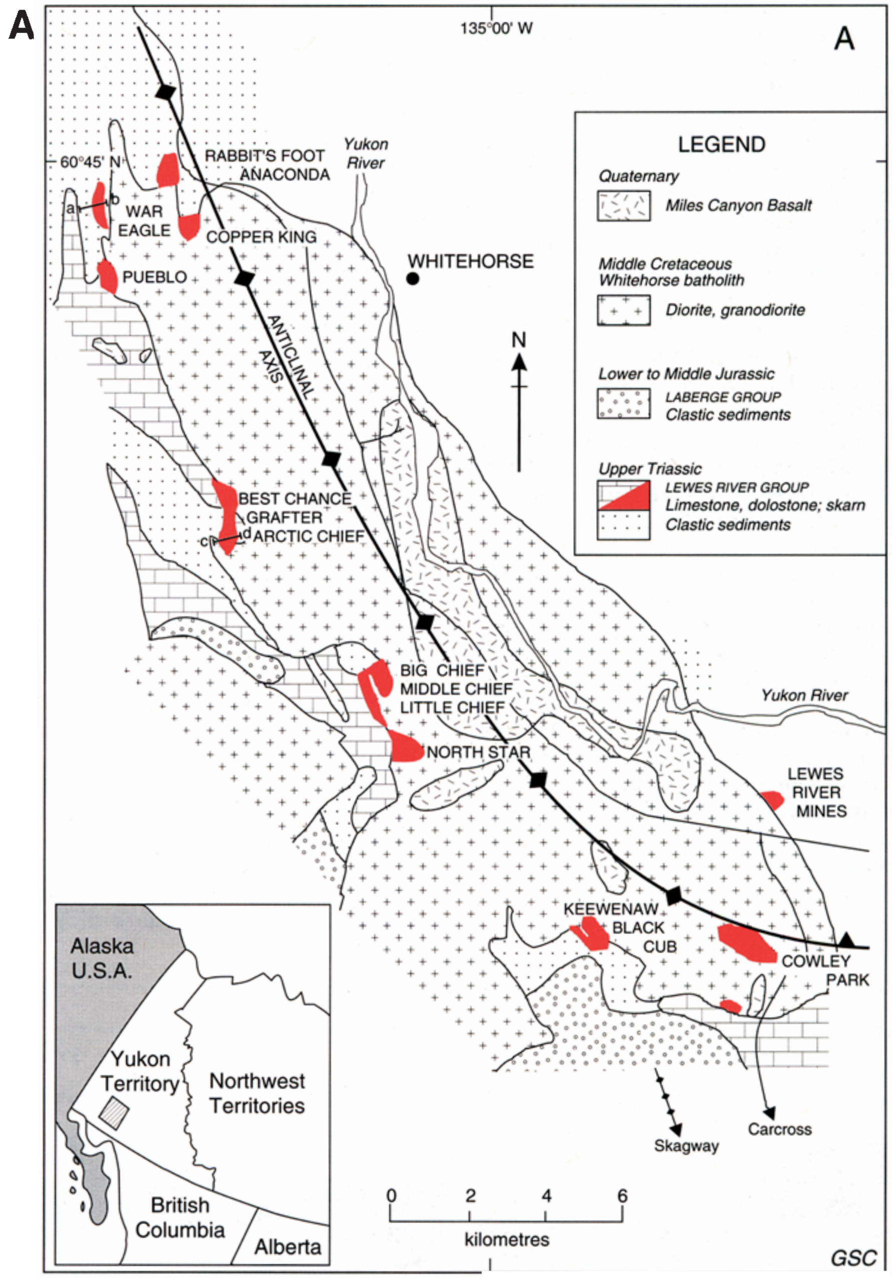
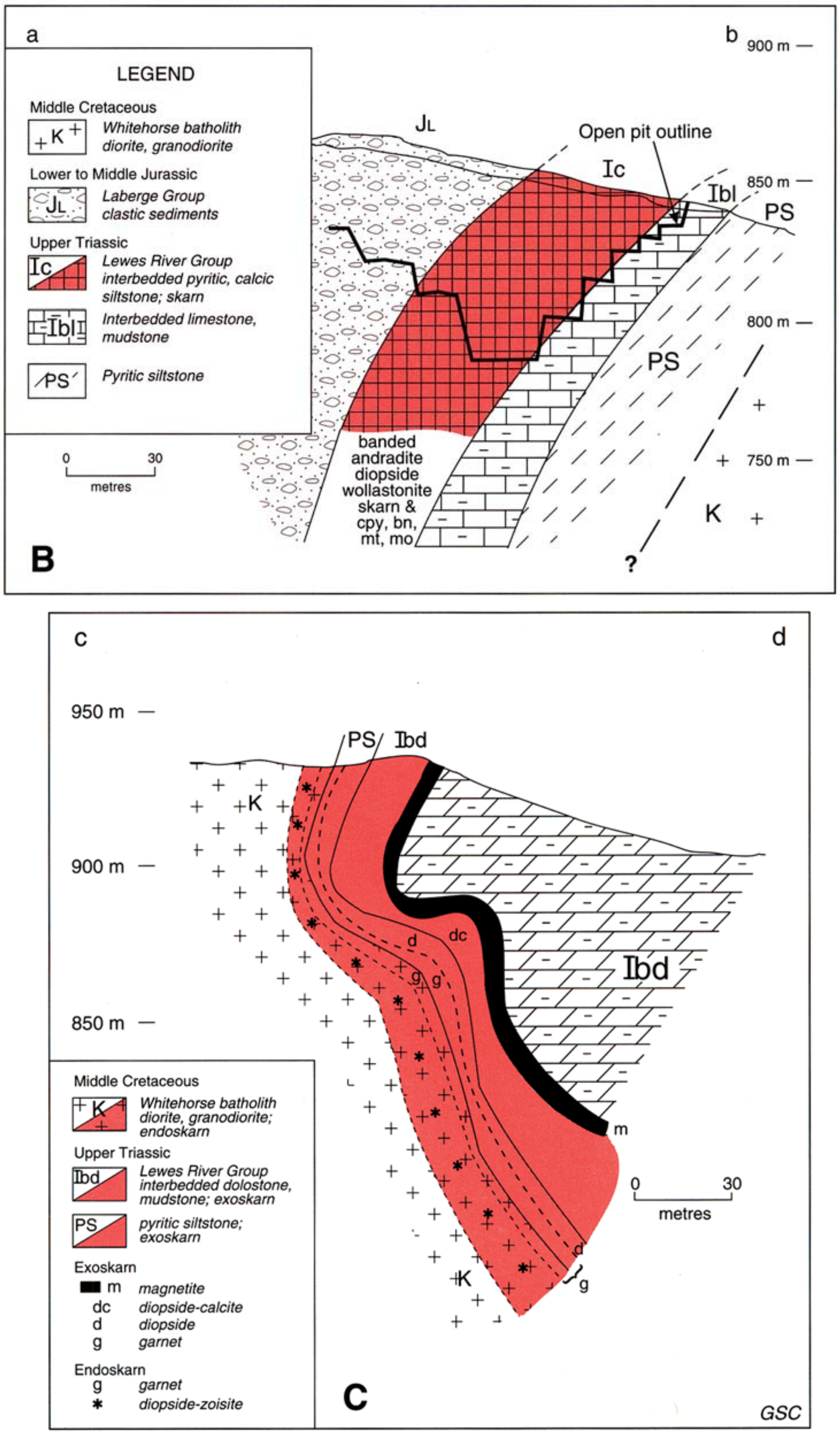


Figure 20.2-5. A) Regional geology of the Whitehorse Copper Belt; vertical cross-sections a-b and c-d are shown in Figures 20.2-5B and 20.2-5C. After Kindle (1964) and Tenney (1981). **B)** Geological cross-section (a-b) of the War Eagle calcic skarn copper deposit, looking north; cpy = chalcopyrite, bn = bornite, mt = magnetite, mo = molybdenite. After Morrison (1981) and Watson (1984). **C)** Geological cross-section (c-d) of the Arctic Chief magnesian skarn copper deposit, looking north. After Morrison (1981) and Watson (1984).


a
b
LEGEND
Middle Cretaceous
K
Whitehorse batholith
diorite, granodiorite
Lower to Middle Jurassic
JL
Laberge Group
clastic sediments
Upper Triassic
Ic
Lewes River Group
interbedded pyritic, calcic
siltstone; skarn
Ibl
Interbedded limestone,
mudstone
PS
Pyritic siltstone
0
30
metres
JL
Open pit outline
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m magnetite
dc diopside-calcite
d diopside
g garnet
Endoskarn
g garnet
* diopside-zoisite
C
GSC

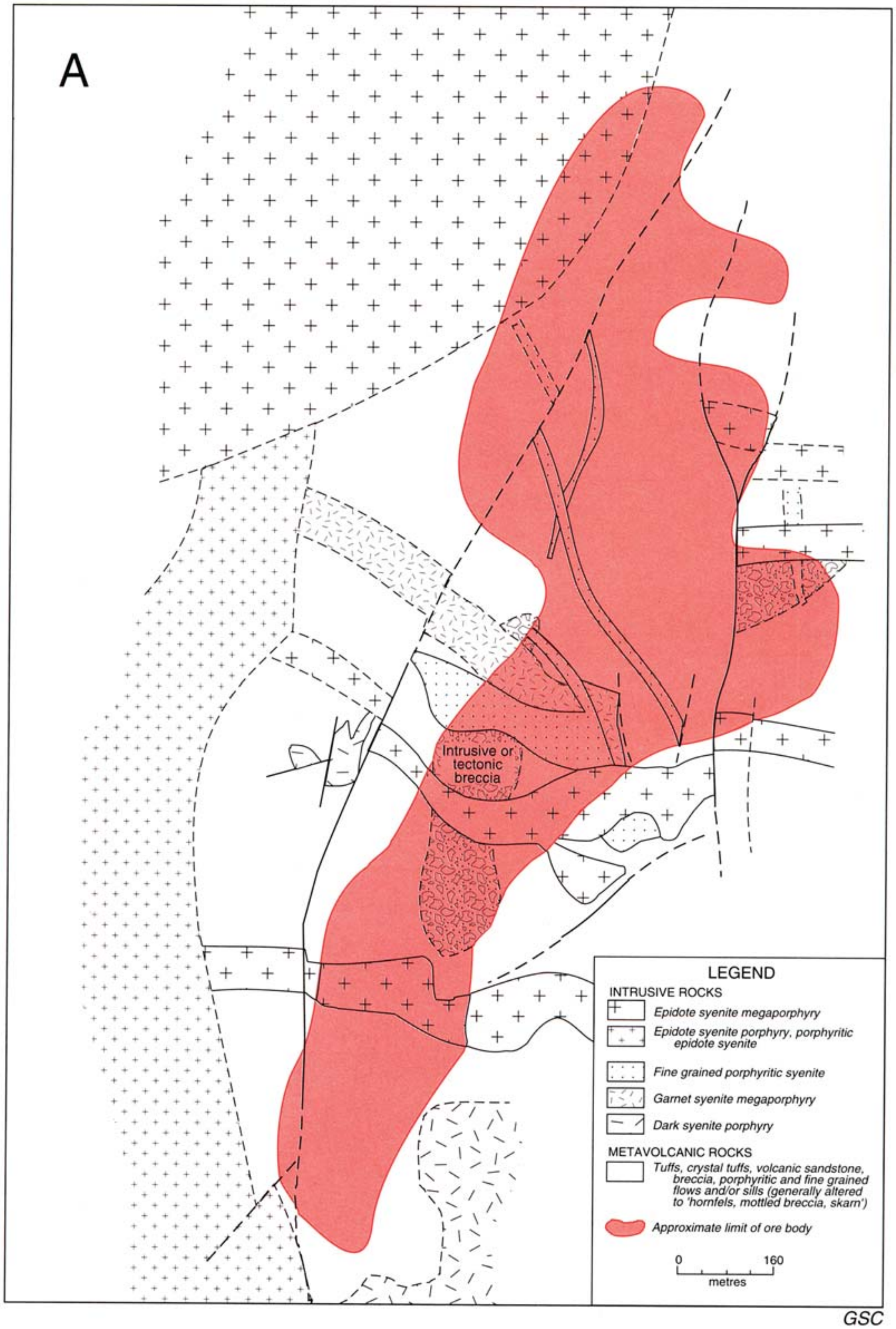
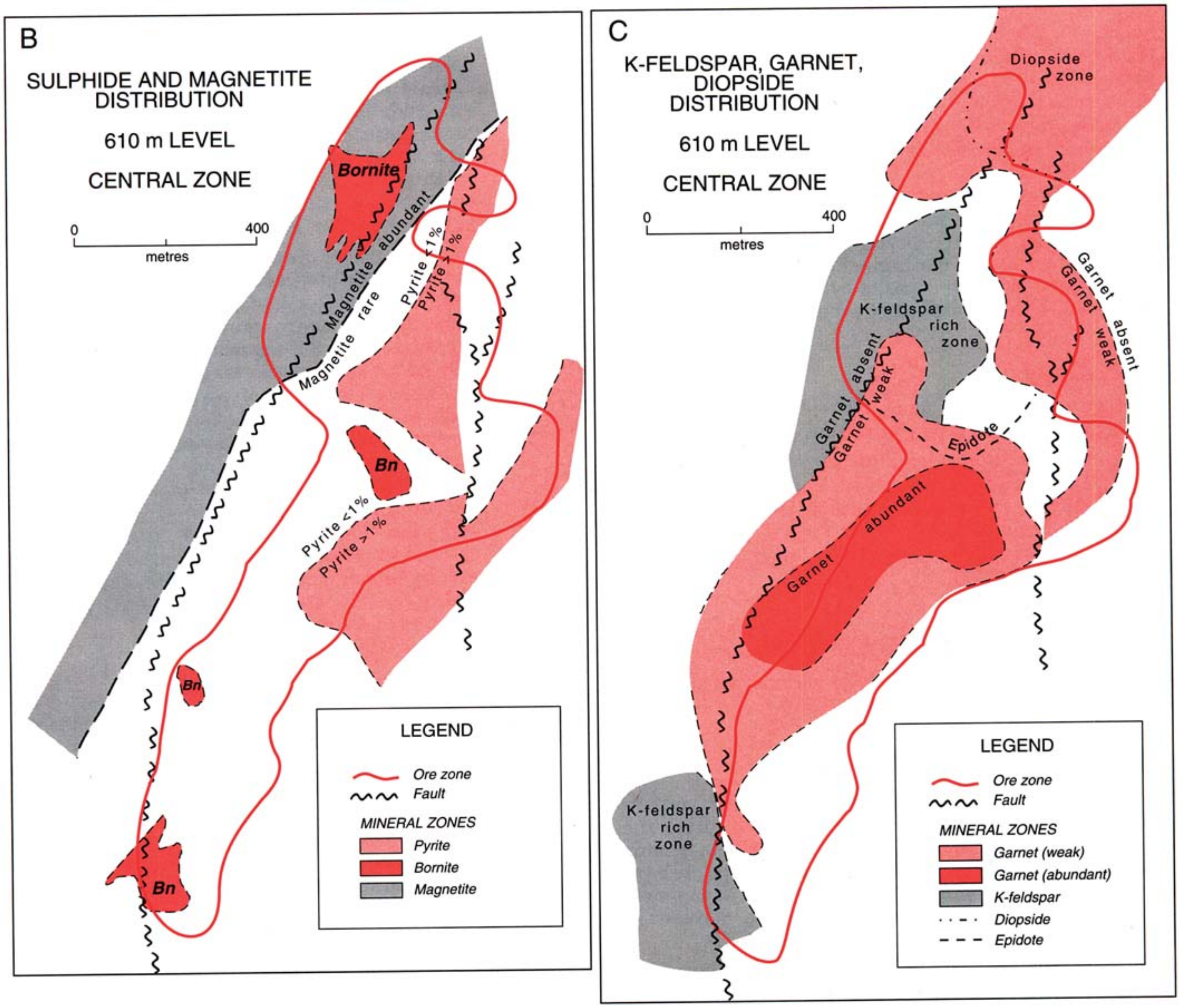


Figure 20.2-6. Galore Creek Cu, Au porphyry-skarn deposit, British Columbia (after Allen et al., 1976) **A)** generalized geology of central zone; **B)** sulphide and magnetite distribution, central zone, 610 m level. Disseminated magnetite occurs in a belt to the west and north, pyrite is mainly to the east; Bn = bornite. **C)** K-feldspar, garnet, and diopside distribution, 610 m level within the central zone. Zones rich in K-feldspar and biotite parallel the syenite dyke contacts; garnet is abundant toward the north end of the breccia pipe, and diminishes away from its contacts.



GSC

Table 20.2-3. Examples of Canadian and selected foreign skarn copper deposits, classified by plutonic association.

Pluton composition	Mineralization in pluton	
	Unmineralized intrusion related	**Porphyry-type mineralization**
Calc-alkaline	Greenwood (Phoenix) British Columbia	Gaspé Copper, Quebec
	Whitehorse Copper Belt, Yukon Territory	Craigmont, Merritt, British Columbia
	Old Sport, Coast Copper (Benson Lake) British Columbia	Ely, Nevada, U.S.A.
	Prescott, Marble Bay, Texada Island, British Columbia	Santa Rita, Arizona, U.S.A.
	Yaguki, Japan	Ertsberg, Irian Jaya, Indonesia
	Sayak 1, Kazakhstan	Gold Coast (Ok Tedi), Papua New Guinea
	Conception del Oro, Mexico	
	Rosita, Honduras	
	Memé, Haiti	
Alkaline		Galore Creek (Stikine Copper) British Columbia
		Ingerbelle (Copper Mountain), Princeton, British Columbia
		Larap, Philippines

within the intrusion, extensive prograde and retrograde potassic (K-feldspar, biotite) and sodic (albite, scapolite) metasomatic alteration, plus a ferric iron-rich, magnesium-poor bulk skarn composition. The most notable compositional characteristics are overall deficiency in silica, elevated contents of Au, Ag, and platinum group elements in the ore (Mutschler and Mooney, in press), and lack of peripheral Pb and Zn sulphides. Like their associated porphyry deposits, alkaline porphyry copper-related skarn deposits are readily distinguished from calc-alkaline porphyry-related skarn deposits by elevated Ag contents, i.e., mean of 4.15 g/t versus 1.66 g/t (Sinclair et al., 1982).

Mineralogy

Principal ore minerals: chalcopyrite, bornite, magnetite, molybdenite, electrum, gold, silver.

Subsidiary ore minerals: platinum group elements, sphalerite, galena, scheelite, Au and Ag tellurides, Ag sulphosalts, tetrahedrite, cobaltite, wittichenite, bismuth, bismuthinite.

Other opaque minerals: pyrite, pyrrhotite, arsenopyrite, marcasite, hematite.

DEFINITIVE CHARACTERISTICS

The definitive characteristics of the various skarn copper subtypes are summarized in Table 20.2-4.

