A review of skarns in the Canadian Cordillera

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Cover photo: Coarse-grained garnet-quartz-scheelite exoskarn. Dimac (Silence Lake) Mine, Clearwater, central British Columbia (photo 18).

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Abstract

The Canadian Cordillera has more than 1000 recorded skarns. These range from small barren occurrences to megaskarns comprising several cubic kilometers of garnet and/or pyroxene alteration, some of which contain deposits with over 30 million tonnes of ore. Megaskarns probably form during a long-lived diachronous hydrothermal process where prograde and retrograde alteration operate coevally. This model has implications for exploration; it explains why the bulk of retrograde alteration in most skarns is barren and its presence is not always a reliable guide to locate ore. Most of the 1000 recorded skarns have calcic mineral assemblages; magnesian skarns are uncommon, excepting some deposits in the Whitehorse Cu belt. The skarns can be broadly separated into the following three groups:

(a) 27 occurrences associated with Cu, Mo, or W porphyry deposits, although the skarn alteration in many is only a minor part of the porphyry system.

(b) 37 occurrences where large Au ± Cu-bearing quartz and/or sulfide veins are enveloped by barren exoskarn. However, in many the genetic and temporal relationships between the veins and the skarn are unknown.

(c) 962 occurrences that are either related to barren intrusions or have no known igneous parent (695 in British Columbia; 267 in the Yukon and a small number in the NWT).

On the basis of chemistry or mineralogy, this group of 962 skarns can be subdivided into Cu (436), Fe (147), Pb-Zn (142), W (117), Au (33), Mo (29), Sn (19), industrial mineral (19), and unknown (16) classes. An additional 4 occurrences in the Yukon may represent U or rare earth element (REE) skarns. Although the Yukon is substantially smaller than British Columbia, it contains far more Sn and W skarns, and much fewer Fe, Au and Cu skarns. The abundance of Sn and W skarns in the Yukon reflects pluton derivation from continental crust enriched in lithophile-elements. In contrast, British Columbia plutons are mainly island arc-related and thus associated with chalcophile skarn deposits.

Most of the >1000 skarns formed during three major plutonic episodes (Early to mid Jurassic, Cretaceous and Eocene-Oligocene) each of which produced skarns with distinctly different metallogenies. Most of the Au, Cu and Fe skarns in British Columbia were generated during the Jurassic episode, whereas most Sn and W skarns across the Canadian Cordillera originated in the Cretaceous.

Skarns occur in 24 terranes and subterranes, but most are in Wrangellia, Stikinia, Quesnellia, Cassiar, Yukon-Tanana, Selwyn Basin, and rocks of ancestral North America. A spatial and temporal relationship exists between certain skarn classes, their metal production, and the character and origin of the host terranes. Over 80 % of the skarns in British Columbia are hosted by terranes with predominantly island-arc rocks, and these account for most of the Fe, Cu, and Au produced from skarns in the province. By contrast, only 5 % of the skarns in British Columbia are hosted by the North American craton, yet these are responsible for all the province’s tungsten production. Parts of the Canadian Cordillera containing abundant intrusive rocks are not necessarily the best areas to find skarn deposits. Although the Coast Belt has the greatest concentration of plutonic rocks in the region, it hosts less than 4 % of the skarn occurrences, all with negligible metal production.

1.0 Introduction

The Cordillera of western Canada has had a long history of mining metal from skarn, and some of its Au, Cu, Fe and W deposits can be classed as "megaskarns" due to their world-class size and metal grade (Fig. 1). The Nickel Plate mine at Hedley in southern British Columbia, for example, represents one of the North America's largest gold skarns; it produced over 71 tonnes of gold metal (Ray et al., 1996) and represented a 13.4 Mt deposit grading approximately 5.3 g/t Au. Some of the largest Cu porphyry deposits are associated with various amounts of peripheral mineralized skarn; they include Ingerbelle (> 80 Mt of c. 0.4 % Cu and 0.2 g/t Au) and Mount Polley (> 48.8 Mt of 0.38 % Cu and 0.55 g/t Au). Other major Cu skarns, which are associated with generally barren igneous rocks, include Craigmont (c. 29 Mt of 1.18 % Cu) and Phoenix (c. 21 Mt of 1.09 % Cu and 1.3 g/t Au) in southern British Columbia, and the Whitehorse Copper Belt (c. 10.1 Mt of 1.5 % Cu) in the Yukon. The world-class W skarns of the northern Cordillera include Mactung (Yukon) with reserves of 57 Mt grading 0.95 % WO_3 and Cantung in the Northwest Territories, with production plus reserves of approximately 9 Mt at 1.42 % WO_3.

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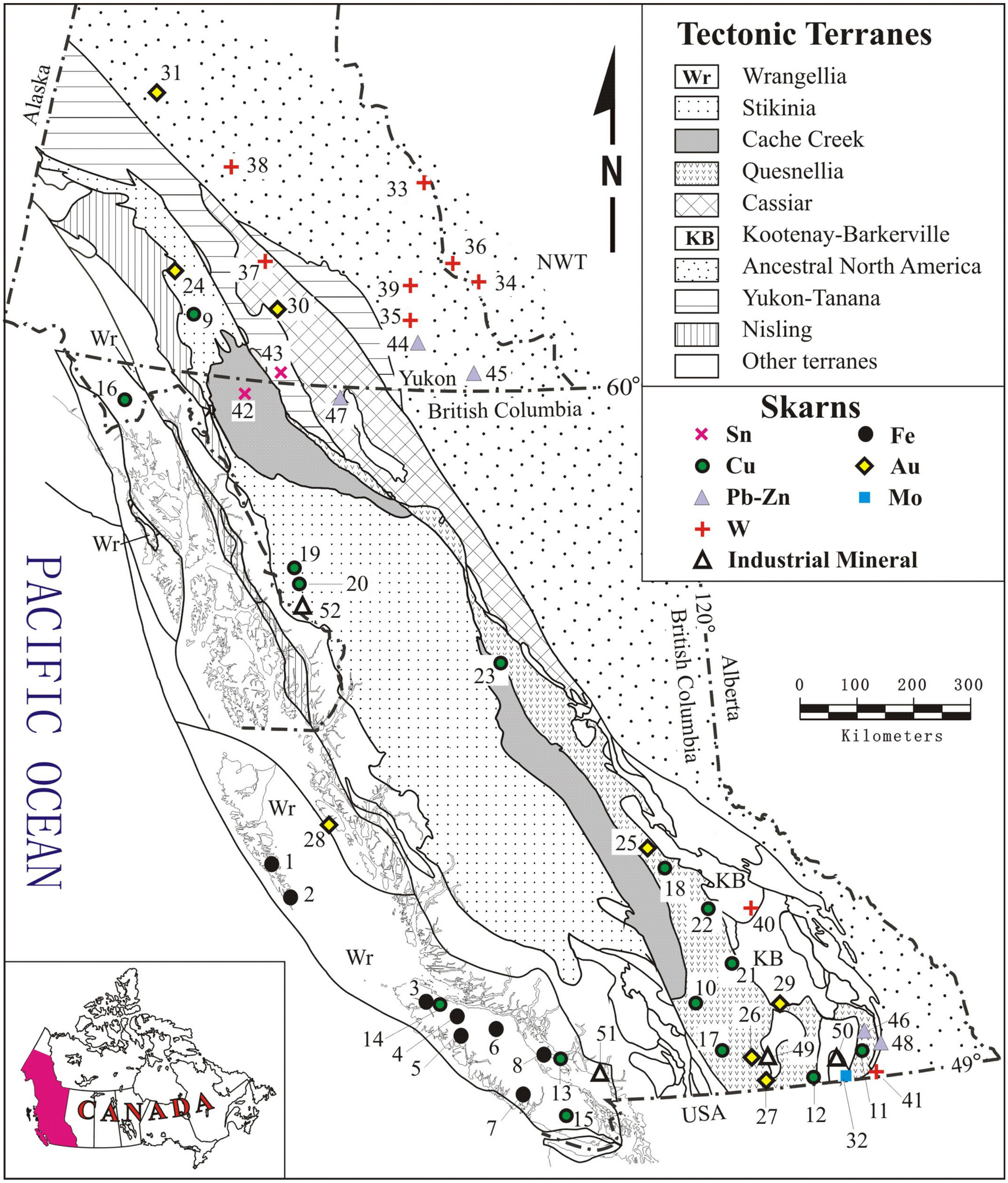

Fig. 1. Simplified terrane map of the Canadian Cordillera (after Wheeler et al., 1991) showing locations of significant skarns or mantos.