GENETIC MODEL

Copper, molybdenum, associated metals, sulphur, and cations other than calcium were derived mainly from the associated pluton by the separation of an orthomagmatic hydrothermal fluid. All types of skarn copper deposits have the following three main evolutionary stages in common; these stages are similar to those for skarn deposits in general, which are represented in Figure 20.2-7:

Stage 1: Isochemical thermal metamorphism of limestone to marble, calcareous pelite to calc-silicate hornfels, and clastic and volcaniclastic rocks to biotite hornfels accompanies the intrusion of magma into upper levels of the crust (Fig. 20.2-7A).

Stage 2: The main stage of prograde skarn formation begins as the crystallizing magma releases hydrothermal fluid through conduits developed by hydrofracturing of the crystallized outer portion of the pluton and hornfels. Some mixing of this hydrothermal fluid with metamorphic fluids can occur, but the degree to which metals and sulphur, derived by the metamorphic dehydration of the host rock, contribute to the skarn assemblage is not known, but is probably minor. Fluids infiltrate the host rock along plutonic and dyke contacts, fractures, breccias, and lithological contacts, to react with either the calcareous host rock, marble, or calc-silicate hornfels to form prograde anhydrous skarn. Endoskarn forms in the pluton by introduction of calcium from the host rock. Calcic exoskarn forms in limestone and calcareous sedimentary rocks, and magnesian exoskarn forms in dolostones. The mineral assemblage of the resultant skarn is influenced by the composition, temperature, and oxidation state of the system. Stage 2 anhydrous skarn is deficient in copper and sulphur, and later skarn stages are enriched in ferric iron and sulphur and depleted in magnesium. Deposition of most magnetite and sulphide minerals starts late in this stage (Fig. 20.2-7B).

Stage 3: The main period of sulphide deposition follows the termination of prograde anhydrous skarn development and accompanies the start of hydrous alteration of early skarn minerals and associated intrusive rocks. Subsequent cooling of the system and influx of meteoric water initiates hydrous retrograde alteration of early calcium-rich silicates to silicates more depleted in calcium, plus iron oxides, carbonates, and plagioclase. Processes occurring at this stage include hydrolytic alteration of rocks and deposition of most sulphides, including some redistribution of earlier-formed sulphides. The assemblage of opaque minerals associated with hydrous retrograde alteration reflects higher oxidation and sulphidation states and lower temperatures than do early prograde opaque minerals (Fig. 20.2-7C).

RELATED DEPOSIT TYPES

1. Skarn gold: Most types of skarn copper deposits are enriched in gold to some degree and, with increasing Au content, will grade into gold skarn deposits. Skarn copper proximal to a copper mineralized porphyry stock at Copper Canyon, Nevada passes laterally to Au-Ag skarns at the Lower and Upper Fortitude and Minnie-Tomboy deposits (Blake et al., 1984; Wotruba et al., 1988).
2. Calc-alkaline and alkaline porphyry copper deposits: Significant porphyry copper deposits with related Cu skarn deposits include Grasberg and Ertsberg, Irian Jaya, Indonesia (MacDonald and Arnold, 1993), and Mount Fubilan and Gold Coast, Ok Tedi district, Papua New Guinea (Hewitt et al., 1980). Several large skarn copper deposits associated with porphyry copper deposits in southwestern United States have been documented by Einaudi (1982).
3. Skarn iron: Copper skarns associated with unmineralized stocks unrelated to porphyry copper deposits share a common plutonic association and tectonic setting with, and may pass laterally into, calcic magnetite, magnetite-copper, and magnetite-gold skarns. Canadian examples include Phoenix, Whitehorse Copper Belt, Benson Lake, and Texada Island.

EXPLORATION GUIDES

Copper skarns associated with calc-alkaline porphyry copper deposits

Geological guides

a) Extensive skarn and hornfels zones adjacent to exposed copper-bearing porphyry stocks, or overlying buried ones.

b) Relatively thick, pure and impure limestone beds in a craton-marginal setting.

c) Stockwork fractures, breccias, and breccia pipes adjacent to porphyry copper stocks.

d) Potassic and sericitic alteration of stocks that contain disseminated Cu- and Mo- sulphides.

Geochemical guides

a) In general, geochemical prospecting techniques, i.e. media, elements analyzed for, sample spacing, etc. are similar to those employed in porphyry Cu exploration.

b) Hydromorphic dispersion from blind orebodies commonly causes proximal anomalies in Mo, Pb, W, and Au, and distal anomalies in Cu, Zn, Ag, As, and Sb.

Geophysical guides

a) Plutonic contacts and common magnetite association with skarn generate strong magnetic anomalies.

b) Relatively massive skarn sulphide mineralization peripheral to disseminated porphyry-style copper-iron sulphides generates an enhanced induced potential and electromagnetic response.

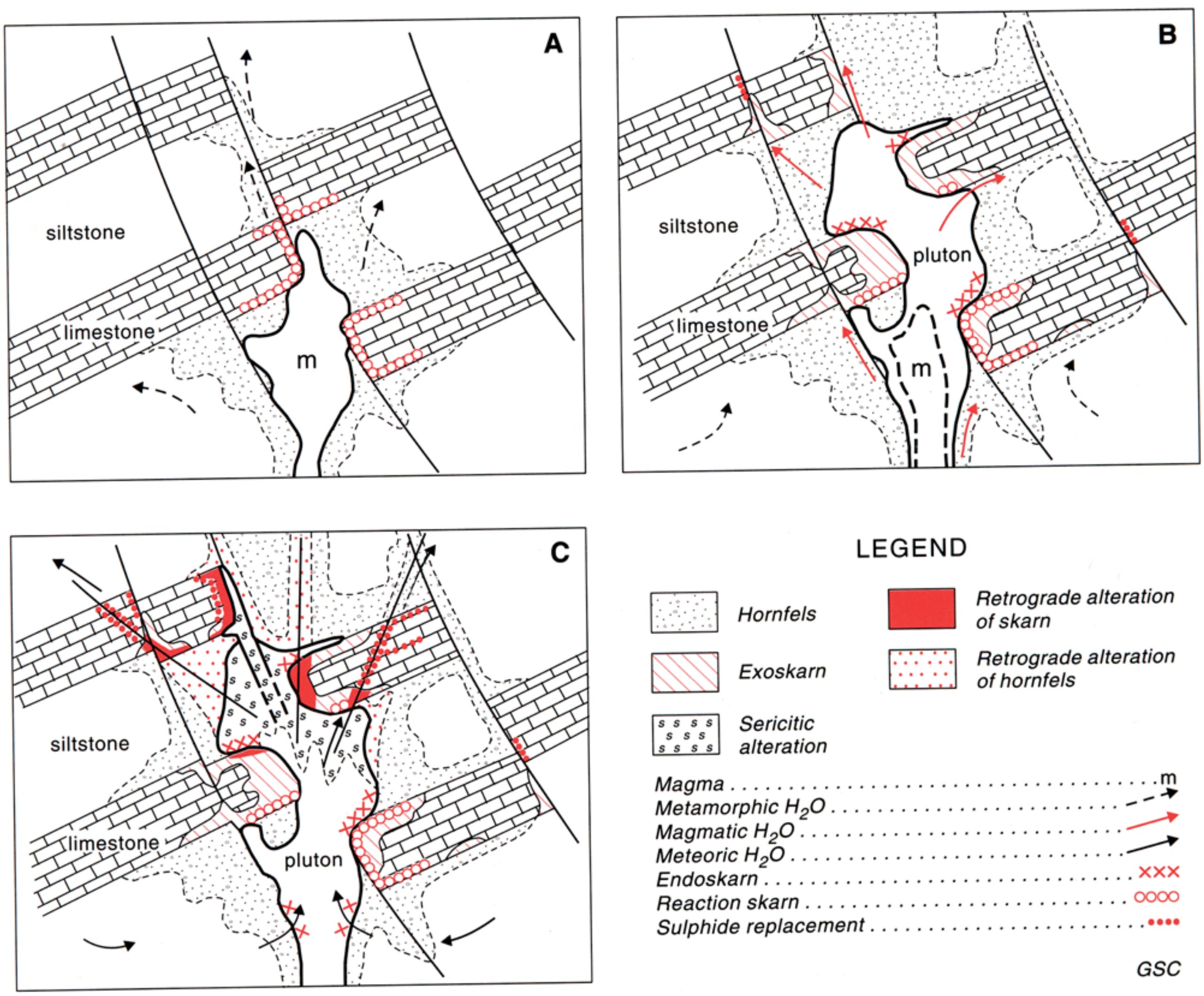


Figure 20.2-7. Stages of evolution of skarn deposits (after Einaudi et al., 1981, Fig. 4). **(A)** Magma emplacement; dehydration; thermal metamorphism; reaction skarn formation. **(B)** Crystallization and magmatic fluid separation; stratigraphically and structurally controlled exoskarn formation; endoskarn formation locally in pluton; peripheral replacement. **(C)** Cooling, meteoric water influx; retrograde alteration of pluton, hornfels and skarn; structurally and stratigraphically controlled sulphide-silica-carbonate replacement.

Table 20.2-4. Definitive characteristics of skarn copper deposits.

SKARN COPPER SUBTYPE	DEFINITIVE CHARACTERISTICS
Skarn Cu associated with calc-alkaline porphyry Cu-related intrusions	Disseminated Cu, Mo mineralization in altered intrusion; high fracture permeability; breccia pipes; thick and extensive skarn; low Au grade; late stage sericite-clay and silica-pyrite alteration; peripheral Zn, Pb mineralization.
Skarn Cu associated with unmineralized nonporphyry Cu-related intrusions	Lack of disseminated Cu, Mo mineralization in relatively small, mafic, unaltered intrusion; massive sulphide orebody relatively rich Cu, Au, and Ag; restricted zones of retrograde alteration.
Skarn Cu associated with alkaline porphyry Cu-Au stocks	Low Mo content in intrusion; low silica in total system; high Au, Ag, and PGE content of ore; sodic and potassic alteration of skarn and intrusion; intrusive breccias and breccia pipes; high magnetite content; limestone host rocks minor to absent

Copper skarns associated with unmineralized stocks unrelated to porphyry copper deposits

Geological guides

a) In the northern part of the North American Cordillera, all examples of this subtype, including the important districts of Greenwood, British Columbia and Whitehorse Copper Belt, Yukon Territory are hosted by Upper Triassic-Jurassic accreted oceanic-arc terranes.

b) Irregularities in pluton-limestone contacts, particularly re-entrants and troughs, tend to serve as structural control.

c) Highest copper and precious metal concentrations frequently occur within structurally controlled zones that have the most intense retrograde alteration.

Geochemical guides

a) Guides are the same as for calc-alkaline porphyry Cu-related skarns, with the addition of Co to the element suite analyzed for, particularly in the case of magnetite-rich Cu skarns.

Geophysical guides

a) The almost ubiquitous association of copper sulphides with magnetite yields strong magnetic anomalies.

b) Lack of disseminated or stockwork sulphides in associated stocks reduces induced potential response.

c) Massive morphology and high chalcopyrite content relative to that of porphyry copper-related skarns generates a strong electromagnetic response.

Skarn copper associated with alkaline porphyry copper deposits

Geological guides

a) Silica-deficient, magnetite-rich composite alkaline intrusions.

b) Limestone deficient, alkaline to subalkaline members of volcanic, volcaniclastic, and clastic sedimentary assemblages in accreted Upper Triassic to Lower Jurassic oceanic-arc terranes in the Canadian Cordillera.

c) Magnetite breccias, breccia pipes, and dykes, with and without associated copper sulphides.

d) Extensive potassic and sodic alteration of the pluton, skarn, and hornfels; sericitic alteration weak to absent; distal Zn and Pb mineralization weak to absent.

Geochemical guides

a) Guides the same as for calc-alkaline porphyry Cu-related skarns, except for a reduced Mo anomaly over the stock and skarn.

Geophysical guides

a) Disseminated magnetite-rich mineral assemblage in the stock demonstrates higher magnetic susceptibility than that of calc-alkaline stocks.

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20.3 SKARN GOLD

K.M. Dawson

IDENTIFICATION

Skarns which contain sufficient gold to be mined economically for that commodity alone, herein termed 'Au skarns', have several common characteristics distinct from other types of Au-bearing skarns. Characteristics of four additional subtypes of skarn deposits, from which byproduct or coproduct Au is recovered, as proposed by Meinert (1988), are outlined below, with examples. Another approach to classification of productive gold-bearing skarn deposits was taken by Orris et al. (1987). They subdivided deposits with 1 ppm gold or more into "gold skarns" and "byproduct-gold skarns", depending upon the primary commodity recovered. A similar approach was taken by Theodore et al. (1991). Tonnage, grade, and subtype classification for significant Canadian and foreign gold skarn deposits are listed in Table 20.3-1. Grades versus tonnages are plotted in Figure 20.3-1. The locations of significant deposits in the Canadian Cordillera are shown in Figure 20.3-2.

Gold skarns, relative to other Au-bearing skarns, in addition to having a relatively high Au grade, are rich in As, Bi, and Te, are deficient in base metals, are dominated by reduced and Fe-rich gangue minerals, including Fe-rich pyroxene and lesser grandite garnet, have a higher clastic component in their host rocks, and are associated with intrusions of more mafic character. Canadian Cordilleran examples, including Hedley, Quesnel River, Dividend-Lakeview, and Tillicum Mountain, are hosted by mainly Upper Triassic volcanic arc lithologies of the accreted Quesnellia terrane, and are associated with Lower to mid-Jurassic dioritic intrusions. Large foreign examples include the Fortitude mine at Battle Mountain, Nevada (Wotruba et al.,1986); McCoy Creek mine, Lander County, Nevada (Lane, 1987); and the Crown Jewel at Buckhorn Mountain, Washington (Hickey, 1992).

Gold-bearing skarns associated with porphyry Cu deposits, compared to other gold-bearing skarns, are relatively large, low in Au grade, and rich in andraditic garnet, diopsidic pyroxene, disseminated Cu sulphides, magnetite, and hematite. Gold occurs with sulphides either in prograde skarn or in zones of intense retrograde alteration. The large copper-gold skarns associated with alkalic porphyry deposits at Ingerbelle (Princeton) and Galore Creek, British Columbia are the most significant Canadian examples (see subtype 20.2, "Skarn copper"). Large foreign deposits of this type include Carr Fork, Bingham, Utah (Cameron and Garmoe, 1987); the Ely district, Nevada (James, 1976); Ok Tedi, Papua New Guinea (Davies et al., 1978); and the Red Dome or Mungana mine at Chillagoe, Queensland, Australia (Torrey et al., 1986; Ewers and Sun, 1988).

Copper-gold skarns are distinguished from porphyry Cu-Au skarns mainly by the lack of disseminated Cu-Mo minerals in the generally more mafic associated intrusion, and also by the smaller size, more massive nature, and higher Au grade of the orebodies. Copper-gold skarns in the North American Cordillera are associated, to varying degrees, with calcic Fe skarns. In the Intermontane Belt of British Columbia, magnetite is only a common component

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Table 20.3-1. Tonnage, grade, and subtype of significant Canadian and foreign gold and gold-rich skarn deposits, listed in decreasing order of contained Au. Skarn subtypes are after Meinert (1988).

	Name	Location	Ore (10^6t)	Average grade g/t Au	Subtype	Reference source
Canadian deposits						
1	Hedley (Nickel Plate)	B.C.	8.4	7.3	Au	Ray et al., 1993
2	Greenwood district	B.C.	31.8	1.1	Cu-Au	Church, 1986
3	Ingerbelle	B.C.	216	0.16	porCu-Au*	Fahrni et al., 1976
4	Whitehorse Copper Belt	Y.T.	~10	1.0	Cu-Au	Meinert, 1986
5	Ketza River district	Y.T.	0.7	13	Au	Canamax Resources Inc., Annual Report, 1987
6	Tillicum Mountain district	B.C.	2.9	2.7	Au	Esperanza Explorations Ltd., 1989
7	Quesnel River (QR)	B.C.	1.0	6.5	Au	Fox et al., 1987
8	Benson Lake (Coast Copper)	B.C.	2.7	1.4	Cu-Au	Sangster, 1969
9	Marble Bay (Texada Iron)	B.C.	0.3	7.9	Fe-Au	Ettlinger and Ray, 1988
10	Banks I. (Tel, etc.)	B.C.	0.14	16.4	Au	Ettlinger and Ray, 1988
11	Tasu (Wesfrob)	B.C.	~18	0.1	Fe-Au	Sutherland Brown, 1968
12	Dividend-Lakeview	B.C.	0.11	4.5	Au	McKechnie, 1964
13	Galore Creek	B.C.	90	0.4	porCu-Au	Allen et al., 1976
14	Mount Polley	B.C.	10	0.55	porCu-Au	Imperial Metals Corp., Annual Report, 1991
Foreign deposits						
15	Carr Fork (Bingham)	Utah, U.S.A.	400	0.6	porCu-Au	Cameron and Garmoe, 1987
16	Ok Tedi (Mt. Fubilan)	Papua New Guinea	265	0.65	porCu-Au	Davies et al., 1978
17	Ely district	Nevada, U.S.A.	339	0.3	porCu-Au	James, 1976
18	Fortitude	Nevada, U.S.A.	10.3	6.9	Au	Wotruba et al., 1986
19	Santa Rita	New Mexico, U.S.A.	350	0.2	porCu-Au	Neilson, 1970
20	Bisbee	Arizona, U.S.A.	120	0.5	porCu-Au	Bryant and Metz, 1966
21	Red Dome	Australia	15	2.6	porCu-Au	Ewers and Sun, 1988
22	Larap	Philippines	20	1.2	Fe-Au	Frost, 1965
23	Salsigne	France	1.5	13	Au	Reynolds, 1965
24	Christmas	Arizona, U.S.A.	80	0.2	porCu-Au	Koski and Cook, 1982
25	McCoy Creek	Nevada, U.S.A.	8.6	1.7	Au	Lane, 1987
26	Minnie-Tomboy	Nevada, U.S.A.	3.9	2.8	Au	Blake et al., 1984
27	Mission	Arizona, U.S.A.	100	0.1	porCu-Au	Einaudi, 1982
28	Continental	New Mexico, U.S.A.	47	0.2	porCu-Au	Einaudi, 1982
29	Copper Canyon	Nevada, U.S.A.	10	0.8	porCu-Au	Blake et al., 1978
30	Naica	Mexico	20	0.4	Zn-Pb-Au	Clark et al., 1986
31	Zackly	Alaska, U.S.A.	1.25	6	Cu-Au	Nokleberg et al., 1988
32	Mount Biggenden	Australia	0.5	15	Au	Clarke, 1969
33	Cable	Montana, U.S.A.	1	6	Au	Earli, 1972
34	Yaguki	Japan	1.2	3	Cu-Au	Shimazaki, 1969
35	Concepcion del Oro	Mexico	25	0.6	Cu-Au	Megaw et al., 1988
36	El Mochito	Honduras	15.5	0.1	Zn-Pb-Au	Shultz and Hamann, 1977
37	La Luz	Nicaragua	16	4.1	porCu-Au	Sillitoe, 1983
38	Bau	Malaysia	2.4	7.2	Au	Wolfenden, 1965
39	Crown Jewel	Washington, U.S.A.	6.5	5.6	Au	Hickey, 1992
40	Siana	Philippines	5.4	5.1	Au	Orris et al., 1987

*porCu-Au = porphyry copper-gold

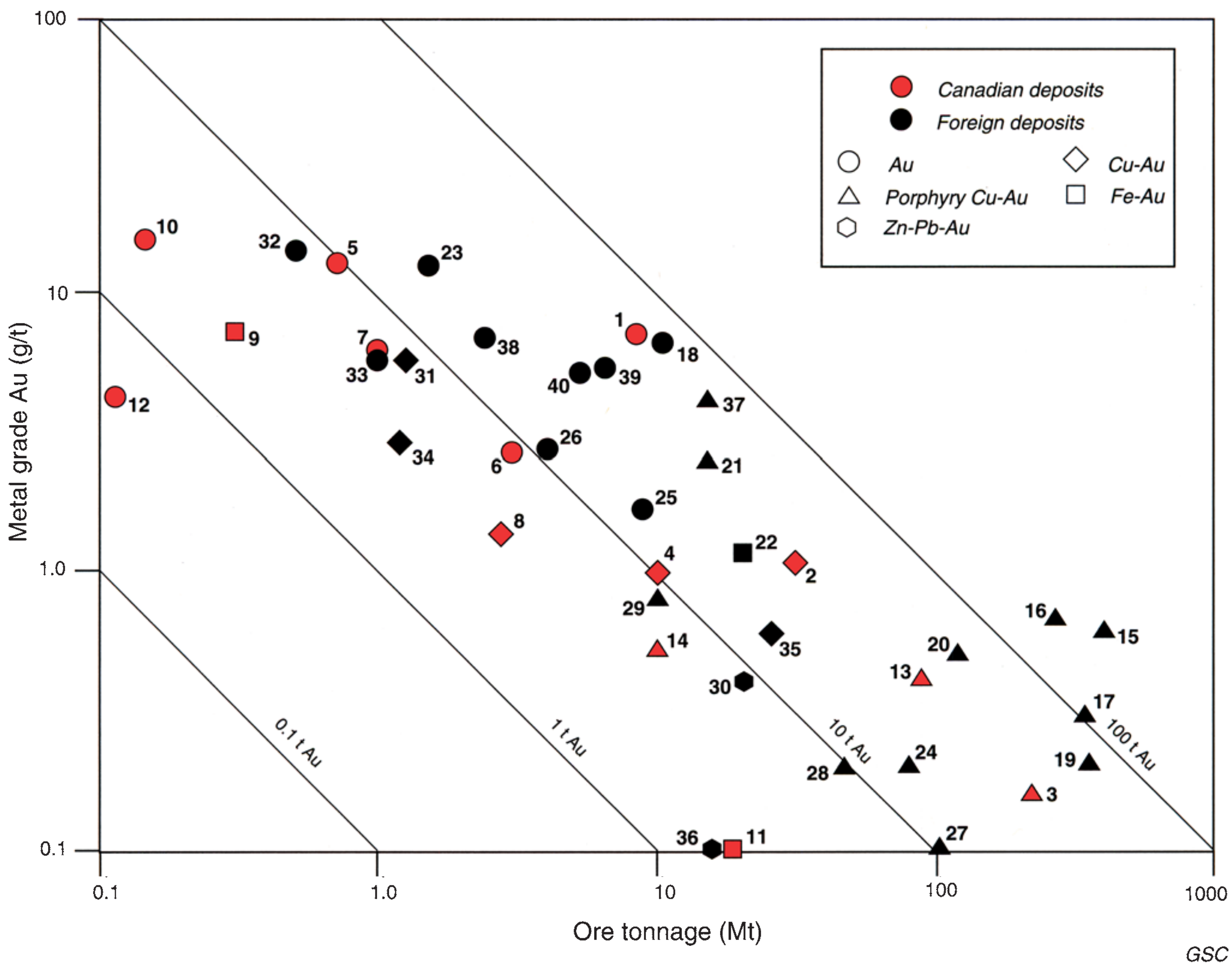


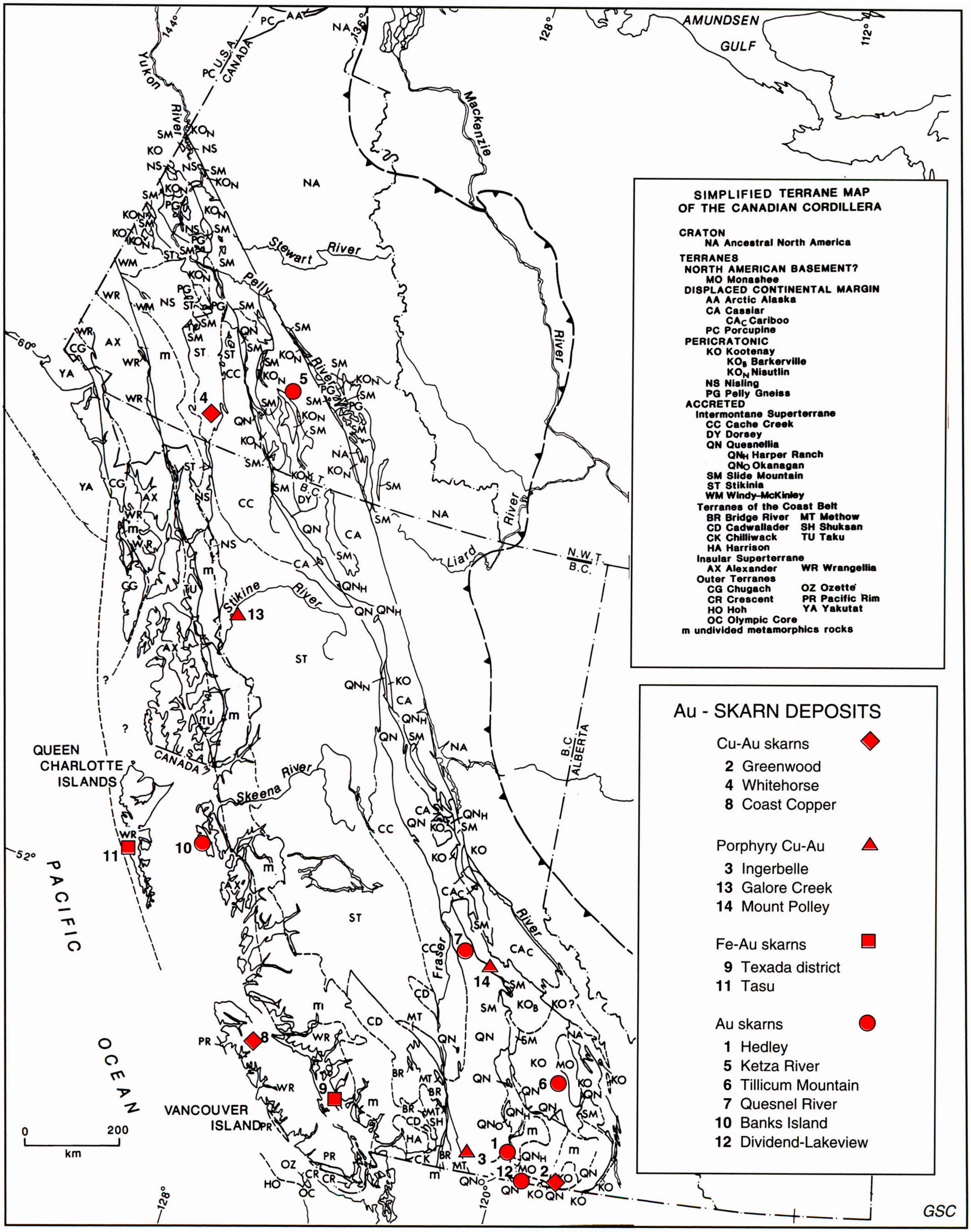
Figure 20.3-1. Grade versus tonnage of significant Canadian and foreign gold skarn and gold-rich skarn deposits. Numbers correspond to deposits listed in Table 20.3-1.

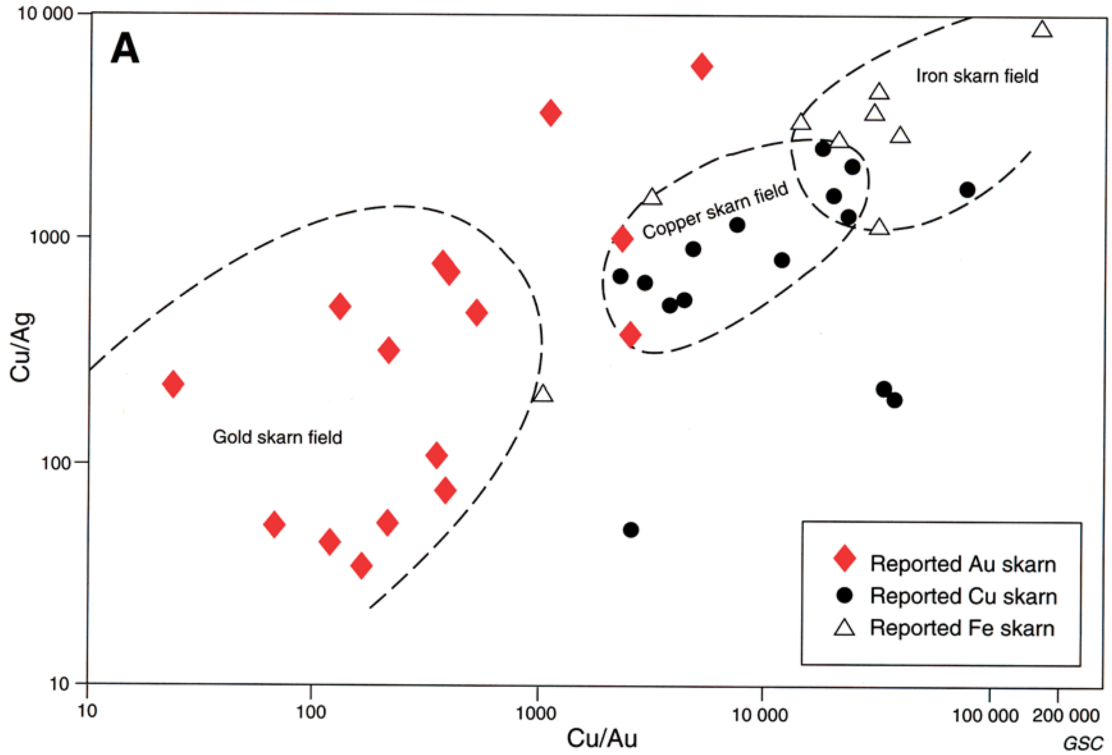
of the Cu-Au skarn mineral assemblage, whereas in the Insular Belt Cu-Au skarns are associated with large calcic magnetite skarn deposits. Almost all deposits of this kind in the northern North American Cordillera, including those in the important districts of Greenwood, British Columbia and the Whitehorse Copper Belt, Yukon Territory, as well as smaller deposits in the Insular Belt, associated with the Nelson batholith in southeastern British Columbia, and in Alaska, are hosted by Upper Triassic to Lower Jurassic carbonate-clastic-volcanic assemblages within accreted oceanic-arc terranes. Foreign examples include Yaguki, Japan (Shimaziki, 1969) and Concepcion del Oro, Mexico (Megaw et al., 1988)

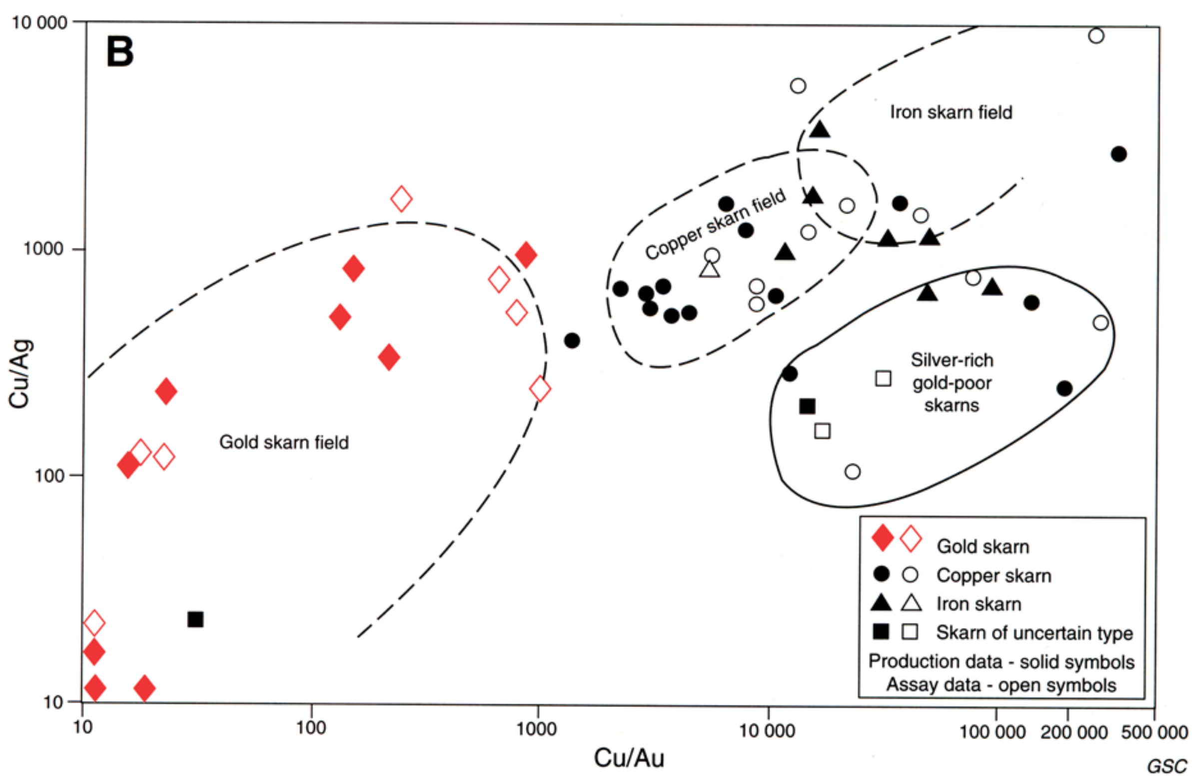
Iron-gold skarns are associated with large calcic magnetite skarns mined primarily for their Fe content, but with significant byproduct Au and Cu. Gold, with Co and As, is concentrated with erratically distributed Fe and Cu sulphides, rather than with the Fe oxides. Canadian examples include Merry Widow (Ettlinger and Ray, 1989), Texada Iron (Lake, Paxton, Prescott, Yellow Kid; Ettlinger and Ray, 1988), and Tasu (Sutherland Brown, 1968); and the Oro Denoro and Emma deposits of the Greenwood district (Church, 1986). Foreign deposits include Larap, Philippines (Frost, 1965) and Nabesna and Rambler deposits, Alaska (Nokleberg et al., 1988).

Zinc-lead skarns and related replacement deposits are more commonly enriched in Ag than in Au. However, three northern Cordilleran Ag-Pb-Zn skarn and replacement deposits, i.e., Midway, YP, and Roy, contain important minor values in Au, mainly in proximal skarn and mantos. Two British Columbia Au skarns, the Dividend-Lakeview and Banks Island, contain substantial amounts of Pb and

Figure 20.3-2. Significant skarn gold deposits of the Canadian Cordillera. Numbered symbols correspond to those in Figure 20.3-1 and Table 20.3-1.


SIMPLIFIED TERRANE MAP
OF THE CANADIAN CORDILLERA
CRATON
NA Ancestral North America
TERRANES
NORTH AMERICAN BASEMENT?
MO Monashee
DISPLACED CONTINENTAL MARGIN
AA Arctic Alaska
CA Cassiar
CA_C Cariboo
PC Porcupine
PERICRATONIC
KO Kootenay
KO_B Barkerville
KO_N Nisutlin
NS Nisling
PG Pelly Gneiss
ACCRETED
Intermontane Superterrane
CC Cache Creek
DY Dorsey
QN Quesnellia
QN_H Harper Ranch
QN_O Okanagan
SM Slide Mountain
ST Stikinia
WM Windy-McKinley
Terranes of the Coast Belt
BR Bridge River
MT Methow
CD Cadwallader
SH Shuksan
CK Chilliwack
TU Taku
HA Harrison
Insular Superterrane
AX Alexander
WR Wrangellia
Outer Terranes
CG Chugach
OZ Ozette
CR Crescent
PR Pacific Rim
HO Hoh
YA Yakutat
OC Olympic Core
m undivided metamorphics rocks
Au - SKARN DEPOSITS
Cu-Au skarns
2 Greenwood
4 Whitehorse
8 Coast Copper
Porphyry Cu-Au
3 Ingerbelle
13 Galore Creek
14 Mount Polley
Fe-Au skarns
9 Texada district
11 Tasu
Au skarns
1 Hedley
5 Ketza River
6 Tillicum Mountain
7 Quesnel River
10 Banks Island
12 Dividend-Lakeview
AMUNDSEN GULF
Mackenzie River
Yukon River
Stewart River
Pelly River
Liard River
Stikine River
Skeena River
Fraser River
QUEEN CHARLOTTE ISLANDS
VANCOUVER ISLAND
PACIFIC OCEAN
U.S.A. CANADA
N.W.T. B.C.
B.C. ALBERTA
0 200 km
GSC


A
Cu/Ag
Cu/Au
10 000
1000
100
10
10
100
1000
10 000
100 000
200 000
Gold skarn field
Copper skarn field
Iron skarn field
Reported Au skarn
Reported Cu skarn
Reported Fe skarn
GSC


B
Cu/Ag
Cu/Au
10 000
1000
100
10
10
100
1000
10 000
100 000
200 000
500 000
Gold skarn field
Copper skarn field
Iron skarn field
Silver-rich gold-poor skarns
Gold skarn
Copper skarn
Iron skarn
Skarn of uncertain type
Production data - solid symbols
Assay data - open symbols
GSC

Zn. Large foreign gold-rich Zn-Pb-Ag skarn and replacement deposits include Naica, Mexico (Clark et al., 1986) and El Mochito, Honduras (Shultz and Hamann, 1977).