Fe skarns: 1) Tasu (Sutherland Brown, 1968; Sangster, 1969); 2) Jessie-Jedway (Sutherland Brown, 1968; Sangster, 1969); 3) Merry Widow, Kingfisher (Eastwood, 1965; Haug, 1977; Ray and Webster, 1991); 4) Iron Crown (Sangster, 1969; Meinert, 1984); 5) Ford (Sangster, 1969); 6) Iron Hill (Sangster, 1969; Meinert, 1984); 7) Brynnor (Sangster, 1969); 8) Texada Island (Prescott, Paxton, Yellow Kid, Lake) (Bacon, 1957, 1984; Webster and Ray, 1990a, b).
legend continues on following page

Fig. 1, continued.
Cu skarns: 9) Whitehorse Cu (Little Chief, Arctic Chief, War Eagle etc.) (Kindle, 1964; Morrison, 1981; Tenney, 1981; Meinert, 1986); 10) Craigmont (Morrison, 1980; Webster et al., 1992); 11) Queen Victoria (Little, 1960; Webster et al., 1992; Ray and Webster, 1997); 12) Greenwood (Phoenix, Motherlode, Emma etc.) (Church, 1986; Ettlinger and Ray, 1989; Ray and Webster, 1997); 13) Texada Island (Marble Bay, Cornell, Little Billie) (Ettlinger, 1990; Webster and Ray, 1990a, b); 14) Old Sport, Benson Lake (Eastwood and Merrett, 1962; Ettlinger and Ray, 1989; Ray and Webster, 1991); 15) Blue Grouse (Fyles, 1955; BC Minfile); 16) Rainy Hollow (Maid of Erin, State of Montana) (Webster et al., 1992); 17) Ingerbelle (porphyry-related) (Fahrni et al., 1976; Preto, 1972); 18) Mount Polley (porphyry-related) (Fraser et al., 1995; Rees, 2013); 19) Galore Creek (porphyry-related) (Enns et al., 1995); 20) McLymont NW (Ray et al., 1991); 21) Heff (Ray and Webster, 2000, 2007); 22) Deer Lake (Schiarizza and Israel, 2001); 23) Lustdust (Megaw, 2001, Ray et al., 2002; Oliver, 2002).
Au skarns: 24) Guder (Yukon MINFILE); 25) Quesnel River (QR) (Fox and Cameron, 1995); 26) Hedley (Nickel Plate, French, Canty etc.) (Billingsley and Hume, 1941; Ettlinger et al., 1992; Ray and Dawson, 1994); 27) Dividend-Lakeview (Ettlinger and Ray, 1989); 28) Banks Island (Ettlinger and Ray, 1989); 29) Tillicum Mountain (Ettlinger and Ray, 1989; BC MINFILE); 30) Ketza River (Manto) (Cathro, 1990; Dawson, 1996b); 31) Marn and Horn (Brown and Nesbitt, 1987; Yukon MINFILE).
Mo skarns: 32) Coxey, Novelty etc. (Little, 1963; Fyles, 1984; Hoy et al., 1992; Webster et al., 1992).
W skarns: 33) MacTung (Dick, 1976, 1980; Dick and Hodgson, 1982, 1983); 34) CanTung (Dick, 1980; Dick and Hodgson, 1983; Bowman et al., 1985); 35) Bailey (Thompson, 1978; DIAND, 1981; Yukon MINFILE); 36) Lened (Dick, 1980; Glover and Burson, 1987); 37) Risby (Northern Miner July 8, 1982, p. 30; Yukon MINFILE); 38) Ray Gulch (Lennan, 1986; Yukon MINFILE); 39) Woah, Cali (Dick, 1980; Yukon MINFILE); 40) Dimac (Dawson et al., 1983; Brown, 1985; Webster et al., 1992); 41) Salmo Camp (Emerald Tungsten, Dodger etc.) (Fyles and Hewlett, 1959; Mulligan, 1984; Ray and Webster, 1997).
Sn skarns: 42) Atlin (Ray et al., 1997, 2000); 43) JC (Viola) (Dick, 1980; Layne and Spooner, 1986, 1991).
Pb-Zn skarns: 44) Sa Dena Hes (Dawson, 1964; Abbott, 1977, 1981; Dick, 1979, 1980); 45) Quartz Lake (Vaillancourt, 1982); 46) Piedmont (Webster et al., 1992; Ray and Webster, 1997); 47) Midway (Manto) (Bradford, 1988; Nelson, 1991); 48) Bluebell (Manto) (Hoy, 1980).
Industrial mineral skarns: 49) Mount Riordan-Crystal Peak (Garnet) (Grond et al., 1991; Ray et al., 1992); 50) Rossland Wollastonite (Wollastonite) (Stinson, 1995); 51) Mineral Hill (Wollastonite) (Ray and Kilby, 1996a,b); 52) Isk-Zippa Mountain (Wollastonite) (Jaworski and Dipple, 1996).

The British Columbia and Yukon MINFILES and the NWT NORMIN databases contain details on more than 1000 occurrences of skarn, as defined by Burt (1977). They record the alteration and mineral assemblages at each skarn, as well as host-rock descriptions, the nature and age of associated intrusive rocks, and details concerning past scientific investigations, exploration, and mining.

At least 735 skarns are recorded in British Columbia, 291 in the Yukon (Fig. 2; Table 1) and a smaller number occur in the NWT. Most are believed to be infiltration skarns related to magmatic-hydrothermal fluids and the majority of these have calcic mineral assemblages (i.e., garnet-clinopyroxene-epidote-wollastonite). However, in a few significant instances (e.g. parts of the Whitehorse Copper Belt) some magnesian silicates are present. Generally however, magnesian skarns with olivine-serpentinite-phlogopite gangue assemblages are relatively rare in western Canada, which reflects the absence of major plutonism in areas with either extensive platformal dolomites or Mg-rich tuffaceous rocks.

Most of the >1000 known skarns are associated with varying amounts of metallic minerals, and they range from small occurrences to large deposits that contain >30 Mt of ore. In addition, a small group of skarns has been explored for their industrial mineral potential due to the presence of abundant high-grade garnet, wollastonite or marble.

This paper lists the significant skarns and skarn deposits in the Canadian Cordillera (Fig. 1) and examines their distribution, age, tectonic setting, and the mineralogy and chemistry of the various skarn deposit classes. It also presents a model to explain the long-lived, diachronous development of megaskarns with huge volumes of exoskarn alteration. Where applicable, information is given about the chemistry of the ore assemblages, the gangue minerals and the associated intrusive rocks (Table 3). Production data presented from some of the historic mining is uncertain. For example, in the databases the tonnage milled may exceed the tonnage mined at some skarn deposits, probably because ore was also processed from other mines in the district. Most of the reserve figures quoted are derived from the MINFILE systems and may not be valid under current National Instrument 43-101 regulations.

2.0 Previous work

Leaning heavily on previous studies and on data from historic mining and exploration, this review updates Ray and Dawson (1998). Reviews on the various classes of skarn deposits in Canada, including the Canadian Cordillera, are given by Anderson (1983), Anderson et al. (1983), Dawson (1996 a,b,c), Dawson and Kirkham (1996) and Gross (1996). Many of the major skarn deposits mined in the Canadian Cordillera during the early part of the 20th Century (e.g. the Whitehorse Copper Belt in the Yukon, and the Phoenix-Greenwood and Hedley camps in British Columbia) received considerable research. Early publications about the Whitehorse Copper belt include McConnell (1909), Cockfield and Bell (1926), Wheeler (1952), and Kindle (1964); later studies are outlined by Morrison (1981), Tenney (1981), Meinert (1986), and Mackay et al. (1993).

Major early advances in understanding the Hedley Au skarn camp are outlined by Camsell (1910), Bostock (1930), Dolmage (1934), Billingsley and Hume (1941), and Dolmage and Brown (1945). Later studies at Hedley were completed by Ettlinger et al. (1992), Dawson (1994), Dawson et al. (1990), Ray and Dawson (1987, 1988, 1994), and Ray et al. (1988, 1996). Work in the Phoenix-Greenwood area (Fig. 1) includes

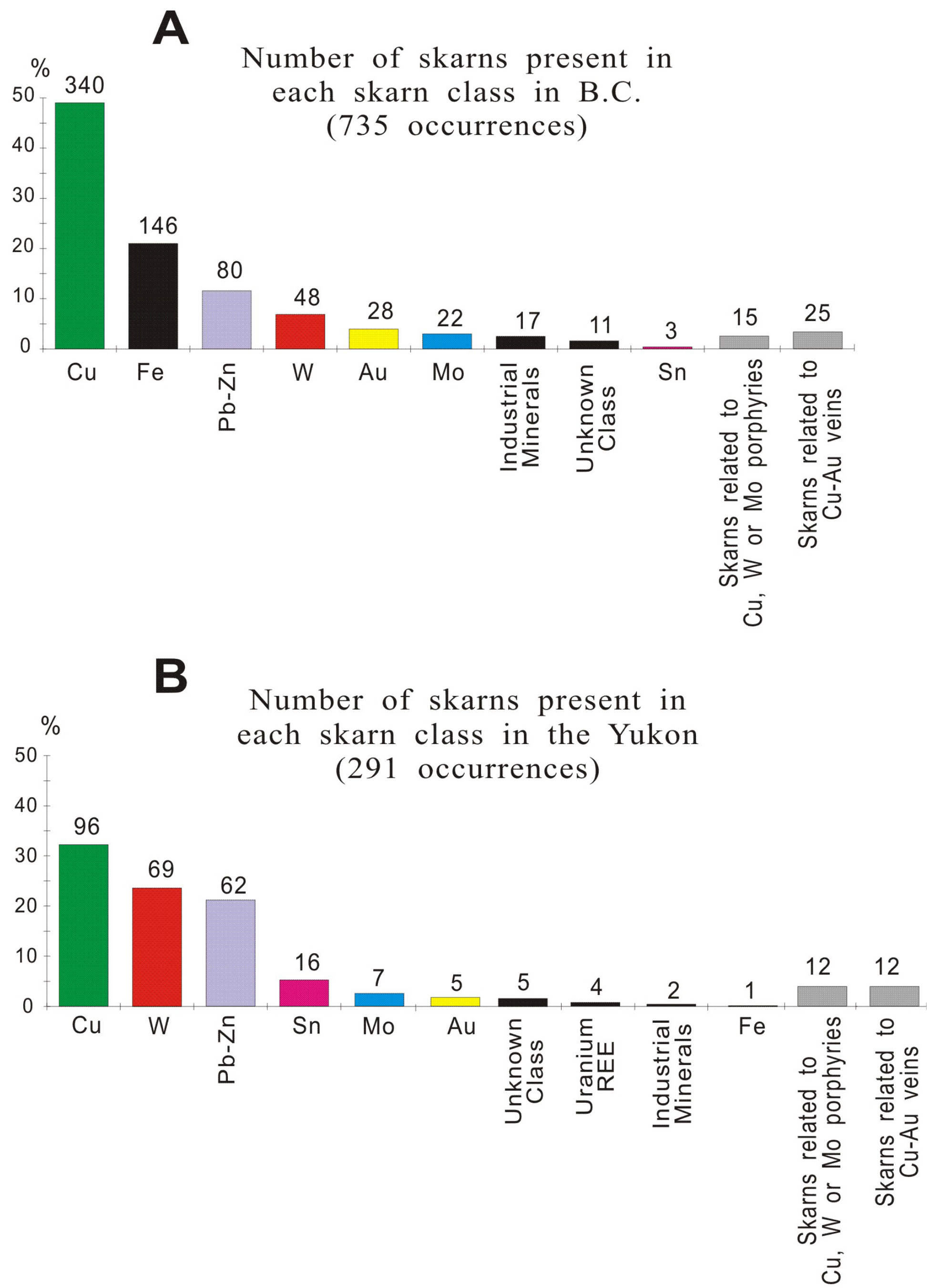

Fig. 2. Number and percentage of occurrences in each skarn class in: (A) British Columbia and (B) the Yukon. Number above each bar = number of skarn occurrences (data from B.C. and Yukon MINFILES; Ray and Webster, 1997).

LeRoy (1912; 1913), McNaughton (1945), and Seraphim (1957), and more recent studies by Church (1986) and Fyles (1990). The magnetite-rich Fe skarn deposits mined along the west coast of British Columbia (Fig. 1) are described by Bacon (1957), Sangster (1965, 1969), Eastwood and Merrett (1962), Eastwood (1965), Meinert (1984), and Webster and Ray (1990a, 1990b).

Dick (1976, 1980) completed pioneer research on more than thirty W-, Sn- and Zn-bearing skarns in northern BC, southern Yukon and the adjoining parts of the NWT, including an examination of the Cantung and Mactung W megaskarn deposits. Microprobe data on skarn minerals, including garnet, pyroxene, vesuvianite, scapolite, biotite, chlorite, and amphibole were presented by Dick and Hodgson (1982, 1993), Meinert (1984, 1986), Brown and Nesbitt (1987), Ettlinger and Ray (1989), Ettlinger et al. (1992), Ray et al. (1992, 2000), Pan et al. (1994) and Ray and Webster (1997).

Isotopic and fluid inclusion studies on skarns in the Canadian Cordillera include those by Christmas (1968), Christmas et al. (1969), Cooke and Godwin (1984), Mathieson and Clark

Table 1A: Number of skarns in B.C. listed by class and tectonic terrane

Skarn class	Cu	Fe	Pb-Zn	W	Au	Mo	Sn	Porphyry-related	Vein-related	IM*	Unknown class	BC TOTAL
Total No.	340	146	80	48	28	22	3	15	25	17	11	735
% of Total	46.3	19.9	10.9	6.5	3.8	3.0	0.4	2.0	3.4	2.3	1.5	100
No. of Producers	63	18	12	7	9	3	0	-	-	3	0	115
TERRANE												
Cassiar	-	-	8	12	-	3	-	-	-	-	-	23
Cache Creek	3	-	-	1		-	3	-	-	-	-	7
Coast/ undiv met complex	8	-	-	-	-	-	-	-	-	-	-	8
Stikine	47	6	11	2	1	1	-	7	3	-	2	80
Nisling	-	1	-	-	2	-	-	-	-	-	1	4
Wrangellia	173	136	25	-	1	-	-	-	5	7	-	347
Alexander	19	1	8	-	4	1	-	-	1	1	-	35
Gambier	2	-	2	-	-		-	-	-	-	-	4
Kootenay	7	1	1	5	2	8	-	1	-	3	-	28
Unknown	-	1	-	-	-	1	-	-	-	-	-	2
Chilliwack	2	-	-	-	-	-	-	-	-	-	-	2
Bridge River	4	-	1	2	-	-	-	-	-	-	2	9
Cadwallader	3	-	1	1	-	-	-	-	-	-	1	6
Quesnellia	64	-	10	1	18	4	-	7	15	2	5	126
Slide Mountain	4	-	2	-	-	-	-	-	-	-	-	6
Dorsey	1	-	1	3	-	-	-	-	1	-	-	6
Barkerville	1	-	-	4	-	-	-	-	-	-	-	5
Monashee	-	-	-	2	-	1	-	-	-	1	-	4
Harper Ranch	-	-	-	-	-	1	-	-	-	1	-	2
Ancestral N. America	2	-	10	15	-	2	-	-	-	2	-	31
SUM	340	146	80	48	28	22	3	15	25	17	11	735

IM* = Industrial mineral skarns

Table 1B: Number of skarns in the Yukon listed by class and tectonic terrane

Skarn class	Cu	W	Pb-Zn	Sn	Mo	Au	Fe	U/REE*	Porphyry related	Vein related	IM*	Unknown class	TOTAL
Total No.	96	69	62	16	7	5	1	4	12	12	2	5	291
% of Total	33.0	23.7	21.3	5.5	2.4	2	0.3	1.4	4.1	4.1	0.7	1.7	100
No. of Producers	7**	0	1	0	0	0	0	0	0	1	1	0	10
Terrane													
Mackenzie Platform	1	10	3	-	-	-	1	1	-	-	-	-	16
Selwyn Basin*	19	26	33	2	2	2	-	2	3	4	-	1	94
Tombstone Plutonics	-	-	-	-	-	-	-	-	1	-	-	-	1
Cassiar Platform*	4	20	12	1	2	-	-	-	2	7	-	1	49
Yukon Tanana	8	9	8	13	1	-	-	1	2	-	1	-	43
Nisling	8	2	3	-	1	-	-	-	-	-	-	-	14
Northern Stikine	47	-	2	-	1	1	-	-	2	-	-	3	56
Whitehorse Trough	2	-	-	-	-	-	-	-	-	-	-	-	2
Cache Creek	1	-	-	-	-	-	-	-	-	-	-	-	1
Coast Plutonic Complex	1	-	-	-	-	1	-	-	-	-	-	-	2
Wrangellia	5	-	-	-	-	1	-	-	-	-	1	-	7
McQueston Plutonics	-	1	-	-	-	-	-	-	2	-	-	-	3
Devonian Intrusion	-	1	-	-	-	-	-	-	-	-	-	-	1
Billings Batholith	-	-	1	-	-	-	-	-	-	-	-	-	1
Cretaceous Intrusions	-	-	-	-	-	-	-	-	-	1	-	-	1
SUM	96	69	62	16	7	5	1	4	12	12	2	5	291