A method of classifying gold and gold-bearing skarns on the basis of Cu:Au and Cu:Ag ratios, proposed by Ettlinger and Ray (1989), broadly differentiates gold skarns from gold-bearing copper and iron skarns. Figure 20.3-3A, a plot of Cu:Au versus Cu:Ag for a database of 40 international skarn deposits, and Figure 20.3-3B, the same plot of 54 precious metal-enriched British Columbia skarns, show the same well differentiated fields, with gold skarns having Cu:Au values less than 1000, copper skarns 2000-25 000, and iron skarns 20 000-160 000. In addition, in Figure 20.3-3B, silver-rich, gold-poor skarns with affinities for Zn-Pb skarns plot in a separate field.

IMPORTANCE

Meinert (1988) estimated that production from all known Au skarn deposits totals about 1000 t Au. This represents about 1% of Boyle's (1979) estimate of total historical Au production up to 1975. Statistics on global Au production from skarns relative to other types of Au deposits are not readily available. However, Ray and Webster (1991) noted that precious metal-enriched skarns in British Columbia have produced about 10% of the world total: 49 skarn deposits have produced 95 t Au and 342 t Ag. Significant production has been attained from four active and several previously-producing Au skarns in the Canadian Cordillera. The economic significance of Au skarn deposits in the Cordillera has been emphasized by the redevelopment, in 1987, of the large Nickel Plate deposit at Hedley as an open pit mine, commencement of production, in 1987, of the Ketza River and Tillicum Mountain deposits, and exploration activity centred on numerous skarn Au prospects, as summarized by Ettlinger and Ray (1988). High-grade gold skarn deposits at Fortitude and McCoy, Copper Canyon district, Nevada, and Crown Jewel, Buckhorn district, Washington have been documented by Wotruba et al. (1986) and Hickey (1992), respectively.

SIZE OF DEPOSIT

Meinert (1988) has compiled data on 69 globally-distributed Au-bearing skarn deposits, as reproduced in Table 20.3-2.

The six Au skarns cited for the Canadian Cordillera in Table 20.3-1 range widely in tonnage and Au grade, but the calculated average of 2.6 Mt of 9.3 g/t Au is similar to the global average. The four Canadian Cu-Au skarns are larger than the global average, but lower in Au grade, at a calculated average of 11 Mt of 1.1 g/t Au. Data for 25 selected Au- and Ag-enriched skarns of the world tabulated by

Figure 20.3-3. (A) Plot showing Cu/Au versus Cu/Ag ratios of 40 international skarn deposits. Gold, copper, and iron skarn types are outlined in discrete fields (after Ettlinger and Ray, 1989, Fig. 50). **(B)** Plot showing Cu/Au versus Cu/Ag ratios of 54 precious metal-enriched skarns in British Columbia. Skarn fields correspond to those in Figure 20.3-3A, with the addition of silver-rich, gold-poor skarns with zinc-lead skarn affinities (after Ettlinger and Ray, 1989, Fig. 51).

Table 20.3-2. Average tonnage and Au grade for Au skarns and Au-bearing skarn subtypes.

Skarn type/ subtype	No.	Mt ore (average)	g/t Au (average)
Au	14	4.6	10.6
Fe-Au	14	1.6	4.4
Cu-Au	19	2.1	2.5
Porphyry Cu-Au	14	153	0.5
Zn-Pb-Au	8	3.8	0.6

Ettlinger and Ray (1989, their Table 1) yield a calculated average of 7.45 Mt at a grade of 2.6 g/t Au. Grades and tonnages of 62 globally distributed Au-bearing skarns with average grades of at least 1 g/t Au have been compiled by Orris et al. (1987) and two subtypes have been proposed: (1) Au skarns, exploited primarily for Au (median grade 6.8 g/t Au); and (2) byproduct Au skarns, mined primarily for their base metal content (median grade 3.4 g/t Au). All Au-bearing skarns have a median size of 400 000 t, and a median grade of 5 g/t Au. Theodore et al. (1991) employed a larger global database and calculated median grades and tonnages for 40 Au skarn deposits as 8.6 g/t Au, 5.0 g/t Ag, and 213 000 t respectively; and for 50 byproduct Au skarn deposits as 3.7 g/t Au, 37 g/t Ag, and 330 000 t respectively.

GEOLOGICAL FEATURES

Geological setting

Gold skarn deposits are found in two principal tectonic settings: continental shelves and oceanic or arc volcanic-sedimentary assemblages. Gold skarns in the southwestern United States and Australia occur commonly in Paleozoic to lower Mesozoic shelf and basinal sedimentary rocks of cratonal origin. Related calc-alkaline plutonism in the United States is late Laramide and in Australia, Carboniferous. Two Canadian Au skarns, i.e., Ketza River, Yukon Territory and Banks Island, British Columbia have similar settings in displaced, rather than autochthonous, cratonal terranes associated with Cretaceous granitoid bodies. The other four Canadian deposits, hosted by oceanic arc carbonate-clastic-volcanic lithologies of accreted Quesnellia, are representative of the other principal setting for Au skarn deposits in allochthonous or accreted rocks with a significant marine volcanic component. Intrusions associated with Au skarns in the Canadian Cordillera constitute a distinctive suite of calc-alkaline to alkaline plutons of synorogenic to late orogenic timing. At Hedley, British Columbia, the quartz dioritic and gabbroic intrusions are enriched in iron, depleted in total alkalis and silica and have low F_2O_3/FeO ratios, i.e., are reduced, relative to intrusions associated with other types of skarn deposits (Ray and Webster, 1991).

The tectonic setting of porphyry Cu-Au skarns is continental margin orogenic belts, which have been intruded by calc-alkaline granodioritic to quartz monzonitic stocks, as exemplified by the deposits in the southwestern United States, i.e., Utah, Arizona, Nevada, and New Mexico. Relatively few deposits of this type, e.g., Ok Tedi, Papua New Guinea and Ingerbelle, British Columbia are known from oceanic-island arc settings and their accreted equivalents. Copper-gold skarns associated with barren stocks unrelated to porphyry deposits, on the other hand, have tectonic settings similar to those of calcic Fe skarns in oceanic island arcs, their accreted equivalents and rifted continental margins (Einaudi et al., 1981). The limited data on the Au-rich subtype of Zn-Pb skarns indicate they have a tectonic setting similar to other Zn-Pb skarns, i.e., they occur in cratonal sediments at continental margins and are associated with synorogenic to late orogenic calc-alkaline stocks.

Age of host rocks, associated rocks, and mineralization

Host rocks for deposits of the Au skarn subtype are metamorphosed equivalents of carbonate rocks which occur either as relatively thick and pure limestones in a miogeoclinal setting or as carbonate units interbedded with clastic and volcaniclastic rocks, tuffites, and flows in an oceanic-island arc setting. Host rock ages range from Cambrian to Miocene, but are dominantly Paleozoic in Australia, Russia, and the southwestern United States, and Late Triassic in British Columbia. Plutonic rocks associated with Au skarns range

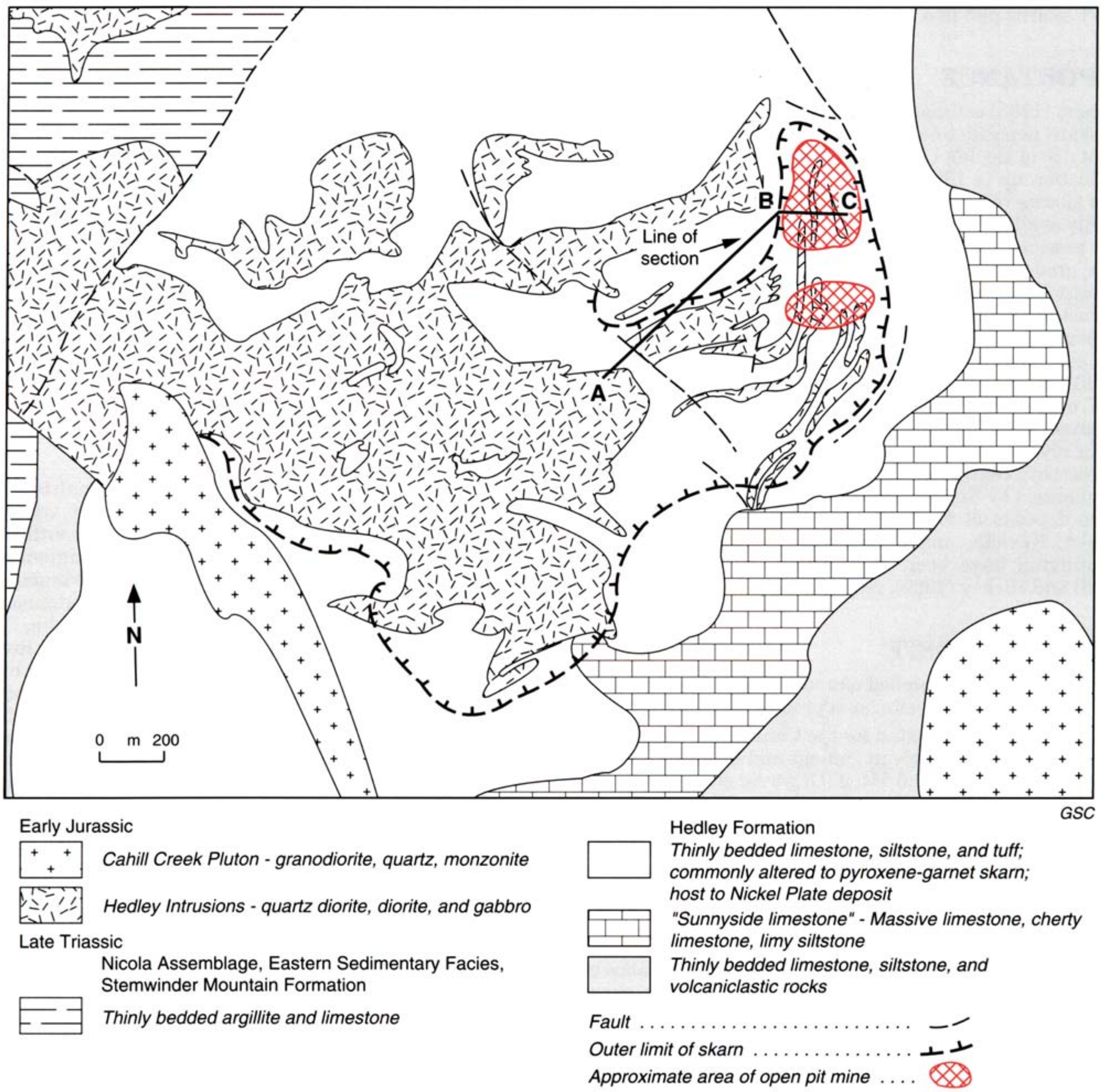


Figure 20.3-4. Surface geology, Nickel Plate Mountain, Hedley, British Columbia (after Ettlinger et al., 1992). Section A-B-C shown in Figure 20.3-5.

in age from Early Paleozoic in Australia to Miocene in the Philippines (Meinert, 1988), and in composition from diorite, gabbro, and syenodiorite in British Columbia to rhyolite porphyry at Bau, Malaysia (Wolfenden, 1965). A general correlation between the global distributions of gold skarns and porphyry copper deposits was noted by Ray et al. (1990). The majority of Au skarn deposits are associated with relatively small, mafic to intermediate plutons. Meinert (1992) noted the association of most high-grade gold skarns with reduced, i.e., ilmenite-bearing, Fe^{+3}/Fe^{+2} less than 0.75, diorite-granodiorite plutons and dyke-sill complexes. Age of mineralization is penecontemporaneous with intrusion, and is dominantly Early Tertiary in southwestern United States, Early to mid-Jurassic in British Columbia, and Paleozoic in Australia and Russia.

Large Cu skarns, all enriched in part in Au, are associated with some porphyry Cu plutons emplaced in continental margin carbonate strata. The largest group of porphyry copper-related gold-rich skarns, associated with the Laramide porphyry Cu province of southwestern United States, is hosted by dominantly Paleozoic cratonal sedimentary rocks. Other notable districts occur in Mexico, Peru, Russia, and Japan. At Ingerbelle, British Columbia, an atypical alkalic (Na-K-Ca) porphyry Cu-Au skarn is hosted by Upper Triassic arc-related andesitic to basaltic volcaniclastic rocks and flows adjacent to alkalic stocks (Preto, 1972; Fahrni et al., 1976) of the Early Jurassic Copper Mountain suite.

Copper-gold skarns and related calcic Fe-Au skarns are hosted by Paleozoic and Mesozoic limestones interbedded with clastic, volcaniclastic, and tholeiitic to calc-alkaline volcanic rocks in several tectonic settings, including oceanic, island-arc, and back arc. The formation of Cu-Au and Fe-Au skarns in the Canadian Cordillera accompanied the emplacement of both pre-accretionary dioritic Early Jurassic plutons and postaccretionary granodioritic mid- to Late Cretaceous plutons.

Form of deposit and associated structures, zoning, and distribution of ore minerals

The morphology of Au skarns is not known to be distinctive. Gold commonly accompanies the dominant sulphide mineral, usually arsenopyrite, pyrrhotite, pyrite, or chalcopyrite, in both prograde skarn and retrograde alteration zones. Both stratigraphic control on the development of

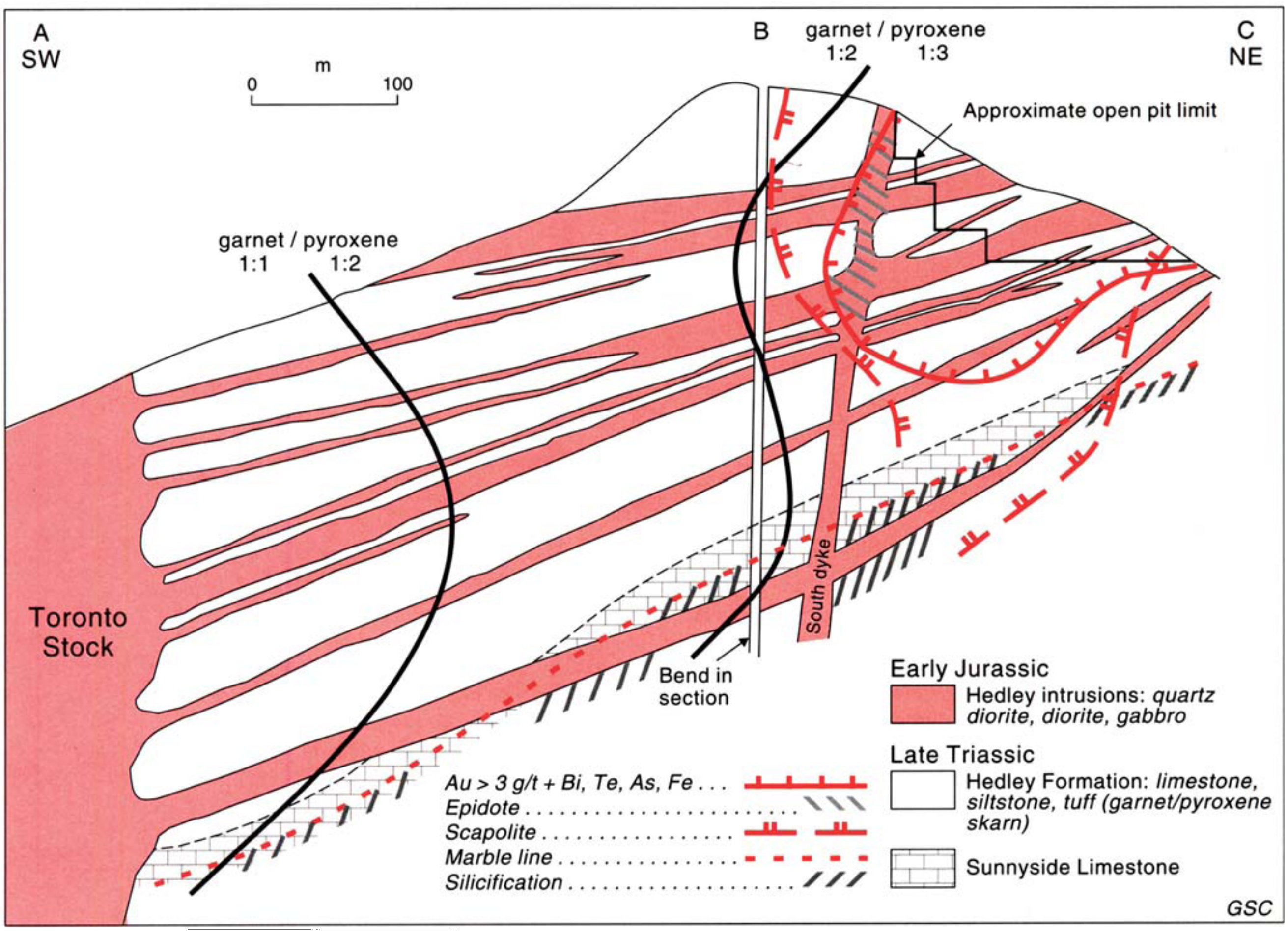


Figure 20.3-5. Cross-section, Nickel Plate deposit, Hedley, British Columbia. Skarn assemblages and sulphide-Au mineralization after Ettlinger et al. (1992).

exoskarn by bedding in the carbonate-clastic rocks, and structural control by intrusive contacts, faults, fractures, and folds are common. No consistent zonal distribution of ore minerals has been recognized, but prograde calcic skarn assemblages typically are zoned toward the intrusive contact from marble, through wollastonite and diopside-hedenbergite, to andradite.

The Nickel Plate skarn Au orebodies at Hedley, British Columbia are semiconformable, tabular sulphide zones developed near the skarn-marble boundary. Host limestone of the Upper Triassic Nicola Group is interbedded with argillite and siltstone and has been intruded by sills and some dykes of Late Triassic to Early Jurassic diorite and gabbro that have yielded zircon U/Pb ages between 219 and 194 Ma (Ray et al., 1993). Alternating layers of garnet-rich and diopside-hedenbergite-rich prograde skarn follow bedding. Gold, together with anomalous amounts of Bi, Te, and Co, is concentrated with arsenopyrite, pyrrhotite, and pyrite in the latest stage, a retrograde quartz-calcite-epidote-sulphide assemblage deposited near the skarn-marble boundary (Billingsley and Hume, 1941; Ettlinger and Ray, 1988, 1989; Ettlinger et al., 1992) (Fig. 20.3-4, 20.3-5, and Table 20.3-1).

The morphologies of gold-rich porphyry Cu skarns reflect a relatively high level of emplacement of the associated intrusive rocks, and resultant intense fracturing, brecciation, and breccia pipe formation. Typically extensive development of thick skarn units reflects the high fracture permeability of the porphyry Cu system. The calc-silicate assemblage of ferric iron-rich andradite and ferrous iron-poor clinopyroxene reflects the relatively oxidized environment, as in Au-deficient Cu skarns associated with porphyry Cu deposits (Einaudi et al., 1981). Most skarns are part of a large zoned system with proximal garnet-rich and distal Zn-Pb-Ag-rich zones, e.g., Fortitude mine at Battle Mountain, Nevada (Theodore and Blake, 1978). Some porphyry Cu-Au skarns, such as Carr Fork, Utah have high concentrations of Au within zones of localized intense retrograde alteration (Cameron and Garmoe, 1987), but gold occurs generally in low concentrations and is recoverable only as a byproduct.

The large disseminated Cu-Au-Ag deposits at Copper Mountain, British Columbia have been classified by Sutherland Brown et al. (1971) as complex porphyry-type deposits of the alkaline suite, and deposits at adjacent Ingerbelle as skarn deposits gradational to a porphyry. Dolmage (1934), Preto (1972), and Macauley (1973) noted

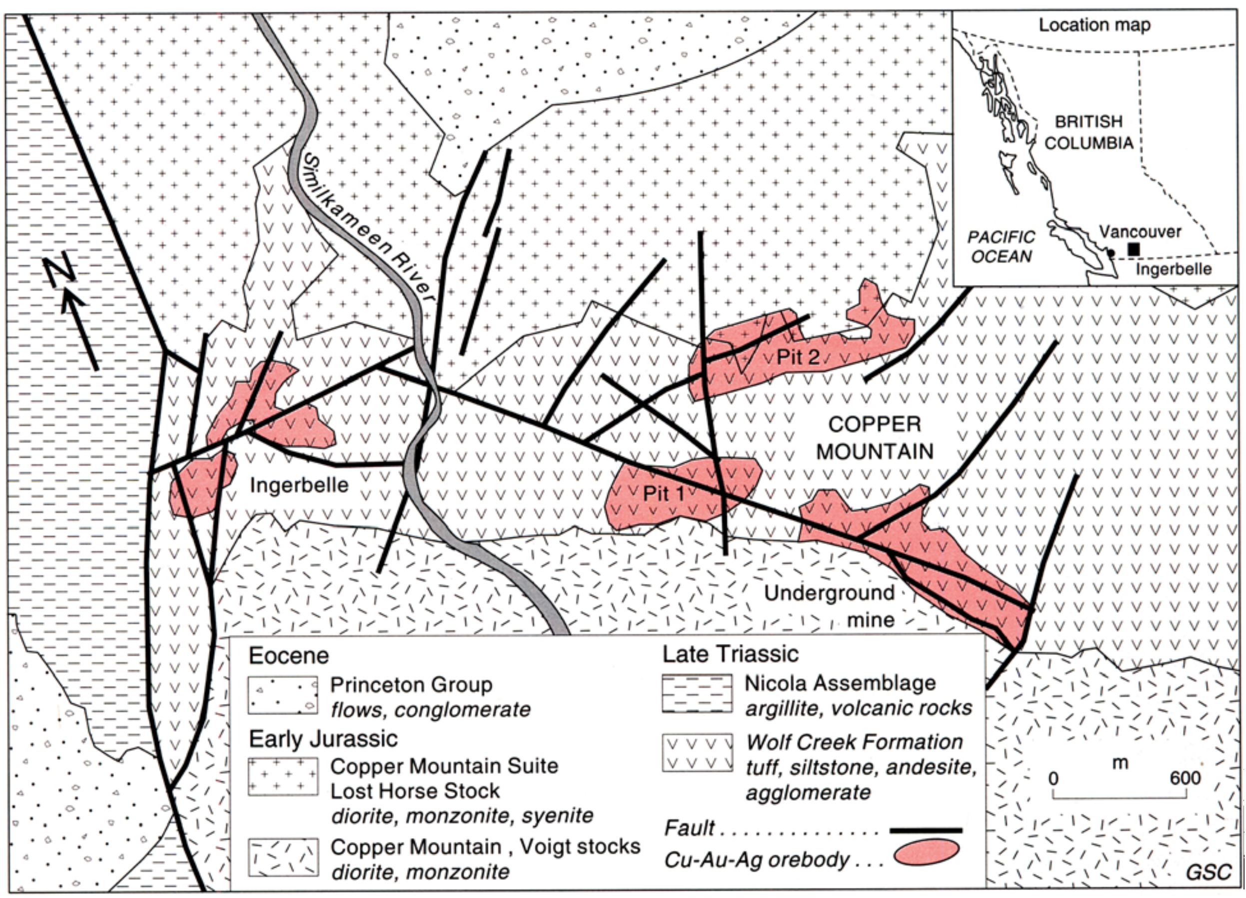


Figure 20.3-6. Geology and Cu-Au-Ag deposits of the Ingerbelle-Copper Mountain district, Princeton, British Columbia (after Fahrni et al., 1976).

the pyrometasomatic characteristics of the Copper Mountain and Ingerbelle deposits. Fahrni et al. (1976) emphasized the zonal distribution of most of the following gangue assemblages at Ingerbelle relative to the contact of the Lost Horse diorite-monzonite-syenite stock: early biotite hornfels overprinted by main stage sulphides plus prograde albite-epidote-chlorite±andradite±diopsidic pyroxene±sphene; and both prograde skarn and stock flooded by retrograde albite, K-feldspar, scapolite, calcite, and hematite. The gold-rich chalcopyrite-bornite ore, about 90% of which occurs in andesitic volcanic host rocks, is distributed along the contacts of the Lost Horse intrusion. These mineral assemblages are interpreted to represent the superposition of silica-deficient, alkali- and alumina-rich magnesian skarn assemblages upon biotite hornfels, developed in an andesite protolith adjacent to an alkalic intrusion. The local geology and distribution of orebodies are given in Figure 20.3-6 after Fahrni et al. (1976). Gold-rich alkalic porphyry copper skarn deposits at Galore Creek (Allen et al., 1976) and Mount Polley (Fraser, 1994), British Columbia are described in "Skarn copper", subtype 20.2.

Copper-gold skarns associated with barren stocks unrelated to porphyry deposits have several features in common with calcic Fe-Au skarns, including tectonic setting, composition of intrusions, and skarn morphology and mineralogy (see deposit subtype 20.2, "Skarn copper"). The highest

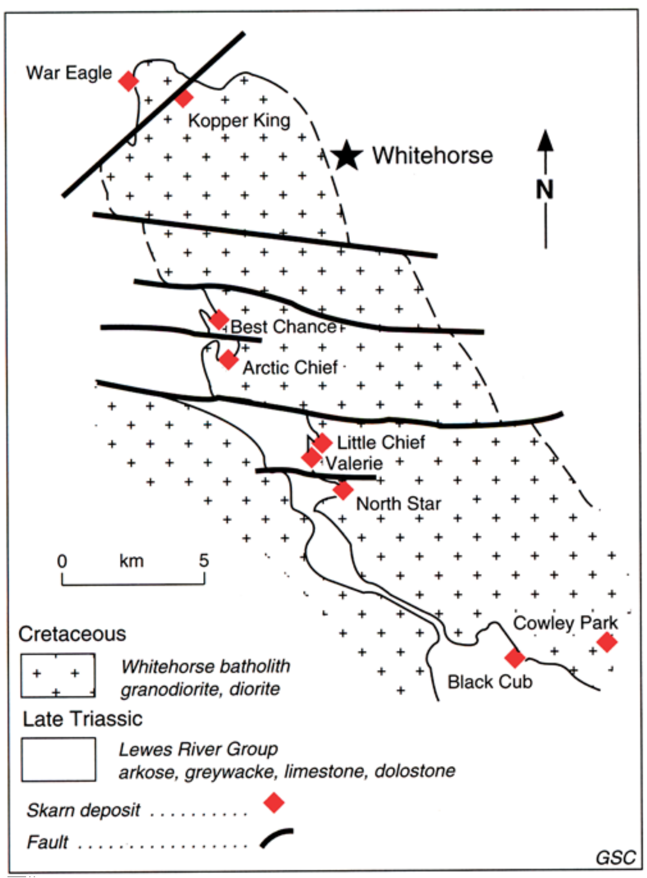


Figure 20.3-7. Simplified regional geological map of Whitehorse Copper Belt showing principal Cu-Au-Ag skarn deposits (after Meinert, 1986).

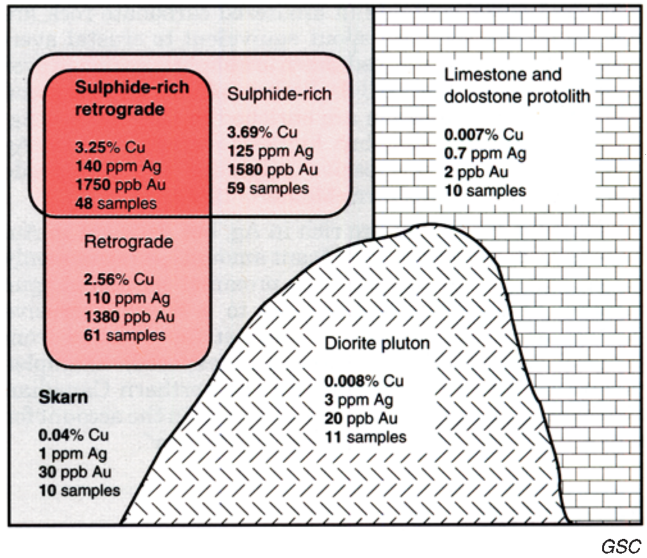


Figure 20.3-8. Schematic illustration of distribution of Cu, Ag, and Au in rock and alteration types in the Whitehorse Copper Belt (after Meinert, 1986).

Au contents occur in zones of coincident high sulphide content and intense retrograde alteration of skarn (Meinert, 1988). Examples of coexisting Cu-Au and Fe-Au skarns can be found in the Texada Island, Benson Lake, and Greenwood districts of British Columbia (Table 20.3-1). Calcic Fe-Au skarns, e.g., Tasu (Wesfrob) and Texada Iron, commonly are large, but Au is in low overall concentration and erratically distributed within Cu- and S-rich zones. Gold and cobalt may, in some cases, be concentrated in the early formed sulphides, chalcopyrite, pyrite, and pyrrhotite, or in later retrograde alteration assemblages with sulphides, magnetite, amphibole, epidote, and ilvaite (Meinert, 1984; Ettlinger and Ray, 1989). The Crown Jewel Au skarn at Buckhorn Mountain, Washington is distant from a proximal Cu-Fe skarn in a large system also zoned in proximal garnet-rich and distal pyroxene-rich assemblages (Hickey, 1992).

A reconnaissance study of the Cu-Au-Ag skarns of the Whitehorse Copper Belt, Yukon Territory by Meinert (1986) illustrates the distribution of Au and its association with retrograde alteration. Copper, iron (molybdenum, gold, silver) skarn deposits are developed in both dolomitic and calcareous carbonate units of the Upper Triassic Lewes River Group, a back-arc succession of arkosic clastic and carbonate rocks. Some 32 skarn deposits and occurrences are localized mainly along the irregular western contact of the Whitehorse batholith (Fig. 20.3-7), a composite calc-alkaline granodiorite pluton with a diorite margin (Morrison, 1981) that postorogenically intruded accreted Stikinia in mid-Cretaceous time (Dawson et al., 1991).

Skarns formed from a limestone protolith at Whitehorse contain abundant andraditic garnet, hedenbergitic pyroxene, wollastonite, vesuvianite, and variable amounts of the retrograde alteration products actinolite, epidote, and chlorite. Skarns with a dolomitic protolith contain abundant prograde magnesian minerals, such as diopside and forsteritic olivine plus andradite, and retrograde phlogopite, brucite, talc, and serpentine. Copper, gold, and silver contents in unaltered carbonate rock are low; in diorite they are about equivalent to crustal averages; and in unmineralized skarn are slightly enriched over protolith values (Fig. 20.3-8). Both sulphide-rich skarn and retrograde-altered skarn are enriched in Cu, Au, and Ag, as would be expected, but highest average Au and Ag grades occur where massive sulphides and retrograde alteration coexist in skarn (Meinert, 1986).

Most Zn-Pb skarns are rich in Ag, but deficient in Au. Where Au is present in significant amounts, it is commonly concentrated with sulphide-rich proximal ore and gangue mineral assemblages either close to a known intrusive contact or in the core of the deposit (as deduced from mineral zonation when no intrusion is exposed). Examples of Au-rich Zn-Pb-Ag skarns from the northern Canadian Cordillera and northern Mexico are given in the account for deposit subtype 20.1, "Skarn zinc-lead-silver".

Mineralogy

Principal ore minerals: gold, electrum, gold tellurides.

Subsidiary ore minerals: chalcopyrite, bornite, sphalerite, galena, molybdenite, scheelite, silver, silver tellurides, silver sulphosalts, tetrahedrite, bismuth, bismuthinite, bismuth tellurides, wittichenite, cobaltite, gersdorffite.

Other opaque minerals: pyrrhotite, pyrite, arsenopyrite, marcasite, hematite, magnetite. Typical prograde and retrograde skarn minerals are listed in Table 20.3-3.

DEFINITIVE CHARACTERISTICS

Skarn deposit classification may be based on various features, such as dominant economic metals, morphology, host rock type and composition, temperature and redox conditions of formation, and tectonic setting. Many modern authors prefer a descriptive classification that first emphasizes dominant economic metals, and is modified by genetic, compositional, morphological, and other factors. This approach is followed in the skarn descriptions in this volume, and adapted to include in the "skarn Au" category gold-rich subtypes of other principal types of skarn deposits. Although gold-rich skarn subtypes possess definitive characteristics as given below, the principal features are similar to those of other skarn deposits, e.g. skarn copper, skarn iron, etc.

1. Gold skarns: ore assemblage rich in As, Bi, and Te; calcic skarn mineral assemblage low in Mn; Fe- and Al-rich pyroxene more abundant than grandite garnet; abundant clastic and volcaniclastic components in host rocks; association with relatively Fe-rich, I-type, ilmenite-bearing subalkalic to calcalkalic intrusions.
2. Copper-gold skarns associated with porphyry Cu deposits: disseminated Cu and Mo minerals in altered intrusion; high fracture permeability; relatively thick and extensive skarn; low Au grade; those in the southwestern United States have a craton margin setting.
3. Copper-gold skarns associated with unmineralized plutons unrelated to porphyry deposits: lack of disseminated Cu-Mo minerals in unaltered intrusion; Au concentrated in sulphide-rich retrograde alteration zones; orebodies more massive and higher in Au grade than Cu-Au skarns associated with porphyry deposits.
4. Iron-gold skarns: high Au, Co, and As contents associated with sulphide-rich zones; calcic magnetite-rich skarn shows gradation distally to Cu and Cu-Au skarn; oceanic-island arc setting.
5. Zinc-lead-silver-gold skarns: high Ag content; Ag concentrated distally to Au±Cu, W-rich proximal skarn; craton margin setting.

Table 20.3-3. Prograde and retrograde skarn minerals.

Prograde skarn minerals	Retrograde skarn minerals
(a) Au: andraditic garnet, hedenbergitic pyroxene, wollastonite, vesuvianite, scapolite	actinolite, hornblende, chlorite, epidote
(b) porphyry Cu: andraditic garnet, diopsidic pyroxene, wollastonite	actinolite, chlorite, montmorillonite, quartz, calcite
(c) Cu: grandite garnet (intermediate between grossular and andradite), wollastonite, diopsidic pyroxene, magnetite, epidote	epidote, actinolite, hornblende, chlorite
(d) Fe: grandite garnet, diopsidic to johannsenitic pyroxene, magnetite, epidote	amphibole, chlorite, ilvaite, epidote
(e) Zn-Pb: johannsenitic pyroxene, andraditic garnet, vesuvianite, wollastonite, bustamite.	manganoan actinolite, epidote, chlorite, siderite and ilvaite; and calcite, quartz, fluorite

GENETIC MODEL

The role of characteristic geological features such as clastic-rich host rocks, tectonic setting, and mafic plutons in the formation of Au skarns is not well understood. Most Au and Au-bearing skarns in the Canadian Cordillera are associated with suites of pre-accretionary subalkaline to alkaline plutons comagmatic with the volcanic component of an accreted arc assemblage. Gold may have been contributed from the marine volcanic, volcaniclastic, and clastic sedimentary host rocks of Quesnellia. Plutons of the same alkaline suite, associated elsewhere with Au- and Ag-rich porphyry Cu deposits, may represent regional enrichment of Au in the relatively undifferentiated synorogenic magma.

In a global context, the compositions of host rocks and intrusions related to Au-rich skarns range widely and compositions of gangue minerals are not well documented. Whether or not these skarns are mineralogically and genetically distinctive remains to be established. The genesis of Au-rich subtypes of porphyry Cu, Cu, Fe, and Zn-Pb skarns does not differ substantially from that of the principal skarn types. Genesis of these principal skarn types is covered elsewhere in this volume (e.g., see deposit subtype 20.2, Skarn copper) and has been discussed in a summary by Einaudi et al. (1981).

RELATED DEPOSIT TYPES

Most Au and Au-bearing skarns in the Canadian Cordillera are associated with a unique suite of dominantly subalkaline to alkaline, Late Triassic to mid-Jurassic granitoid plutons which, elsewhere in the same Quesnellia host rock sequences, contain significant porphyry Cu-Au-Ag deposits. Examples of deposits related to these intrusions and host rocks include the Ingerbelle and Galore Creek porphyry Cu-Au-Ag skarns (Allen et al., 1976), and Au skarns such as the Nickel Plate (Ettinger et al., 1992). The Au vein deposits at Rossland (Wilson et al., 1990; Höy and Andrew, 1991) and near Nelson, British Columbia (Second Relief; Ettlinger and Ray, 1989) possess some mineralogical characteristics of Au skarns, and may be related. Skarn deposits of several types are enriched in Au, particularly in S-rich and intensely retrograde altered zones. Porphyry Cu (Mo) skarns and Cu skarns are enriched in coproduct and byproduct Au to the greatest degree, whereas W, Sn, and Mo skarns are poorest in Au.

EXPLORATION GUIDES

General guidelines for the discovery of the principal types of skarn deposits, covered elsewhere in this volume, also apply to Au-rich subtypes of those deposits. Most skarns, except those of W, Mo, and Sn, are potentially rich in Au, and some specific guides to Au-rich skarns are as follows:

1. Gold skarns contain anomalous amounts of Bi, Te, and Ag, in addition to Cu and As.
2. Gold-rich parts of calcic Fe skarns also are enriched in Cu, Co, and As, in addition to S.
3. Gold is concentrated in S-rich parts of most skarns, particularly calcic Cu and Fe skarns.
4. Gold and silver are concentrated in intensely retrograde altered zones of calcic Cu and porphyry Cu skarns.
5. Gold is, in some cases, concentrated in proximal parts of Zn-Pb skarn and replacement deposits that are enriched in Cu, W, and Fe.

General exploration guides to discovery of Au skarns are:

1. Gold skarns may be discovered in either craton marginal or oceanic-island arc settings, commonly in interbedded carbonate-clastic-volcaniclastic sequences and adjacent to relatively small dioritic plutons.
2. In the Canadian Cordillera, most Au skarns are hosted by accreted sedimentary and volcanic assemblages of Quesnellia where these rocks have been intruded by Late Triassic to Middle Jurassic, mainly subalkaline to alkaline plutons that are comagmatic with the volcanic rocks. Good potential exists for discovery of Au-rich skarns adjacent to known porphyry Cu-Au-Ag deposits hosted by and associated with this plutonic suite.