** includes multiple producers in the Whitehorse Cu belt
*Selwyn Basin includes plutonic suites
*Cassiar Platform includes Cassiar Batholith
*U/REE = Uranium/rare-earth-element skarns
*IM = industrial mineral skarns

Table 2: Characteristic controls and examples of skarn deposits in the Canadian Cordillera

Skarn Class	CHARACTERISTIC CONTROLS	TYPICAL OREBODY MORPHOLOGY AND EXAMPLES
Fe	Pluton margins, stratigraphic contacts and local structures are important. Economic Fe deposits are confined to the Wrangellia Terrane and are mostly concentrated along the upper and lower contacts of the Quatsino Formation or equivalent limestone units.	Stratiform orebodies, sheets, massive lenses, irregular veins and rarely (*e.g. Kingfisher*) as vertical, sub-cylindrical pipes. Examples: (B.C.) *Tasu, Jessie-Jedway, Merry Widow*, *Iron Crown, Prescott, Iron Hill, Lake.*
Cu	Pre-skarn structures and host rock permeability are important. Many orebodies are controlled by intrusive margins, sedimentary lithologies and fault structures. Ore bodies tend to lie proximal to the related plutons, but the Cu skarns in the Phoenix mine area are strongly controlled by stratigraphy.	Highly variable morphology: stratiform and tabular orebodies, vertical pipes and irregular lenses. Examples: (B.C.) *Ingerbelle, Craigmont, Phoenix.* (Yukon) *Whitehorse Copper Belt (Copper King, Carlisle, Pueblo, Valerie, Grafter, Arctic Chief, War Eagle).*
Au	Strong stratigraphic and structural controls. Pre-skarn structures (faults, fold axes, sill-dike contacts) are important. The pyroxene-rich Nickel Plate deposit is developed distal to the Toronto stock (although the higher grade orebodies commonly lie close to sills & dikes). Garnet-rich Au skarn orebodies can form either proximal or distal to the igneous source-rocks.	Variable from irregular lenses and veins to tabular or stratiform orebodies with lengths and widths ranging up to many hundreds of metres. Examples: (B.C.) *Nickel Plate, French, Canty, Hood Hope, QR (Quesnel River).* (Yukon) *Marn, Newry, Guder; Ketza River (Manto).*
Mo	Deposits commonly develop in carbonate or calcareous rocks within thermal aureoles adjacent to intrusive margins.	Irregular orebodies along, and controlled by intrusive contacts. Examples: (B.C.) C*oxey, Novelty.* (Yukon) *Molly.*
W	Deposits favour calcareous rocks within extensive thermal aureoles of intrusions. However, dolostones tend to inhibit W skarn development. Controls include: gently inclined bedding, intrusive contacts, structural and stratigraphic traps in sedimentary rocks or in irregular parts of the pluton-hostrock contacts.	Stratiform, tabular and lens-like orebodies. Deposits can be continuous for hundreds of metres, following intrusive contacts. Examples: (B.C.) *Emerald Tungsten, Feeney, Dodger, Invincible, Dimac (Silence Lake).* (Yukon) *MacTung, Bailey, Risby, Ray Gulch.* (NWT) *CanTung, Lened*.
Pb-Zn	Carbonate rocks, particularly along structural and/or lithological contacts (e.g. shale-limestone contacts or pre-ore dikes). Deposits may form considerable distances (>500m) from the related intrusions.	Variable: subvertical chimneys or veins along faults and fissures to subhorizontal blankets or mantos along igneous and stratigraphic contacts or along flat lying structures. Examples: (B.C.) *Piedmont, Contact.* (Yukon) *Silver Hart, Sa Dena Hes, Quartz Lake.*
Sn	Differentiated, peraluminous plutons intruding carbonates. Dolostones form favourable host rocks. Ore bodies controlled by fractures, lithological or structural contacts, and may form some distance (up to 500m) from the related pluton.	Variable: stratiform, stockwork, pipe-like or irregular vein-like orebodies. Example: (B.C.) *Daybreak, Atlin Magnetite.* (Yukon) *JC (Viola), Can, Mulligan.*

Table 3: Characteristic mineralogies of skarn deposits in the Canadian Cordillera

Skarn Class	ORE MINERALOGY & GEOCHEMISTRY (Principal and *Subordinate*)	EXOSKARN & ENDOSKARN ALTERATION
Fe	Magnetite, *chalcopyrite, pyrite, sphalerite cobaltite, pyrrhotite, arsenopyrite, galena, molybdenite, bornite, hematite, martite, gold.* Rarely, contain *tellurobismuthite, fluorite, scheelite.* Geochemical signature: Fe, Cu, Co, Au, Ag, As and Cr.	**Exoskarn**: high Fe, low Mn, diopside-hedenbergite clinopyroxene (Hd0-70). Pyroxenes of Hd70-90 composition are generally absent (Ray & Webster 1997) although some include johannsenite-hedenbergite solid solutions (up to Jo50; Meinert 1984). Low Mn grossular-andradite garnets (Ad20-95). Fe skarns hosted by dolomitic rocks may include some Mg silicates; *e.g.* phlogopite, Mg-chlorite, serpentine. **Endoskarn** extensive with Na-silicates ± garnet ± pyroxene ± epidote ± scapolite.
Cu	Chalcopyrite ± pyrite ± magnetite in inner garnet-pyroxene zone. Bornite ± chalcopyrite ± *sphalerite* ± *tennantite* in outer wollastonite zone. Hematite, pyrite, pyrrhotite or magnetite may predominate (depending on the oxidation and sulfidation states). *Scheelite, chalcocite, molybdenite, bismuthinite, galena, cosalite, arsenopyrite, enargite, tennantite, loellingite, cobaltite, goethite, tetrahedrite, covellite, digenite, electrum, native gold, native copper and rutile.* Geochemical signature: Cu-Au-Ag-rich inner zones grading outward through Au-Ag zones with high Au:Ag ratios to an outer Pb-Zn-Ag zone. Geochemical signature for reduced Cu skarns: Co-As-Sb-Bi-Mo-W.	**Exoskarn** commonly has high garnet:pyroxene ratios. High Fe, low Al, Mn andradite garnet (Ad35-100), and diopsidic clinopyroxene (Hd2-50). Other minerals include K-feldspar, biotite, amphibole, clinozoisite, epidote, wollastonite, scapolite and sericite. Mineral zoning from stock out to marble is commonly: diopside + andradite (proximal); wollastonite ± tremolite/actinolite ± garnet ± diopside ± vesuvianite (distal). Late minerals include actinolite, chlorite, montmorillonite, K-feldspar, epidote and sericite. Cu skarns hosted by mafic tuffs (e.g. Ingerbelle) have an exoskarn dominated by epidote, actinolite, biotite and chlorite. Cu skarns associated with alkalic porphyry Cu-Au deposits in British Columbia contains late scapolite. Cu skarns hosted by dolomitic rocks may include some Mg silicates; *e.g.* phlogopite, Mg-chlorite, brucite. **Endoskarn** includes K-feldspar, epidote, sericite ± pyroxene ± garnet. Some retrograde actinolite, talc, chlorite and clay minerals.
Au	**Pyroxene-rich type**: Native gold, pyrrhotite, arsenopyrite, *chalcopyrite, tellurides, bismuthinite, cobaltite, native bismuth, pyrite, sphalerite, maldonite*. Generally high sulfide content and high pyrrhotite-pyrite ratios. **Garnet-rich type**: Native gold, pyrite, magnetite, *chalcopyrite, arsenopyrite, sphalerite, hematite, pyrrhotite, galena, tellurides, bismuthinite.* Generally low to moderate sulphide content and low pyrrhotite:pyrite ratios. **Epidote-rich type**: Native gold, chalcopyrite, pyrite, *arsenopyrite, pyrrhotite, galena.* Moderate to high sulfide content with low pyrrhotite-pyrite ratios. Geochemical signature for pyroxene and garnet-rich types:Au, As, Bi, Te, Co, Cu, Zn or Ni.	**Pyroxene-rich type**: extensive exoskarn with high pyroxene:garnet ratios. Prograde minerals: K-feldspar, Fe-rich biotite, low Mn grandite garnet (Ad10-100), wollastonite, diopsidic to hedenbergitic clinopyroxene (Hd20-100; Jo0-20) and vesuvianite. Trace rutile, axinite and sphene. Late minerals include epidote, chlorite, clinozoisite, vesuvianite, scapolite, tremolite-actinolite, sericite and prehnite. **Garnet-rich type**: extensive exoskarn with low pyroxene:garnet ratios. Prograde minerals: K-feldspar, low Mn grandite garnet (Ad10-100), wollastonite, diopsidic clinopyroxene (Hd0-60), epidote, vesuvianite, sphene and apatite. Late minerals include epidote, chlorite, clinozoisite, vesuvianite, tremolite-actinolite, sericite, dolomite, siderite and prehnite. **Epidote-rich type**: extensive exoskarn with abundant epidote and lesser garnet, chlorite, quartz and late carbonate. Epidote-pyrite and carbonate-pyrite veinlets and coarse aggregates are common.
Mo	Molybdenite, *scheelite, powellite, chalcopyrite, arsenopyrite, pyrite, pyrrhotite, bismuthinite, sphalerite, fluorite*. Rarely, Mo skarns carry *galena, magnetite, uraninite, pitchblende, cassiterite, cobaltite, stannite, and gold.* Geochemical signature: Mo, Zn, Cu, Sn, Bi, As, F, Pb, U, Sb, Co (Au).	**Exoskarn**: hedenbergite pyroxene (Hd50-80, Jo-3) ± low Mn grossular-andradite garnet (Ad40-95) ± wollastonite ± biotite ± vesuvianite. Retrograde amphibole, epidote, chlorite and muscovite. **Endoskarn**: clinopyroxene, K-feldspar, hornblende, epidote, quartz veining and sericite.

Table 3 continued.

Skarn Class	ORE MINERALOGY & GEOCHEMISTRY (Principal and *Subordinate*)	EXOSKARN & ENDOSKARN ALTERATION
W	Scheelite, molybdenite, chalcopyrite, pyrrhotite, sphalerite, arsenopyrite, pyrite, powellite. May contain trace *wolframite, fluorite*, *cassiterite, galena, marcasite and bornite.* Reduced types carry pyrrhotite, magnetite, *bismuthinite, native bismuth* and have high pyrrhotite:pyrite ratios. Variable amounts of quartz-vein stockwork (with local molybdenite) can cut both the exoskarn and endoskarn. The Emerald Tungsten skarns in B.C. include pyrrhotite-arsenopyrite pods that carry up to 9 g/t Au. Geochemical signature: W, Cu, Mo, As, Bi and B. Less commonly Zn, Pb, Sn, Be, F (Au).	**Exoskarn**: inner zone of diopside-hedenbergite (Hd60-90, Jo5-20) ± grossular-andradite (Ad10-50, Spess5-50) ± biotite ± vesuvianite, with outer barren wollastonite-bearing zone. An innermost zone of massive quartz may be present. Late-stage spessartine ± almandine ± biotite ± amphibole ± plagioclase ± phlogopite ± epidote ± fluorite ± sphene. Reduced types characterized by hedenbergitic pyroxene, Fe-rich biotite, fluorite, vesuvianite, scapolite and low garnet:pyroxene ratios, whereas oxidized types are characterized by salitic pyroxene, epidote and andraditic garnet and high garnet:pyroxene ratios. Exoskarn can be associated with extensive areas of biotite hornfels. **Endoskarn**: pyroxene ± garnet ± biotite ± epidote ± amphibole ± muscovite ± plagioclase ± pyrite ± pyrrhotite ± trace tourmaline and scapolite; local greisen developed.
Pb-Zn	Sphalerite, galena, pyrrhotite, pyrite, *magnetite*, *arsenopyrite, chalcopyrite, bornite*. Fe-rich sphalerite predominate over galena in a ratio of about 3:2. Other trace minerals include *scheelite, bismuthinite, stannite, native gold cassiterite, tetrahedrite, molybdenite & fluorite.* Rarely, boronsilicates such as *datolite*, *danburite* and *borospurrite* may occur (Dawson, 1996a). Proximal skarns tend to be richer in Fe, Cu & W, and more rarely in Au. Distal skarns contain higher amounts of Pb, Ag and Mn ± Sb ± As. Geochemical signature: Pb, Zn, Ag, Cu, Mn, As, Bi, W, F, Sn, Mo, Co, Sb, Cd and Au.	**Exoskarn**: Mn-rich hedenbergite-johannsenite pyroxene (Hd30-90, Jo10-50), andraditic garnet (Ad20-100, Spess2-10) ± wollastonite ± bustamite ± vesuvianite ± rhodonite. Late-stage Mn-rich actinolite ± epidote ± ilvaite ± chlorite ± dannermorite ± rhodochrosite ± axinite ± rhodonite ± fluorite. Yukon deposits have distinctive prograde assemblages of abundant epidote, rare andradite & intergrown diopside and Mn-hedenbergite (Dick, 1979). **Endoskarn**: in many distal Pb-Zn skarns the endoskarn is unknown but Zn-rich skarns formed near stocks are often associated with abundant endoskarn with epidote ± amphibole ± chlorite ± sericite and lesser rhodonite ± garnet ± vesuvianite ± pyroxene ± K-feldspar ± biotite and rare topaz. Marginal phases may contain greisen and/or tourmaline.
Sn	Cassiterite, scheelite, arsenopyrite, pyrrhotite, chalcopyrite, stannite, magnetite, *bismuthinite, sphalerite, pyrite, ilmenite, galena* & *stanniferous tetrahedrite.* Geochemical signature: Sn, W, F, Be, Bi, Mo, As, Zn, Pb, Cu, Rb, Li, Cs and Re.	**Exoskarn**: grandite garnet (Ad15-75, pyralspite 5-30) (sometimes Sn, F, and Be enriched), hedenbergitic pyroxene (Hd40-95) ± vesuvianite (sometimes Sn and F-enriched) ± malayaite ± Fe and/or F-rich biotite ± stanniferous sphene ± gahnite ± rutile ± Sn-rich ilvaite ± wollastonite ± adularia. Late minerals include axinite, wollastonite, vesuvianite, beryl, muscovite, Fe-rich biotite, chlorite, tourmaline, fluorite, sellaite, stilpnomelane, epidote and amphibole (latter two minerals can be Sn rich). Associated greisens carry quartz and muscovite ± tourmaline ± topaz ± fluorite ± cassiterite ± sulphides. Sn skarns hosted by dolomitic rocks may include some Mg silicates; *e.g.* olivine, serpentine, phlogopite, Mg-chlorite, brucite, spinel, ludwigite and talc.

(1984), Bowman et al. (1985), Gerstner et al. (1989), Layne and Spooner (1986, 1991), Layne et al. (1991), Godwin et al. (1991), and Dunne and Ray (2002).

3.0 Regional geology

The Canadian Cordillera is divided into a number of geological terranes that have distinctive lithological and/or temporal characteristics (Wheeler and McFeeley, 1991; Wheeler et al., 1991) and terranes hosting some of the most important skarn deposits are shown in Figure 1. The Cordillera represents a collage of arc, accretionary complexes, pericratonic terranes, craton margin sedimentary successions, overlap assemblages, and ocean-floor rocks that fringed the ancestral North American continent (Monger and Nokleberg, 1995; Nelson and Colpron, 2007). Much of this collage formed along the edge of the North American plate above subducting oceanic plates of the Panthalassa and Pacific Ocean basins (Monger and Nokleberg, 1995).

Before and during the Proterozoic, the North American craton formed part of a supercontinent (Rodinia). About 750 million years ago, the breakup of Rodinia led to the creation of the north-west-trending craton margin along which the Cordillera evolved. Subsequent subduction and oblique slip movements led to the accretion of a number of terranes against the western continental margin and its belt of pericratonic crustal blocks. Many of the accreted terranes, such as Stikinia, Wrangellia and Quesnellia (Fig. 1) represent oceanic arcs while others include substantial oceanic floor components (e.g. the Cache Creek and Slide Mountain terranes).