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20.4 SKARN IRON

20.4a Contact metasomatic (associated with intrusive rocks)
20.4b Stratiform in metamorphic terrane

G.A. Gross

INTRODUCTION

The term "skarn" is used here as a lithological term, without specific genetic connotations, to designate a large group of mineral deposits that have a significant proportion of gangue rock composed of calcium and magnesium silicate minerals that formed by metamorphic and metasomatic processes in a diversity of geological settings and terranes. Skarn iron ore deposits have developed in many different metallogenes[1] and minerogenic environments, but commonly formed along the contacts of igneous intrusions with limestone, dolomite, and shale or volcanic rocks by metasomatic processes; by metamorphism and alteration of sequences of sedimentary, volcanic, and intrusive rocks; and in metallogenetic environments controlled principally by tectonic and structural features (Einaudi et al., 1981; Meinert, 1993).

Skarn-type iron deposits are usually composed of complex mineral assemblages consisting of pyroxene, amphibole, epidote, garnet, biotite, and chlorite, with associated magnetite, hematite, siderite, titaniferous magnetite, pyrite, pyrrhotite, and chalcopyrite, that are developed in the host rocks by metamorphic and metasomatic replacement processes. Skarn-type deposits as a group are important sources of iron, copper, tungsten, lead, zinc, molybdenum, and tin and some may contain significant amounts of other ferrous, nonferrous, and precious metals. They are also sources of graphite, asbestos, wollastonite, magnesite, phlogopite, talc, and fluorite (Gross, 1967a; Einaudi et al., 1981; Meinert, 1983, 1993).

Skarn deposits that provide significant resources of iron belong to two main subtypes:

1. contact metasomatic or replacement skarn deposits developed along the margins of igneous intrusions in association with limestone, dolomite, argillaceous sediments, and mafic volcanic rocks; and
2. stratiform skarn deposits hosted in sequences of highly metamorphosed sediments and volcanic rocks, that may have no evident or demonstrated association with intrusive rocks, and that may have developed by metamorphism of iron-bearing protolithic rocks of unknown origin.

The term "skarn iron" is usually not used or recommended for stratiform metalliferous deposits in which the nature and kinds of protolithic rocks bearing calcium and

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[1] The term metallogene is used to designate sequences of interrelated geological processes associated with prominent sedimentary, igneous, metamorphic, and/or structural features in a geological domain that have produced concentrations of elements and minerals in deposits of significant size and type. More than one type of mineral deposit may be developed in a single metallogene (Gross, 1977).

magnesium silicate "skarn type" mineral assemblages have been positively identified or demonstrated, as in the case of metamorphosed lithofacies of iron-formation or other iron-bearing sedimentary and volcanic rocks.

Examples of intrusion-associated, contact metasomatic skarn deposits in Canada include Tasu, Iron Hill, and Texada Island in British Columbia. Foreign examples include Cornwall, Pennsylvania; Iron Springs, Utah; Iron Hat, California; Tayeh, China; and Sarbai, Sokolovsk, and Magnitnaya in the former U.S.S.R.

Canadian examples of stratiform skarn deposits in metamorphic terranes include the Marmora deposit, Ontario; the Hilton mine, Quebec; and probably many others derived from iron-formations in which primary features and the nature of the protolithofacies has been destroyed by metamorphism or is not clearly defined. Foreign examples include the Marcona deposits in Peru and numerous deposits in northern Sweden which may have been derived from ferruginous sediments, including highly metamorphosed iron-formations.

IMPORTANCE

Iron ore production from skarn deposits has probably now fallen to less than 2% of total world production, and some skarn deposits are only mined because copper and other byproduct minerals are recovered in the processing of the ore. The greatest production has been from the large skarn deposits in the former U.S.S.R., China, Peru, and U.S.A. Although production of iron ore from other skarn deposits has been relatively small, the mines developed in them have had an important impact on the economy of local communities in Canada, China, and many other countries.

Past production of iron ore from skarn deposits in Canada was generally less than one million tonnes of concentrate per year, from deposits containing less than 30 Mt of ore and with grades ranging from 35 to 50% Fe. Production of iron ore concentrate from the skarn deposits in southwestern British Columbia was developed for an export market and, although small by world standards for iron ore (less than 2 Mt per year) was an important factor in the regional economy. For example, the total production from British Columbia in 1964 from the larger mine areas,

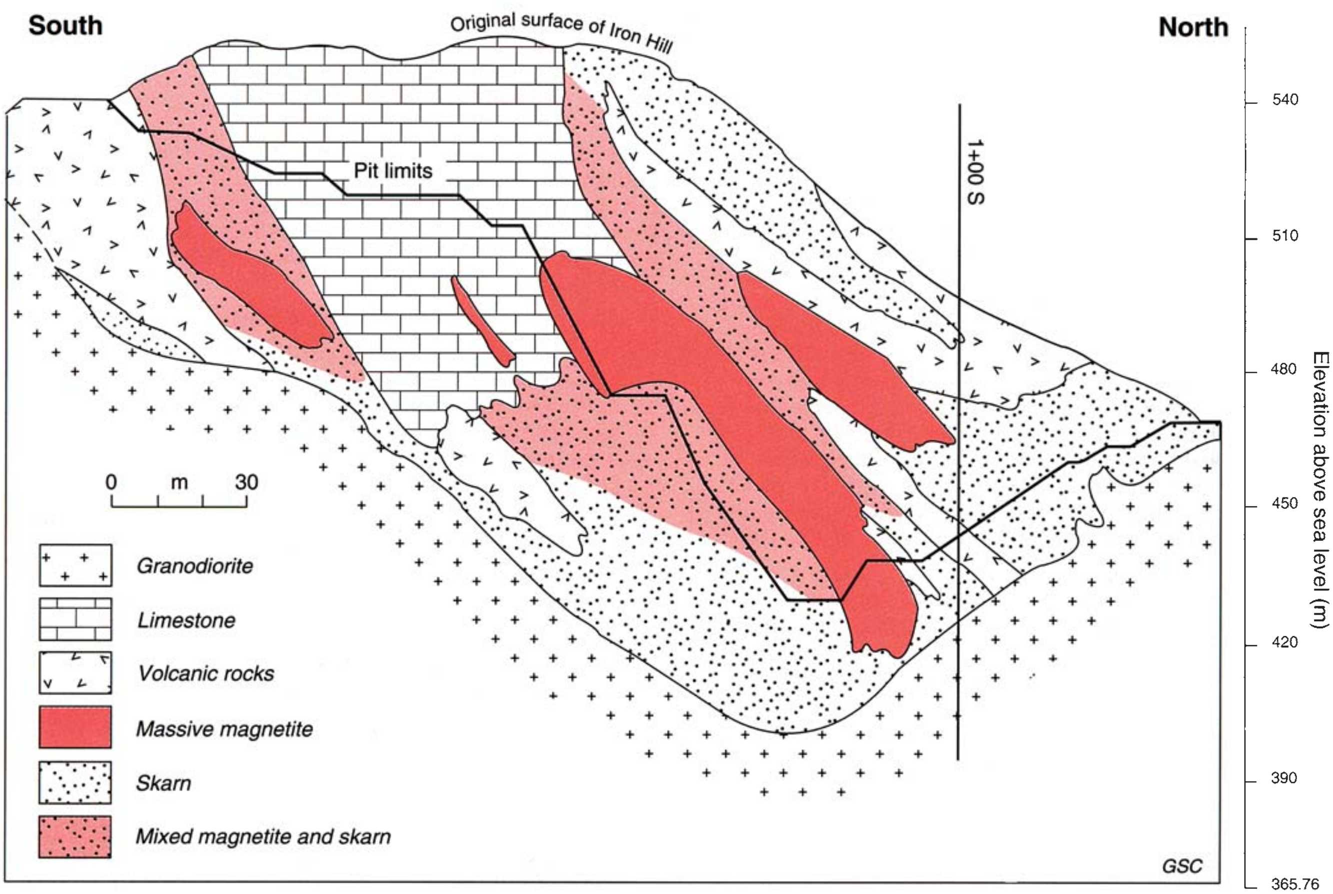

Figure 20.4-1. Geology in section of the Iron Hill iron deposit, Vancouver Island (after Sangster, 1969).

Texada Mines Ltd., Zeballos Iron Mines, Jedway Iron Ore, Empire Development, Coast Copper Co., and Brynnor Mines, was about 1.7 Mt of magnetite concentrate, which was recovered from about 3 Mt of crude ore containing 30 to 54% Fe. The iron content of the concentrate ranged from 54.1 to 62.56% Fe, and the SiO_2 content from 3.3 to 8.4%.

Production of iron ore concentrate on the west coast of Canada began on Texada Island in 1952. Most of the larger mine areas continued production of less than 0.5 Mt of magnetite concentrate per year for periods of about 10 years from the early 1950s to the late 1960s.

Copper was a prime product with the iron ore concentrate at the Coast Copper Co. mine, and was recovered as a byproduct in the concentration of the skarn iron ore from some of the deposits in the region. The copper content ranged from 0.2 to 1.3% at Tasu, formerly the Wesfrob mine, on Moresby Island, Queen Charlotte Islands, and production of copper with the iron ore concentrate was an important factor in extending production in this mine area.

Wesfrob Mines at Tasu Harbour began production in 1967 at a rate of about one million tonnes per year of crude iron ore, and in 1983 produced more than 490 000 t of magnetite concentrate grading 63.3% natural iron (69.1% dry analysis) from about 850 000 t of ore mined. Production from the mine ceased in late 1983.

The Marmora deposit in Hastings County, Ontario is typical of stratiform iron-rich skarns in the Grenville Province of eastern Canada. It was first detected by an airborne geophysical survey in 1949 by the Geological Survey of Canada and the Ontario Department of Mines, below a 30-40 m thick capping of Paleozoic limestone. The first shipment of pellets was made in 1955 following the removal of 20 Mt of limestone and the normal production rate during mining operations was about 0.5 Mt of pellets a year. A total of 1.126 Mt of waste rock was removed in 1959 and 0.313 Mt of concentrate grading 66.25% Fe was obtained from 762 785 t of ore treated in the mill.

SIZE AND GRADE OF DEPOSITS

The largest skarn iron deposits in the world, such as Sokolovsk and Sarbai in the former U.S.S.R., contain 1000 Mt of ore, but most in North America have less than 50 Mt, and grade from 35 to 50% Fe. Proven reserves in most of the contact metasomatic deposits in southern British Columbia were less than 20 Mt and ore from a cluster of small deposits was concentrated at central mills. Individual deposits ranged in size from less than 2 to 10 Mt of crude ore grading 30 to 54% Fe. The Tasu skarn deposit on Moresby Island was probably the largest in the British Columbia coastal region. It produced about 21 Mt of ore from 1914 to 1983 at recovered grades of about 40% Fe, 0.29% Cu, 2.4 g/t Ag, and 0.064 g/t Au.

The initial drilling program at the Marmora stratiform skarn iron deposit indicated about 20 Mt of ore grading 35 to 37% Fe within the projected limits of an open pit mine extending to a depth of about 150 m. Production from 1955 to 1978 was about 28 Mt of ore at a grade of 42.8% Fe.

GEOLOGICAL FEATURES

Geological setting

Contact metasomatic skarn deposits are commonly formed in volcanic arc and rifted continental margin tectonic settings at the contacts of felsic or mafic intrusions with carbonate, calcareous clastic, and volcanic rocks. The more complex stratiform-type skarn deposits occur in highly metamorphosed terranes such as the Grenville Province in eastern Canada where deposits of known sedimentary and replacement origin have been subjected to several stages of tectonic deformation and metamorphism with considerable remobilization of the iron and major constituents.

Age of host rocks

Skarn mineralization occurs in rocks of all ages, but is probably most abundant in Mesozoic and younger tectonic belts.

Form of deposits

Skarn deposits vary greatly in form and mineralogy. Contact metasomatic deposits range from irregular, massive and disseminated patches, to veins and dyke-like masses (Fig. 20.4-1, Iron Hill). Stratiform skarn deposits are more uniform, tabular, massive, or layered conformable bodies. Mineral distribution in both subtypes is patchy to uniform and textures vary greatly. The patchy and irregular to erratic distribution of magnetite in skarn deposits is typical, and generally the whole mass, composed of high grade pods, lenses, stringers, and disseminated ore, is mined and processed to produce a magnetite concentrate.

Mineralogy

The ore minerals in iron-rich skarns are magnetite, hematite, martite, and goethite, with minor amounts of pyrite, pyrrhotite, and chalcopyrite. They are associated with gangue mineral assemblages consisting of calc-silicate skarn minerals, pyroxene, amphibole, chlorite, epidote, calcite, dolomite, siderite, and variable amounts of apatite, alkali feldspar, biotite, garnet, and quartz. Skarn ores may vary from massive bodies of nearly pure magnetite to disseminated zones with less than 10% iron oxide. Skarn ore containing as little as 15% Fe has been mined successfully, but the average iron content of most of the ore mined is 35 to 50% Fe or greater.

Because of the great diversity in genetic processes that form skarn iron deposits, they often contain recoverable amounts of other ferrous, nonferrous, and precious metals, as well as tin, tungsten, molybdenum, titanium, phosphate, and a wide variety of other elements which reflect the composition and petrology of the associated intrusions.

Distribution of ore and gangue minerals and relationships to host rocks

Skarn deposits differ greatly in their mineral assemblages, textures, internal structures, and composition, depending on fundamental differences in their tectonic setting, nature of the host rocks and kinds of associated intrusions, and the metamorphic and alteration processes that produced them. Meinert (1983) pointed out that underlying the variations in size, texture, and mineralogy of skarn deposits are common patterns of 1) early initial isochemical metamorphism, 2) multiple intermediate stages of metasomatism, and 3) late retrograde alteration.

Contact metasomatic skarns in the coastal regions of British Columbia are composed mainly of garnet (andradite-grossularite), pyroxene (diopside-hedenbergite), epidote, and magnetite. Chalcopyrite, pyrite, pyrrhotite, and arsenopyrite are locally abundant (Sangster, 1969). The skarn deposits of this area are irregular masses that vary in composition and mineralogy depending on the associated host rocks. Most of the deposits have replaced volcanic rocks near contacts with limestone, some occur entirely within limestone, and rarely in the intrusive rocks. Stocks adjacent to the deposits are usually intermediate in composition, but range from gabbro to quartz monzonite. Folds and faults and the presence of limestone or other calcareous rocks are important controls for the development of skarn deposits.

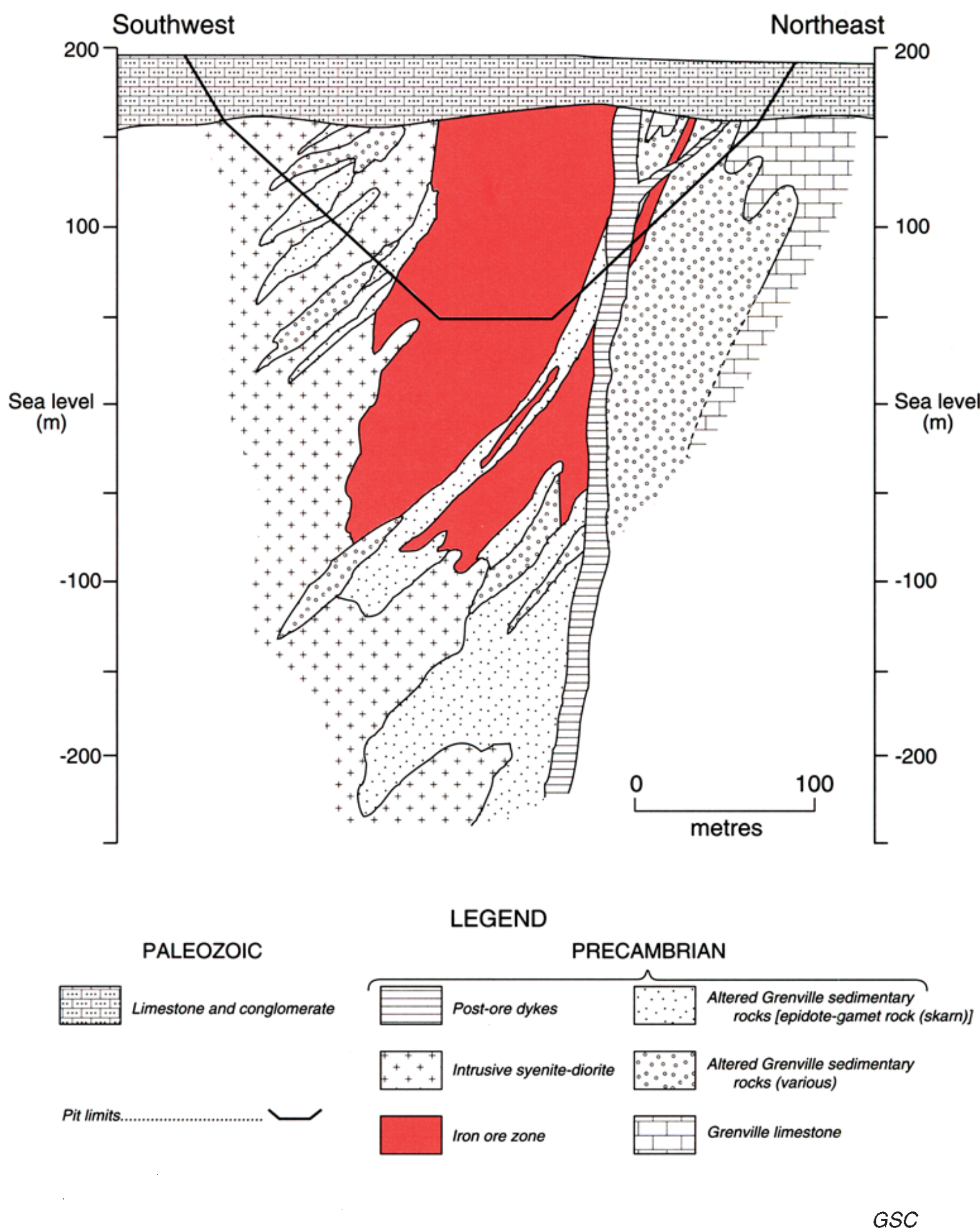

Figure 20.4-2. Geology in section of the Marmora iron mine, Hastings County, Ontario (after Rose, 1958).

Numerous small skarn deposits of all types in the southwestern part of the Grenville Province in Ontario and Quebec were studied extensively by Rose (1958, 1969) and Gross (1967a). Many of the deposits in this highly metamorphosed terrane are stratiform lenses of skarn developed in metasedimentary and metavolcanic rocks, gneisses, and schists.

The Marmora deposit lies within a belt of metasedimentary rocks composed of crystalline limestone, amphibolite, granite gneiss, and quartzitic gneiss that have been intruded by rocks of the gabbro-anorthosite-diorite group, by later granite and syenite, and finally by diabase dykes. The metasedimentary rocks in the mine strike north-northeast and dip 60°W. Marble predominates on the east side and considerable impure metaquartzite is distributed in the magnetite skarn and with the grey syenite and diorite intrusive masses which cut the skarn ore zone in the southwestern side and deeper parts of the mine (Fig. 20.4-2).

The ore deposit consists of a number of thin sinuous magnetite-rich zones, 15 to 30 m wide, composed of skarn rock impregnated with magnetite, that are roughly parallel to the strike and dip of the metasediments and form a large tabular mass about 130 m thick and 800 m long that extends in depth to 250 m. Most of the skarn, especially in the eastern part of the deposit, consists of medium- to fine-grained dark green pyroxene and amphibole and variable amounts of epidote, garnet, chlorite, and talc. Epidote-garnet-pyroxene skarn is more prevalent and coarser grained in the western part of the deposit near the syenite intrusions (Fig. 20.4-3).

Magnetite is mostly fine- to medium-grained and is disseminated in granoblastic textures with the skarn minerals, or forms thin lenses, shoots, and stringers in the skarn zone. Pyrite, pyrrhotite, and traces of chalcopyrite in fractures in the magnetite skarn were most abundant in the western part of the deposit where they formed less than 5% of the ore.

Figure 20.4-3. Banded magnetite ore with amphibole, pyroxene, garnet, and epidote gangue minerals, Marmora deposit, Ontario (GSC 152352 1-7-58; from Gross, 1967a).

GENETIC MODEL

Genetic processes for skarn deposits may vary greatly even in a single metallogene, and the complexities in the processes involved have been shown by studies of hydrothermal alteration in the Iron Hat skarn deposit in California by Hall et al. (1988). Major factors that influence the nature and distribution of skarn deposits are: 1) tectonic setting and geological history of an area; 2) depth of emplacement of intrusive rocks, mineral replacement, or metamorphism; 3) temperature of intrusions and wall rocks; 4) composition and petrogenesis of the associated igneous intrusions; and 5) composition of the sedimentary and associated volcanic rocks that were intruded.

Every skarn deposit is developed under a unique set of conditions and by a specific sequence of genetic processes which are difficult to discern in the final complex mineral assemblage.

Typical contact metasomatic skarn development takes place within the metamorphic aureoles developed around the margins of intrusive stocks where there is extensive circulation of hydrothermal solutions highly charged with metals derived by alteration and metamorphism of the wall rocks, and by cooling and differentiation of the adjacent magma. Hydrothermal solutions ranging in temperature to as great as 600°C may produce wall rock alteration and skarn mineral development at several stages or intervals during the formation of a deposit. In the course of wall rock alteration and skarn development, the hydrothermal solutions react most extensively with the carbonate rocks, resulting in an increase in their pH, silicification of the wall rock, development of silicate skarn minerals, and deposition of magnetite and other associated oxide and sulphide minerals. Three episodes of skarn formation in calcareous wall rocks adjacent to granite intrusions and two alteration events in the associated plutons have been documented for the Iron Hat skarn deposits in California (Hall et al., 1988).

Stratiform skarn deposits were probably derived from metasedimentary rocks originally rich in iron, or from mafic magmatic rocks in which the iron was mobilized to some extent during subsequent metamorphism. The genesis of skarn and igneous metamorphic deposits was discussed at some length by Park and MacDiarmid (1970), and Einaudi et al. (1981) and Meinert (1993) have given extensive consideration to the genesis of skarn deposits in general.

The large stratiform iron deposits of northern Sweden originally referred to as skarn iron ores are now considered by many to be highly metamorphosed sedimentary rocks and iron-formations, in which there has been considerable mobilization of the iron and of the magnesium and calcium constituents of the skarn minerals (Frietsch, 1973, 1974, 1977, 1978, 1979, 1980a, b, 1982a, b). The mineral assemblages and textures of many of the highly metamorphosed lithofacies of iron-formation in the Mount Wright and northeast regions of the Grenville Province in Canada (Gross, 1968) are very similar to those found in some of the stratiform skarn deposits.

RELATED DEPOSIT TYPES

Deposits related to skarn iron deposits may be classified into two principal groups. The first group includes syngenetic mineral concentrations in: a) the associated igneous intrusions, such as the banded and injected ilmenite and titaniferous magnetite deposits in anorthosite, gabbro, syenite, and granite; and b) the associated sedimentary and volcanic rocks, such as iron-formation and metalliferous sediments (Gross, 1968, 1986; Frietsch, 1973, 1974, 1977, 1978, 1980a, b, 1982a, b).

The second group includes skarn deposits of many different types and compositions that developed by replacement and alteration processes in the contact aureoles of intrusions, and consist of pegmatite dykes, veins, and disseminated mineralization in skarn zones.

Deposits of the second group are usually classified on the basis of the principal metals recovered and include iron-rich skarns as described above, copper-bearing skarn deposits, (e.g., Tasu, British Columbia); tungsten skarns, (e.g., MacMillan Pass, Yukon Territory); molybdenum skarns, (e.g., Little Boulder Creek, Idaho); zinc-lead-bearing skarns, (e.g., Naica, Mexico); tin-bearing skarns (e.g., Moina, Tasmania, and Pingyung in northern Kwangtung Province, China). Some deposits of this group associated with pegmatite dykes contain niobium, tantalum, uranium, rutile, and zirconium.

Skarn-related iron deposits also occur in volcanic breccias, volcanic necks, and calderas in association with explosive and intrusive breccia cemented by hematite, magnetite, siderite, pyrite, pyrrhotite, copper-bearing sulphides, uranium oxide, gold, silver, and rare-earth elements. The Olympic Dam deposits in Southern Australia are considered to be outstanding examples of skarn-related mineralization associated with intrusive and volcanic breccia (Kennedy, 1988).

A wide variety of nonmetallic mineral resources occur in skarn environments, including wollastonite, feldspar, mica, brucite, magnesite, talc, serpentinite, tremolite, spodumene, amblygonite, apatite, and graphite.

EXPLORATION GUIDES

Skarn deposits are most likely to be found in the contact zones and alteration aureoles around intrusive stocks, especially where these are associated with carbonate and calcareous clastic sediments, and volcanic rocks. Skarn mineral zones are usually indicated by a) hydrothermal alteration in the potential host rocks, especially in carbonate and mafic rocks that react readily to neutralize solutions of low pH; b) by evidence of silicification, chloritization, epidotization, and/or albitization in host rocks; and c) volatile constituents in the host rocks that could have been introduced by alteration processes.

Highly metamorphosed and deformed supracrustal sequences that contain iron-rich and calcareous strata are favourable host rocks for the development of stratiform skarn deposits.

Magnetic anomalies in highly metamorphosed terrane, even of a diffuse and irregular configuration, should be examined as they may indicate metalliferous zones that have been highly deformed, and where considerable mobilization of metals and rock constituents has taken place.

Many skarn deposits are too small to give geochemical anomalies, or they do not contain conspicuous marker elements that can be detected easily by geochemical prospecting methods. However, these methods may be used successfully in conjunction with detailed studies of host rock petrology and alteration aureoles.

Studies of host rock petrology may provide useful indicators of rock alteration and skarn development.

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20.5 SKARN TUNGSTEN

K.M. Dawson

IDENTIFICATION

Tungsten skarns are typically coarse grained assemblages of ore and calc-silicate gangue minerals that form commonly in the thermal aureole at the contact between felsic, calc-alkaline intrusive and calcareous sedimentary rocks. Scheelite, commonly with pyrrhotite and either chalcopyrite or molybdenite, is unevenly distributed throughout a prograde calc-silicate assemblage of mainly hedenbergitic pyroxene and grossular-andradite-almandine garnet, and a hydrous retrograde assemblage of mainly hornblende and biotite. Significant Canadian examples include Canada Tungsten, Northwest Territories; Salmo district, British Columbia; and MacMillan Tungsten, Yukon Territory. Some large foreign deposits include King Island, Tasmania; Sangdong, South Korea; Tyrnyauz and Vostok-2, Russia; Shizhuyuan, China; and Bishop district, California.

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IMPORTANCE

Almost 100% of Canadian tungsten production, which at one time constituted about 5% of the annual world production, has been derived from skarn deposits. Skarns are the second most important type of economic tungsten deposit after vein-stockwork deposits, and account for an estimated 30% of total world production.

SIZE OF DEPOSIT

The bulk of the world's skarn tungsten production and reserves is accounted for by relatively few deposits with greater than 10 000 t contained metal (Fig. 20.5-1). A few open pit mines, operated during World War II, produced ore with grades below 0.4% WO_3, but most underground operations require average grades of at least 0.4% WO_3. Remote areas, such as the northern Canadian Cordillera, require large scale mining of ore with an average grade of 1% WO_3 or greater. Tonnages and grades of significant Canadian and foreign skarn tungsten deposits are given in Figure 20.5-1 and Table 20.5-1. Size, grade, and other characteristics of global tungsten skarns have been tabulated by Einaudi et al. (1981).

GEOLOGICAL FEATURES

Geological setting

Tungsten skarns in the North American Cordillera are commonly localized in the thermal aureole of Mesozoic plutons that have discordantly intruded Paleozoic cratonal shelf carbonate-pelite sequences. In the Omineca Belt of the eastern Canadian Cordillera, tungsten-rich skarns are hosted by North American miogeoclinal shelf limestone-pelite assemblages and their displaced equivalents. Several developed prospects with large reserves define an arcuate belt which includes Canada Tungsten (Cantung) mine and flanks Selwyn Basin on the east and northeast (Fig. 20.5-2).

Tungsten skarns are emplaced in a generally deeper, higher temperature, and more reduced environment than Cu- and Zn-rich skarns, as deduced from extensive thermal aureoles, coarse grained intrusive textures, presence of aplites and pegmatites, lack of breccias and hydrothermal alteration, low ferric:ferrous ratios in calc-silicate gangue, and abundant carbon and pyrite in host rocks. A typical example of a pluton associated with a reduced tungsten skarn is the MacMillan Tungsten (Mactung) stock (Dick and Hodgson, 1982), a coarse grained K-feldspar megacrystic quartz monzonitic member of the calc-alkaline Selwyn plutonic suite (Anderson, 1983). An oxidized subtype of tungsten skarn, exemplified by King Island, Tasmania, formed in noncarbonaceous or hematitic rocks at lesser depths (Newberry, 1979).

Age of host rocks, associated rocks, and mineralization

Host rocks for tungsten skarns are the contact metamorphosed equivalents of relatively pure limestones and calcareous to carbonaceous pelites: skarn, calc-silicate hornfels, and biotite-pyrite hornfels. On a global basis, host rocks ranging in age from late Proterozoic to early Mesozoic have been intruded by granitoid plutons that are dominantly Paleozoic to late Mesozoic. Exceptions include the Fostung (Ontario) and Yxsjöberg (Sweden) deposits, which are associated with Proterozoic granite plutons, and the San Alberto (Mexico) deposit, which is associated with a Tertiary pluton. Cordilleran skarns have developed preferentially in the lowest thick limestone bed of an Upper Proterozoic to Carboniferous cratonal or pericratonic sedimentary sequence. A typical Canadian Cordilleran setting is Cambrian shelf limestone, underlain by and interbedded with pelite and carbonaceous shale, and intruded by a postorogenic mid-Cretaceous quartz monzonite stock.

Intrusive rocks associated with tungsten skarns are calc-alkaline felsic stocks, plutons, or batholiths. Quartz monzonite is most common; quartz diorite is least common. Newberry and Swanson (1986) noted that most granitoids associated with scheelite skarns in the western United States show features characteristic of the 'I-type granites' of Chappell and White (1974). Tungsten skarn-related granitoid plutons in the northern Canadian Cordillera, on the other hand, are both 'S-type' and 'I-type' (Anderson, 1983). Plutons commonly are coarse grained, porphyritic, and unaltered, but border phases are in some cases locally

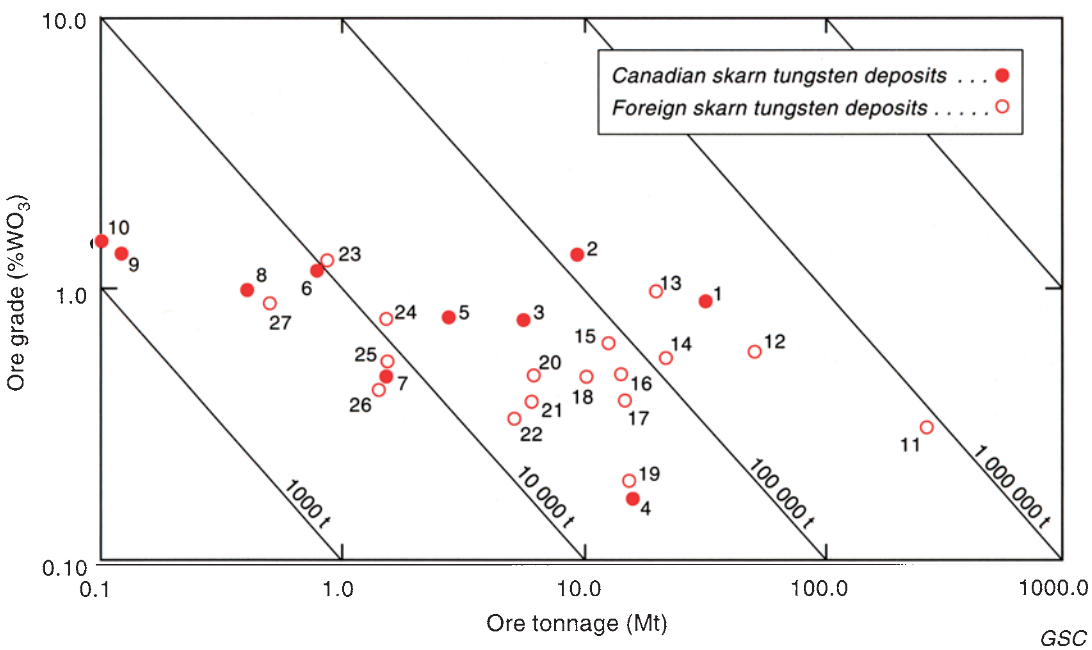

Figure 20.5-1. Grade versus tonnage of significant Canadian and foreign skarn tungsten deposits. Numbers correspond to deposits listed in Table 20.5-1.

Contents

argillized, greisenized, or tourmalinized. Stockwork quartz+scheelite+molybdenite veins are not extensive, but are more abundant in the intrusive rock than in the skarn. Porphyritic dykes are rarely associated with W skarns, but aplite and pegmatite dykes are common. Breccia pipes, intrusive and shatter breccias, and other features indicative of high levels of emplacement are absent.

Ore deposition is penecontemporaneous with emplacement of associated intrusive rocks: dominantly Paleozoic in Europe, the former Soviet Union, and Australia; Late Mesozoic in eastern Asia; and Late Jurassic to Early Tertiary, but mainly Cretaceous, in the North American Cordillera. A few deposits, as cited above, are Proterozoic in age.

Table 20.5-1. Tonnage and grade of significant Canadian and foreign tungsten skarn deposits, listed in decreasing order of contained tungsten metal.

Deposit	Tonnage; grade	Comments/references
Canadian deposits		
1. MacMillan Tungsten (Mactung), Yukon Territory	32 Mt; 0.92% WO_3	Reserves (Atkinson and Baker, 1986)
2. Canada Tungsten (Cantung), Northwest Territories	9 Mt; 1.42% WO_3	Production plus reserves (Mathieson and Clark, 1984)
3. Ray Gulch, Yukon Territory	5.44 Mt; 0.82% WO_3	Reserves (Lennan, 1986)
4. Fostung, Ontario	16.2 Mt; 0.23% WO_3	Reserves (Ginn and Beecham, 1986)
5. Risby, Yukon Territory	2.7 Mt; 0.81% WO_3	Reserves (The Northern Miner, 8 July, 1982, p. 30)
6. Lened, Northwest Territories	about 0.75 Mt; 1.2% WO_3	Reserves (Glover and Burson, 1986)
7. Salmo district, British Columbia	about 1.5 Mt; 0.5% WO_3	Production 1943-1973 (Mulligan, 1984)
8. Bailey, Yukon Territory	0.4 Mt; 1.0% WO_3	Reserves (D.I.A.N.D., 1981)
9. Baker, Northwest Territories	about 0.12 Mt; 1.4% WO_3	Reserves (S. Bartlett, pers. comm., 1986)
10. Clea, Yukon Territory	about 0.1 Mt; 1.5% WO_3	Reserves (Godwin et al., 1980)
Foreign deposits		
11. Shizhuyuan, China	170 Mt; 0.33% WO_3	Reserves, about 2/3 is skarn (Zhang, 1980)
12. Tyrnyauz, Russia	50.8 Mt; 0.6% WO_3	In situ resources (Anstett et al., 1986)
13. Sangdong, South Korea	about 20 Mt; 1.0% WO_3	Production 1916-1985, plus reserves (Yih and Wang, 1979; Anstett et al., 1986)
14. Vostok-2, Russia	22 Mt; 0.58% WO_3	In situ resources (Anstett et al., 1986)
15. King Island, Tasmania	13 Mt; 0.65% WO_3	Production 1911-1972, plus reserves (Danielson, 1975)
16. Uludag, Turkey	14.5 Mt; 0.5% WO_3	Reserves (Karahan et al., 1980)
17. Brejui/Barra Verde/Boca de Lage, Brazil	about 15 Mt; 0.4% WO_3	Production 1943-1985, plus reserves (Willig and Delgado, 1985)
18. Pine Creek, California	about 10 Mt; 0.5% WO_3	Production 1918-1977 (Yih and Wang, 1979)
19. Indian Springs, Nevada	15.8 Mt; 0.2% WO_3	Reserves (Nevada State Journal, 05 October 1969)
20. Brown's Lake, Montana	about 6 Mt; 0.5% WO_3	Production 1953-1958, plus reserves (J.E. Elliott, pers. comm., 1985)
21. Mill City district, Nevada	about 6 Mt; 0.4% WO_3	Production 1925-1958, plus reserves (J.E. Elliott, pers. comm., 1985)
22. Yxsjöberg, Sweden	5 Mt; 0.3-0.4% WO_3	Production 1938-1963, plus reserves (Hübner, 1971)
23. Salau, France	0.85 Mt; 1.48% WO_3	Production 1972-1977, plus reserves (Reymond, 1981)
24. Los Santos, Spain	1.5 Mt; 0.8% WO_3	Reserves (Billiton Espanola, internal report, 1987)
25. San Alberto, Mexico	about 1.5 Mt; 0.55% WO_3	Reserves (W. Gruenweg, pers. comm., 1986)
26. Osgood Mountains, Nevada	1.4 Mt; 0.45% WO_3	Production 1942-1955 (Hotz and Willden, 1964)
27. Strawberry, California	0.5 Mt; 0.9% WO_3	Production 1942-1966, plus reserves (Nokleberg, 1981)

Form of deposit and associated structures, zoning, and distribution of ore and gangue minerals

Tungsten skarns commonly form as essentially stratiform exoskarns tens to hundreds of metres away from an intrusive contact and are continuous for as much as hundreds of metres along a lithological, e.g., carbonate-pelite, contact. Tungsten skarns also form as semiconcordant to discordant bodies immediately adjacent to an intrusive contact, either as early reaction skarn, metasomatic exoskarn, or as retrograde alterations of both. They form less commonly as endoskarn, either as replacements of the intrusive rock itself or of xenoliths, roof pendants, and screens within a plutonic border phase. In both prograde and retrograde skarn assemblages, essentially stratiform replacement textures predominate over discordant, vein-like morphology. Abundant fractures, like other indications of forceful emplacement of the intrusion, are lacking. Vein skarns are rare. The structurally and lithologically controlled evolutionary stages and morphologies of a typical skarn are shown in Figure 20.2-7 (in subtype 20.2, "Skarn copper").