Subduction and docking of the accretionary complexes were accompanied by several phases of plutonism that were mostly I-type and arc-related, and varied compositionally from alkaline to sub alkaline. The most economically significant plutonic phase occurred during late Triassic to mid Jurassic times when many of the regions skarns and Cu porphyry deposits formed. During Mesozoic and Tertiary times, oblique plate convergence resulted in fragmentation of the arcs, commonly accompanied by major dextral fault displacement (Monger and Nokleberg, 1995).

4.0 Number and distribution of skarns

The more than 1000 skarns recorded in the Canadian Cordillera can be broadly separated into three groups. One small group of 27 occurrences is associated with Cu ± Au, Mo, or W porphyry deposits (Fig. 2). However, in most of these cases, skarn alteration represents only a minor part of the overall porphyry system, although the Cu-Au skarn component at the Ingerbelle porphyry Cu deposit (Fig.1) is a notable exception.

Another group comprising 37 occurrences, is characterized by generally barren wallrock skarn assemblages that are associated with large Au ± Cu-bearing quartz and/or sulfide vein systems (Fig. 2). In many cases, the genetic and temporal relationship between the veins and the skarn envelopes are unknown; however, those in the Rossland area of southern British Columbia, for example, appear to be related and coeval (Höy et al., 1992).

The third and largest group comprises 962 occurrences of which 695 are in British Columbia, and 267 in the Yukon (Fig. 2). On the basis of their chemistry or predominant minerals, these are classed as follows: 436 Cu, 147 Fe, 142 Pb-Zn, 117 W, 33 Au, 29 Mo, 19 industrial mineral, 19 Sn skarns, and 16 occurrences of unknown class. An additional 4 occurrences in the Yukon may be classed as U or rare-earth-element (REE) skarns. Although the Yukon is substantially smaller in area than British Columbia, it contains a significantly greater number of Sn and W skarns, and a smaller number of Fe, Au and Cu skarns (Fig. 2). This difference reflects the relative abundance of island arc-related plutonic rocks and associated chalcophile skarn deposits in British Columbia, whereas many intrusions in the Yukon were derived from continental crust (Woodsworth et al., 1991), and consequently their associated skarn deposits tend to be enriched in lithophile-elements.

Skarns are found in at least 24 different terranes and subterranes (as defined by Wheeler et al., 1991), but most are concentrated in Wrangellia, Stikinia, Quesnellia, Cassiar and Yukon-Tanana, and in Selwyn basin rocks and the Ancestral North American Craton (Ray et al., 1995; Tables 1A and B). The 24 terranes vary considerably in character (Wheeler et al., 1991). They include those with predominantly island-arc rocks (e.g., Wrangellia, Stikinia and Quesnellia), those with abundant oceanic crust (e.g., Cache Creek and Slide Mountain), others with pericratonic or displaced platformal rocks deposited at or relatively close to the ancestral continental margin (e.g., Nisling, Kootenay, Yukon-Tanana and Cassiar) or rocks representing either cratonic basement (e.g., Monashee) or supracrustal rocks deposited on Ancestral North America (e.g., Selwyn Basin and MacKenzie Platform).

A spatial and temporal relationship exists between certain skarn classes, their metal production, and the character and origin of the host terranes. Skarns are poorly developed in terranes composed primarily of ocean-floor material. Over 80 % of the skarns in B.C. are hosted by terranes with predominantly island-arc rocks, and these have accounted for virtually all the Fe, Cu, and Au metal produced from skarns in the province (Ray et al., 1995). By contrast, only 5 % of the skarns in British Columbia are hosted by the North American Craton, yet these have been responsible for all the province's tungsten production. Although the terranes of the Coast Plutonic Belt (e.g., Chilliwack, Cadwallader, Bridge River, and undivided metamorphic complex; Monger et al., 1982; Wheeler et al., 1991) have the greatest concentration of plutonic rocks in the Canadian Cordillera, they host less than 4 % of the skarn occurrences, all with negligible metal production (Ray and Webster, 1997).

There is no consistent relationship between the number of skarn occurrences in a terrane and its metal production from skarn. For example, Wrangellia and Quesnellia have the greatest number of Fe and Au skarns respectively (Table 1A), they host the largest Fe and Au skarn deposits (Fig. 1), and have had the most Fe and Au metal production from skarn (Ray et al., 1995). In contrast, although Wrangellia contains over half of the Cu skarns in British Columbia, its copper metal production has been negligible compared to Quesnellia, which hosts less than 20 % of the province's Cu skarns.

5.0 Tectonic setting and age of skarn-related plutonism

Pre-Middle Triassic skarns are extremely rare in the Canadian Cordillera; in British Columbia for example, only four skarns of Paleozoic age are recorded. Most skarns in the region formed during three time periods (Fig. 3A) that had distinctly different metallogenies. The oldest and most important in British Columbia was during the Early to mid Jurassic when over half of the skarns formed. The other two periods were during the Cretaceous and the Eocene-Oligocene.

These periods of skarn development coincide with three major plutonic episodes. The first two were associated with magmatism related to subducting oceanic crust (Armstrong, 1988), whereas the youngest was related to transtensional

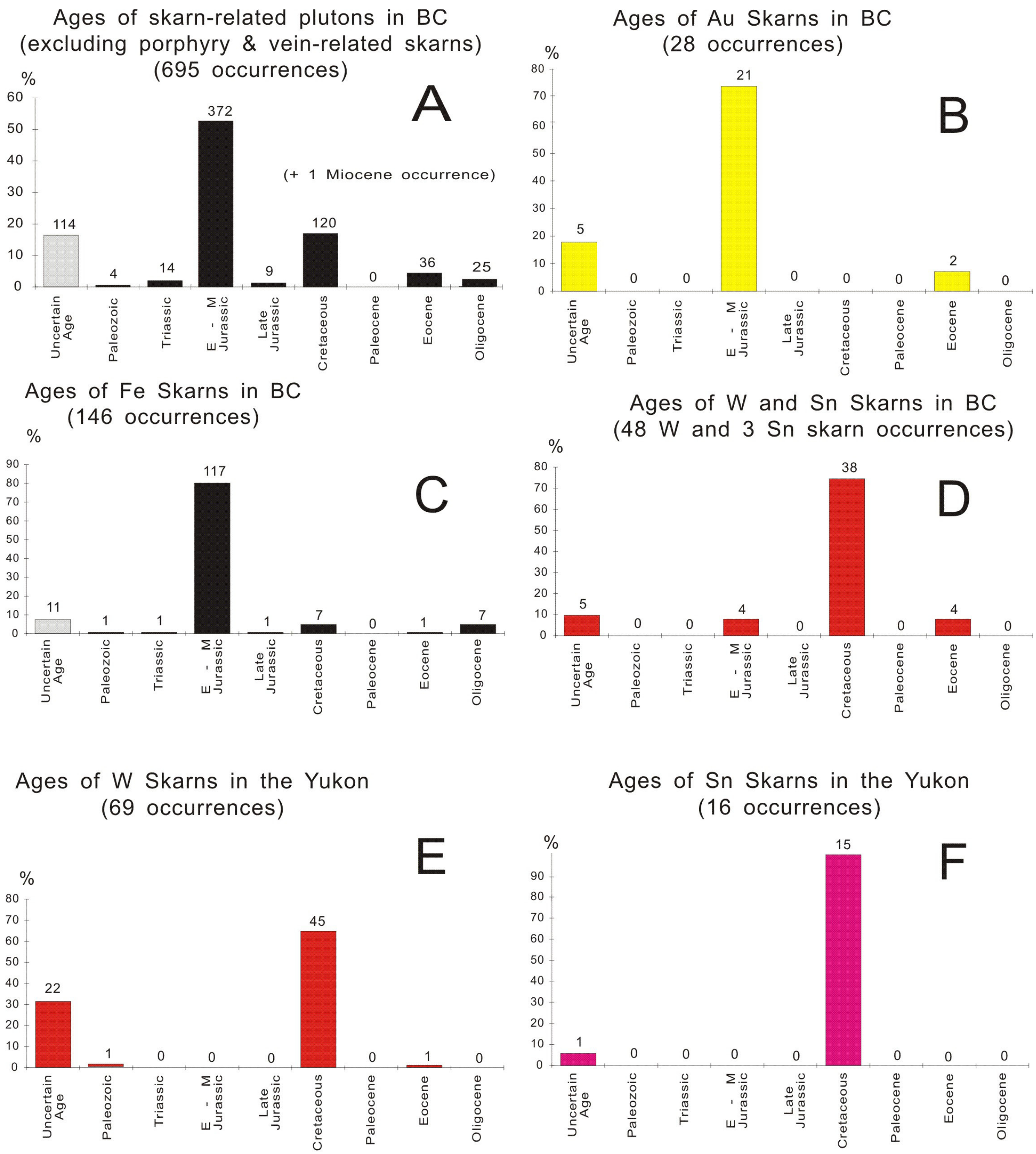

Fig. 3. Relative ages of the plutonic rocks associated with skarns in the Canadian Cordillera (after Ray et al., 1995). (A) Plutons related to all 695 skarn occurrences in B.C. (includes 11 occurrences of unknown class). (B) Plutons related to Au skarns in B.C. (C) Plutons related to Fe skarns in B.C. (D) Plutons related to W and Sn skarns in B.C. (E) Plutons related to W skarns in the Yukon. (F) Plutons related to Sn skarns in the Yukon.