Scheelite commonly occurs in an essentially stratiform almandine-hedenbergite exoskarn assemblage that metasomatically overprints and replaces earlier metamorphic calc-silicate hornfels. Scheelite also may be erratically redistributed in association with structurally-controlled retrograde amphibole-biotite alteration. Scheelite, commonly with pyrrhotite and either chalcopyrite or molybdenite, is unevenly distributed throughout the prograde and retrograde calc-silicate mineral assemblages. Mineral zoning may be well developed and typically consists of sphalerite deposited peripherally to scheelite-rich skarn. Pyrrhotite and biotite-amphibole-rich skarn assemblages are structurally controlled, and retrograde alteration products of garnet and pyroxene-rich skarn and pyrite occupy late structures.

Prior to its 1986 closure, the Canada Tungsten (Cantung) mine at Tungsten, Northwest Territories (Fig. 20.5-2) was the largest tungsten producer in the western world. Other significant Canadian production has been obtained from four skarn deposits in the Salmo district of southeastern British Columbia (Fig. 20.5-1 and 20.5-2). At Cantung, three high-grade scheelite skarn orebodies are localized in the limbs of an overturned anticline composed of the Lower Cambrian 'Swiss Cheese limestone' and 'Ore limestone' host rocks which are underlain by phyllite and overlain by quartzite and dolomite (Blusson, 1968). A schematic geological cross-section through the mine area (Fig. 20.5-3) shows the E-zone orebody developed in the lower limb adjacent to the shallowly dipping contact of a mid-Cretaceous quartz monzonite stock. This deposit, which had initial reserves of 4.2 Mt of 1.6% WO_3, is unusually large and high grade. Zonal distribution of skarn facies and relative W contents of the E-zone orebody are shown in Figure 20.5-4.

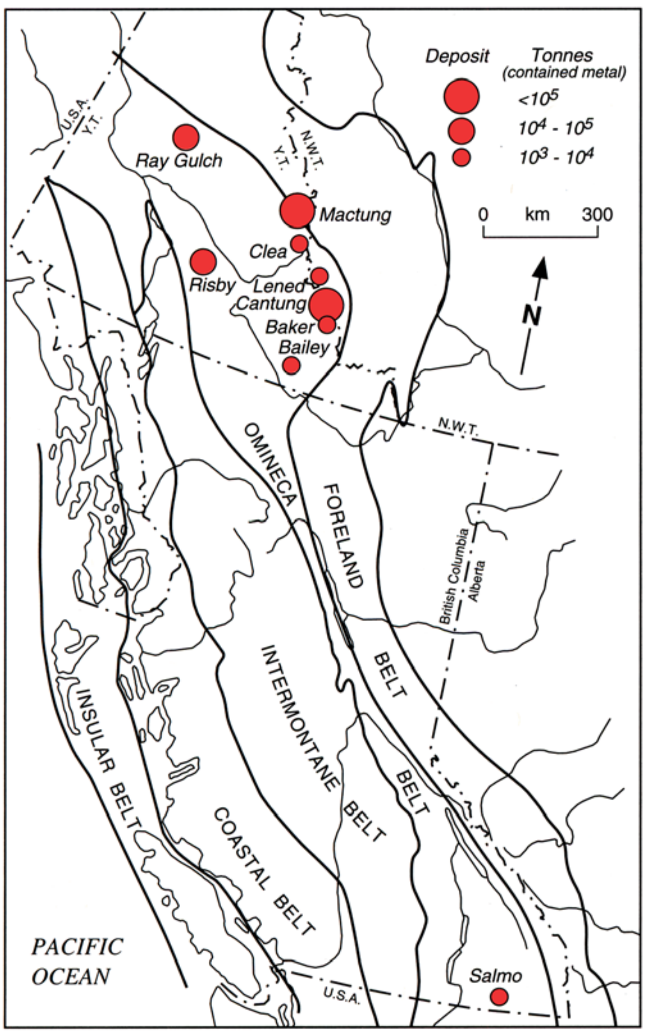

Figure 20.5-2. Significant skarn tungsten deposits of the Canadian Cordillera.

Mineralogy

Principal ore mineral: scheelite.

Opaque minerals: chalcopyrite, sphalerite, molybdenite, pyrrhotite, pyrite (late), magnetite, bismuth, bismuthinite.

Prograde skarn minerals: pyroxene (hedenbergite-diopside), garnet (grossularite-andradite-almandine); calcite, dolomite, quartz, vesuvianite, wollastonite.

Retrograde skarn minerals: hornblende, biotite, plagioclase, epidote, sphene, chlorite, actinolite, apatite.

DEFINITIVE CHARACTERISTICS

1. Stratiform skarn morphology dominates over discordant and vein-like forms.
2. Extensive thermal aureoles are commonly developed in shelf carbonate-pelite host rocks.
3. Associated intrusions are coarse grained, unaltered, porphyritic, felsic, calc-alkaline granitoid stocks.
4. Associated dykes are pegmatite and aplite, rarely porphyry.
5. Breccias, breccia pipes, intense stockwork fractures in the intrusion and other high level structures are generally absent.

6. Deposits of reduced subtype have low ferric:ferrous ratios in skarn, and pyrite and carbon are present in their host rocks; deposits of oxidized subtype have high ferric:ferrous ratios, and hematite is present in their host rocks.

GENETIC MODEL

Tungsten, associated metals, sulphur, and cations other than calcium were derived mainly from the associated pluton by the separation of a magmatic-hydrothermal fluid. Constituents of opaque minerals, deposited abundantly during the cooling of the system, were derived mainly from an evolved hydrothermal fluid and, to a lesser extent, from the alteration of early minerals. The contribution of metals and sulphur from host and basement rocks by the late stage influx of meteoric waters, relative to associated plutonic rocks, is not known. Isochemical thermal metamorphism of limestone to marble and calcareous pelite to calc-silicate hornfels preceded the main stage of prograde metasomatic reactions. Hydrothermal fluids, released by crystallization and hydrofracturing of the pluton, infiltrated stratigraphic and structural channelways to react with calcareous host rock and calc-silicate hornfels to form prograde skarn. Chemical components of the system are of both local and exotic derivation: endoskarn forms in the pluton by introduction of calcium from the host rock, magnesian exoskarn forms in dolostones, and calcic exoskarn forms in limestones. The mineral assemblage of the resultant skarn is influenced by the composition, temperature, and oxidation state of the system. A typical calcic assemblage would include contemporaneously developed almandine-hedenbergite-scheelite exoskarn in calc-silicate hornfels, wollastonite-vesuvianite distal metamorphic skarn in marble, and hornblende-pyroxene-biotite-plagioclase endoskarn in the pluton and

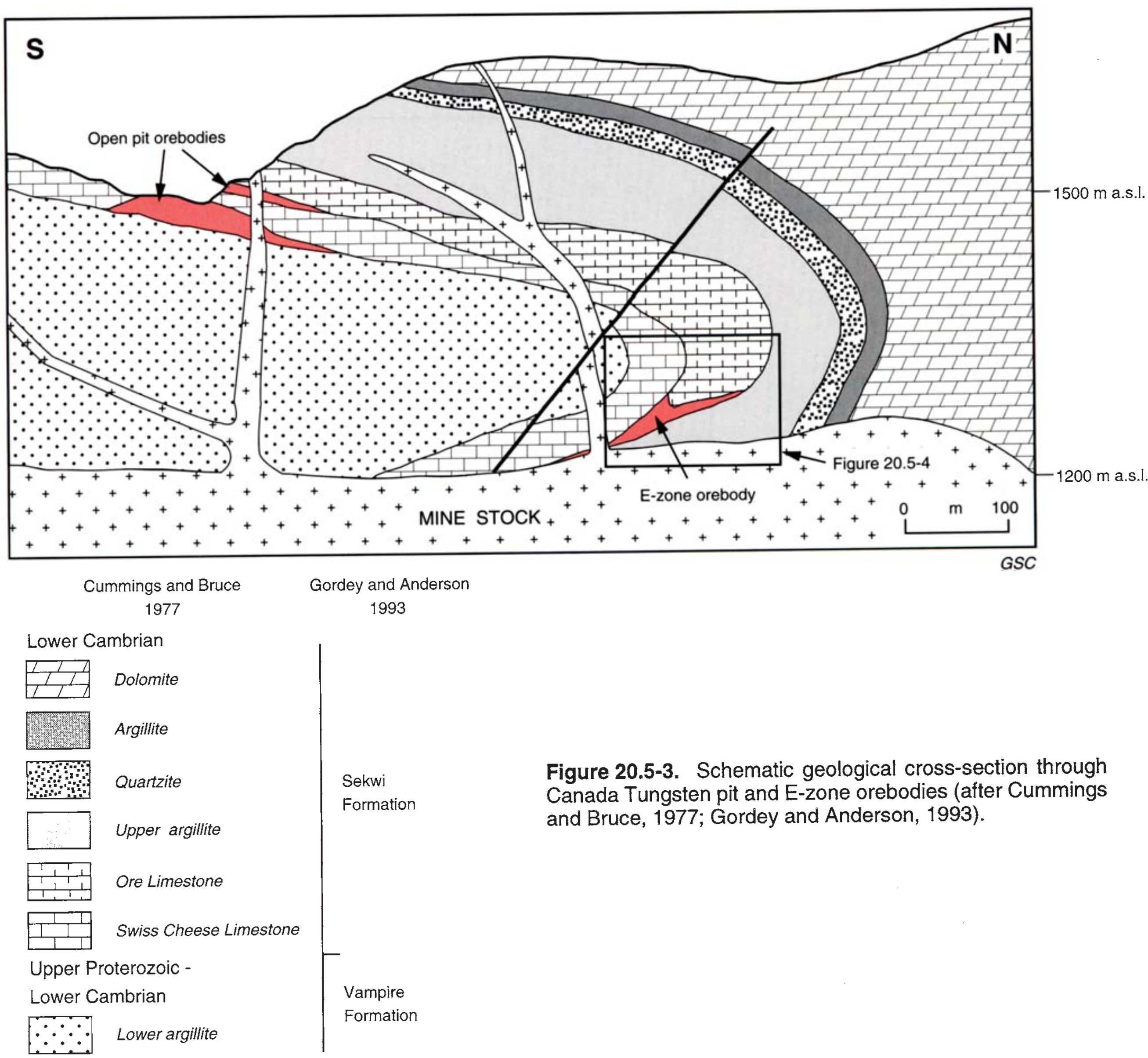

Figure 20.5-3. Schematic geological cross-section through Canada Tungsten pit and E-zone orebodies (after Cummings and Bruce, 1977; Gordey and Anderson, 1993).

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in pelitic hornfels. Early anhydrous skarn is deficient in tungsten and sulphides, late stage prograde calcic skarn is enriched in ferric iron, manganese, sulphides, and scheelite. The main period of deposition of opaque minerals followed the termination of prograde skarn development, and accompanied the start of hydrous alteration of early skarn minerals and associated intrusive rocks. Subsequent cooling of the system and influx of meteoric water initiated hydrous retrograde alteration of early, calcium-rich silicates to calcium-depleted silicates, iron oxides, carbonates, and plagioclase. Processes occurring at this stage may have included hydrolytic alteration of associated intrusive rocks, deposition of most sulphides, and either primary deposition of scheelite or its redistribution with both depletion and upgrading. The suite of opaque minerals associated with hydrous retrograde assemblages reflects higher oxidation and sulphidization states and lower temperatures than conditions associated with early prograde opaque minerals. Evolutionary stages for skarns in general are given in Figure 20.2-7.

RELATED DEPOSIT TYPES

Some skarn tungsten deposits in the northern Canadian Cordillera are associated with quartz-molybdenite-scheelite stockworks in the adjacent intrusion, but none of these stockworks approach economic proportions as porphyry molybdenum-tungsten deposits. Molybdenum- and tungsten-bearing veinlets are confined mainly to altered border phases of the plutons, but in some cases overprint the adjacent scheelite-rich calc-silicate skarns. Several Mo-W stockwork-skarn deposits of this type, hosted by Lower Paleozoic limestones of the Cassiar Terrane in northern British Columbia and southern Yukon Territory, include the Logtung, Mount Haskin, and Boya prospects (Dawson et al., 1991; see Type 19, "Porphyry copper, gold, molybdenum, tungsten, tin, silver"). A large foreign example is the Shizhuyuan composite W skarn, W-Bi-Mo greisen-stockwork deposit in southern Hunan, China (Yang, 1982).

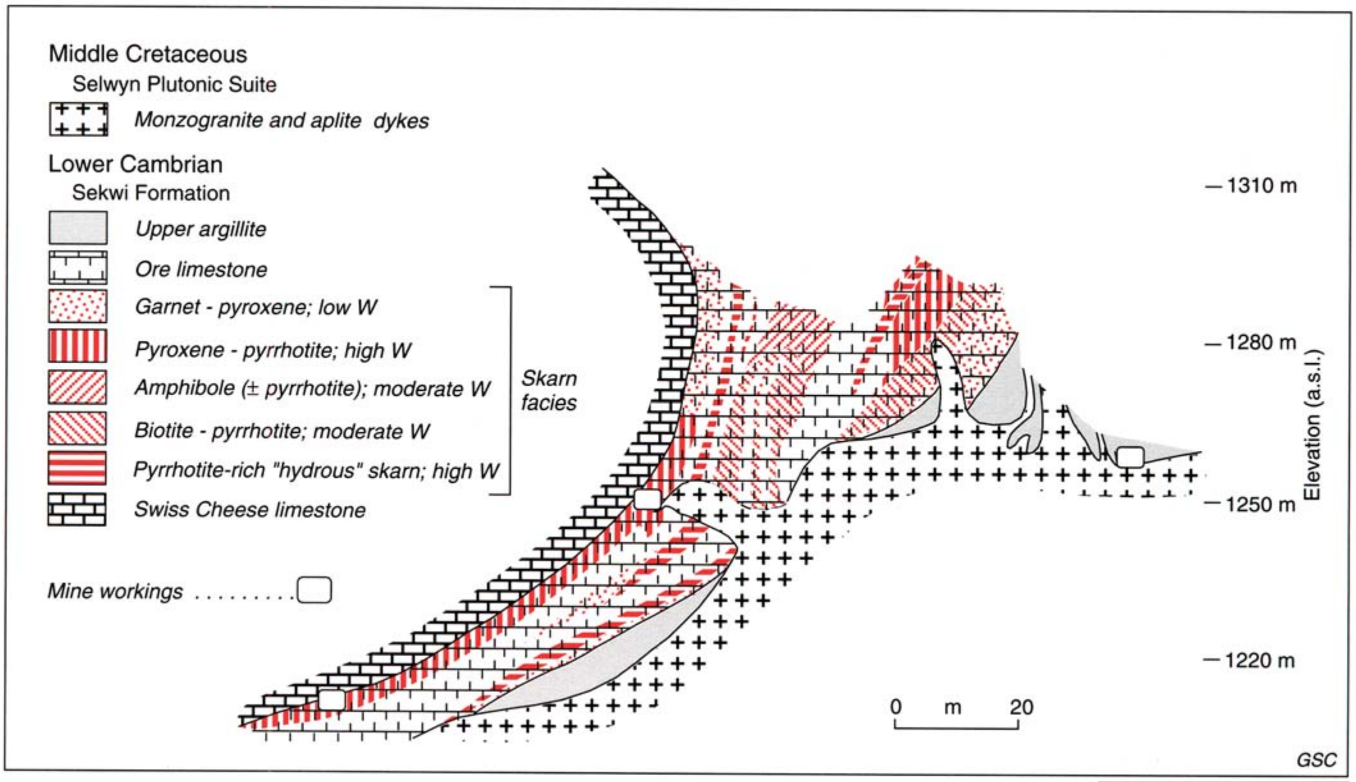

Figure 20.5-4. Cross-section 1215W through the Cantung E-zone orebody, lying to the west of the schematic section in Figure 20.5-3 (after Mathieson and Clark, 1984). Note anhydrous skarn along the Ore limestone unit in the footwall and hanging wall, and hydrous, in part pyrrhotite-rich, skarn facies in the axial zone (after Mathieson and Clark, 1984).

EXPLORATION GUIDES

Geological guides

The following geological features within a prospective terrain are favourable exploration guides:

a) Extensive hornfels zone adjacent to an exposed pluton, or overlying a buried one.
b) Relatively thick, pure and impure limestone beds.
c) Shallowly dipping pluton-limestone contacts.
d) Structural and stratigraphic traps in carbonate-pelite host rocks.
e) Irregularities in pluton-limestone contact, particularly reentrants and troughs.
f) Stockwork fracturing along pluton-limestone contact.

Geochemical guides

In regional geochemical soil and silt sampling surveys, samples of conventional size are less effective in detecting the dominantly particulate scheelite than are bulk samples of alluvium collected from principal drainages and reduced to a heavy mineral concentrate.

The elements Cu, Mo, and Zn, generally associated with W in skarns, may be used as pathfinders in regional geochemical surveys. Waters draining from plutons related to W skarns may be enriched in F.

Geophysical guides

Shallowly buried plutons, which may have controlled the development of W skarns, may be detected readily by airborne magnetic surveys due to their characteristically annular magnetic high surrounding a central low.

Multispectral satellite imagery may be selected to enhance colour anomalies associated with oxidized pyritic hornfels developed extensively in pelitic host rocks adjacent to the less extensive W skarn.

Prospecting guides

The effectiveness of the ultraviolet lamp as a scheelite prospecting tool is improved markedly by first locating, in daylight, prospective terrain, such as the base of a talus slope below a granite-limestone contact. The area should then be systematically prospected with the lamp during darkness, and any scheelite marked for follow-up examination in daylight.

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