tectonics and anatectic melting of the Ancestral North America Craton and its platformal sediments (Woodsworth et al., 1991). The first, an Early to mid Jurassic episode of alkalic and calc-alkalic I-type plutonism was commonly cogenetic with volcanism in several island-arc terranes. This magmatic event occurred both prior to and during terrane amalgamation and subsequent accretion to Ancestral North America. It was concentrated largely in Wrangellia, Stikinia, and Quesnellia at a time when they lay outboard of North America, and it was the most economically important metallogenic epoch in the Canadian Cordillera. This plutonism resulted in most of the Au, Fe (Fig. 3B and C), and Cu skarns, and many of the Cu-Au and Cu-Mo porphyry deposits in the region (Preto, 1972; Preto et al., 1979; Dawson et al., 1991). Notable exceptions however,

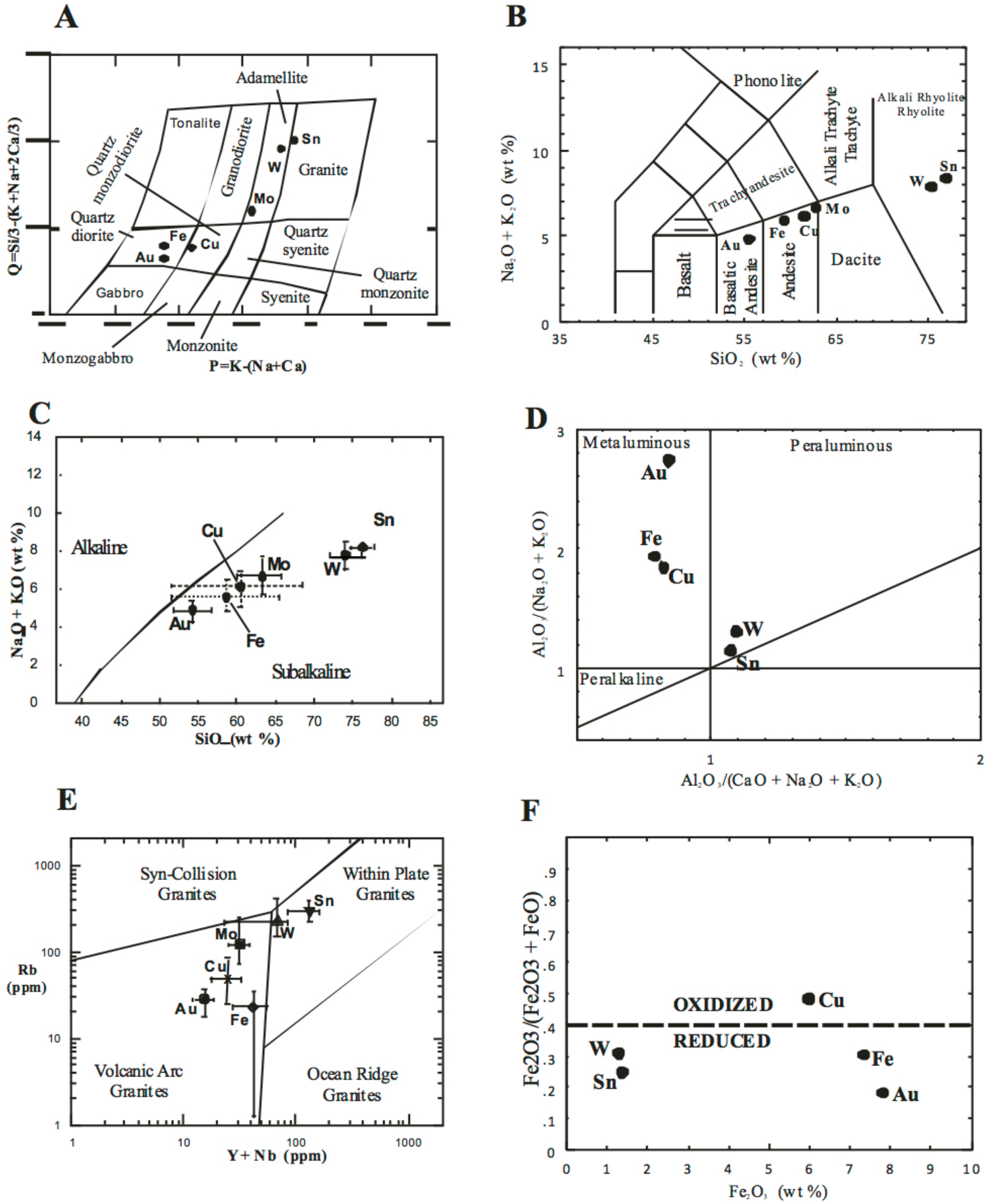

Fig. 4. Chemistry of non-porphyry-type plutonic rocks related to Fe, Cu, Au, Mo, W, and Sn skarns in British Columbia (data from Ray et al., 1995; Ray and Webster, 1997). Points represent mean values for each skarn deposit class; bar lines represent one standard deviation. (A) mean composition of skarn-related non-porphyry igneous rocks. Plot after Debon and Le Fort (1983). (B) Alkali versus silica plots showing igneous rock compositions (after Le Maitre et al., 1989); (C) Alkali versus silica plots (after Irvine and Barager, 1971). Note the strong sub-alkaline affinity of the non-porphyry igneous rocks associated with all the skarn classes, and the progressive increase in alkali and silica contents from the Au to the Sn skarn-related plutons. (D) Aluminum saturation plot (after Maniar and Piccolli, 1989) showing the metaluminous character of Au, Fe and Cu-skarn-related plutons and the peraluminous character of the W and Sn-skarn-related igneous rocks. (E) Trace element discrimination plots (after Pearce et al., 1984), illustrating the "volcanic arc" character of the non-porphyry-type intrusions related to Fe, Cu, Au and Mo skarns, and the "within-plate" character of those related to Sn and most W skarns. (F) Calculated Fe_2O_3/(calculated Fe_2O_3 + FeO) versus total Fe as Fe_2O_3. Horizontal oxidized-reduced line after Meinert (1995).

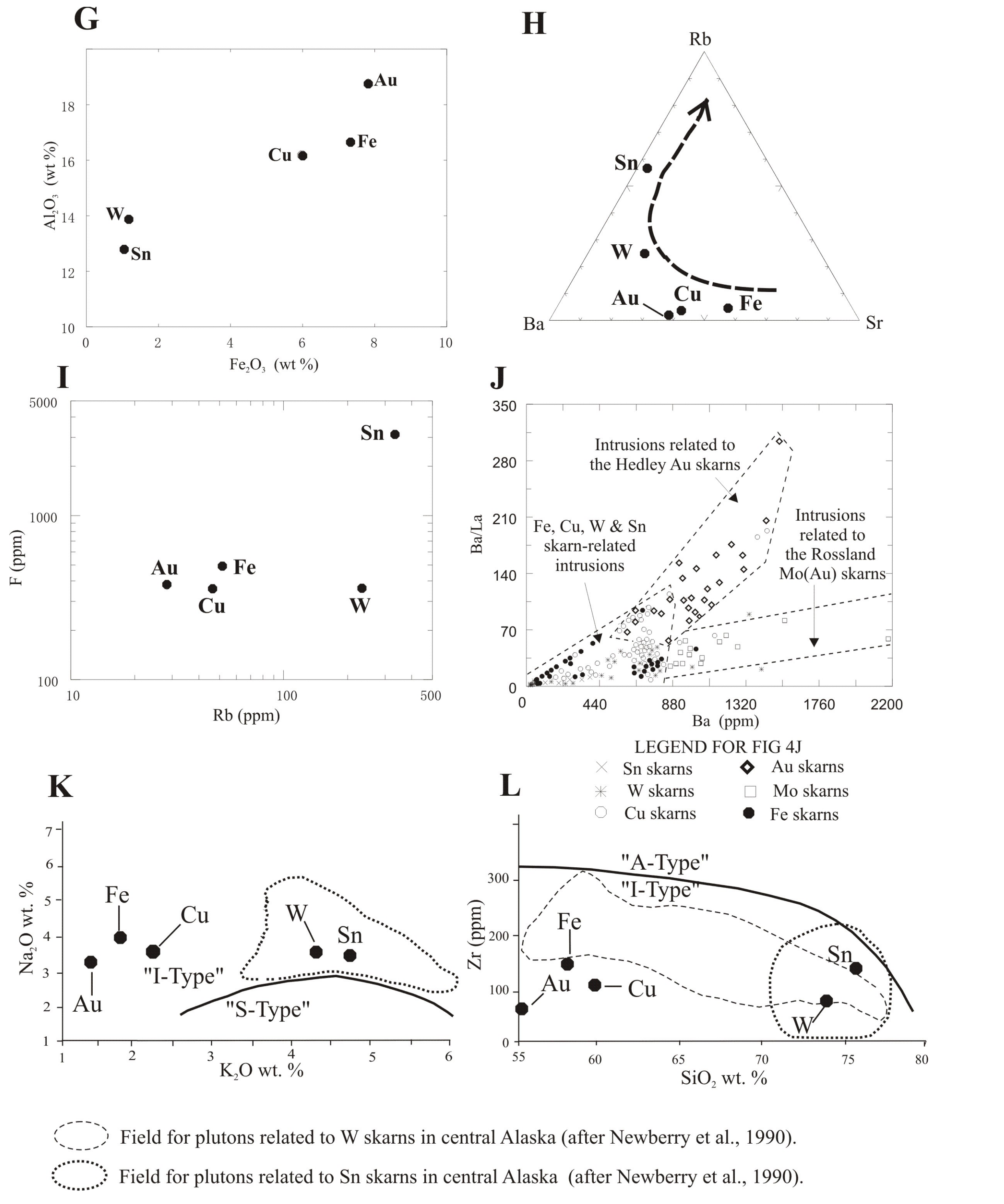

Fig. 4 continued. Plots comparing the chemistry of non-porphyry-type plutonic rocks related to Fe, Cu, Au, Mo, W, and Sn skarns in British Columbia (data from Ray et al., 1995; Ray and Webster, 1997). (G) Al_2O_3 versus total iron as Fe_2O_3, illustrating the progressive decrease in Al and Fe from the Au to the Sn skarn-related plutons. (H) Ternary Ba-Rb-Sr plots illustrating increasing differentiation from Fe to Sn-related plutons (arrow is typical differentiation trend). (I) Fluorine versus rubidium plot showing the F-rich chemistry of Sn-related igneous rocks. (J) Ba/La versus Ba plot for non-porphyry-type intrusions related to Fe, Cu, Au, Mo, W and Sn skarns. Note the higher Ba content in plutons related to the Hedley Au skarns and the Au-bearing Rossland Mo skarns. (K) and (L) Na_2O versus K_2O (K) and Zr versus silica (L), illustrating the "I-type" character of Au, Fe, Cu, W and Sn skarn-related plutons in British Columbia (from Ray et al., 2000). Mean values from Ray et al. (1996). Fields for Alaskan W and Sn skarn-related plutons after Newberry et al. (1990). Dividing lines between A-, S- and I-type granites after Collins et al. (1982) and White and Chappell (1983).

include the Whitehorse Copper Belt deposits and some Cu skarns in the Greenwood camp of southern British Columbia (Fig. 1), which are related to the Cretaceous plutonic episode (Morrison, 1981; Tenney, 1981; Meinert, 1986; Church, 1986; Fyles, 1990).

The Cretaceous plutonism was concentrated in two major metamorphic zones (Monger et al., 1982; Woodsworth et al., 1991), the easternmost of which resulted in mostly felsic, I and S-type intrusions with initial 87Sr/86Sr ratios greater than 0.706 (Armstrong, 1988). This eastern zone was an indirect result of collision, during the mid Jurassic, between the Intermontane Superterrane and Ancestral North America, which produced thickening of the continental crust in the outer part of the platformal sedimentary wedge. This was followed by I and S-type plutonism that culminated in mid-Cretaceous time (Woodsworth et al., 1991). These Cretaceous plutons, which are commonly peraluminous two-mica granites, were responsible for most of the W and Sn skarns (Fig. 3D, E and F) in the eastern part of the region (Fig. 1). These include the I-type, peraluminous and fluoritic plutons of the Surprise Lake Suite and their associated Atlin Sn skarns (Ray et al., 2000), as well as intrusions related to the Cassiar W and Sn occurrences (Dick, 1980; Dick and Hodgson, 1982, 1983; Cooke and Godwin, 1984; Ray et al., 1995, 1997). Contemporaneous I-type plutons responsible for the Whitehorse Belt Cu skarns are part of an extensive continent-margin arc that formed in mid-Cretaceous to early Tertiary time. This arc resulted from collision of the Gravina-Gambier arc and its Wrangellia-Alexander basement with previously accreted arc and pericratonic terranes (Monger and Nokleberg, 1995).

Compared to the Jurassic and Cretaceous episodes, the Eocene-Oligocene magmatism was less important for skarn development (Fig. 3A), and only resulted in a relatively small number of Pb-Zn, Fe, Cu and W skarns (Ray et al., 1995), including the Eocene-age Lustdust Cu-Au skarn in central BC (Fig. 1; Ray et al., 2002).

6.0 Chemistry of the skarn-related intrusions

A summary of major and trace elements in plutonic rocks associated with the various skarn-deposit-classes in British Columbia is given by Ray et al., (1995). Major-element plots illustrate that the plutons range from gabbro-quartz diorite to granite (Fig. 4A). Most of the skarns are genetically related to sub-alkalic, calc-alkaline igneous rocks (Fig. 4B and 4C); notable exceptions include the Ingerbelle, Galore, and QR deposits, which are associated with alkalic porphyry Cu-Au systems (Preto, 1972; Fox and Cameron, 1995).

Major-element plots demonstrate systematic geochemical variations of the igneous rocks associated with the skarn deposit classes (Fig. 4). The igneous rocks related to Fe, Au, and Cu skarns generally contain the least SiO_2 and total alkalis and the most CaO, MgO, Al_2O_3, ferrous Fe and total Fe. In contrast, the plutons related to Sn and W skarns are of granite-adamellite composition, have the highest average SiO_2 contents, and the lowest amounts of total Fe, MgO, Al_2O_3 and CaO.

A strong relationship exists between the skarn deposit classes, the peraluminous or metaluminous character of the intrusions, and the orogenic environment in which melts were generated (Figs. 4D and 4E; Meinert, 1995; Ray and Webster, 1997). Gold, Fe, and Cu skarns are mostly associated with metaluminous intrusions that have a "pre-plate collisional" chemical signature (as defined by Batchelor and Bowden, 1985), whereas the W and Sn skarns in British Columbia are related to fractionated, peraluminous leucogranitoids that are either "syncollisional" or "post-orogenic" (Ray and Webster, 1997).

The intrusions also display systematic changes in total alkali content and K_2O/Na_2O and Fe_2O_3/FeO ratios (Ray and Webster, 1997). Gold and Fe skarn-related plutons generally have the lowest total alkali content (averaging <5.8 %) and those associated with Sn skarns have the highest (averaging >8 %). Plutons related to Fe, Cu, and Au skarns also tend to have low K_2O/Na_2O ratios (<0.7) compared to those related to Mo, W, and Sn skarns, which are characterized by ratios averaging between 1.2 and 1.4. Igneous rocks associated with the more reduced W and Au skarn systems are characterized by low Fe_2O_3/FeO ratios (averaging <0.4), in contrast to plutons related to the more oxidized Cu skarns (averaging 0.8).

The plutonic rocks associated with Au, Fe, and Cu skarns contain higher amounts of Cr, Sc, Sr, and V, whereas those related to Sn and W skarns are enriched in large-ion lithophile elements such as Rb, Ce, Nb, Ta, and La (Figs. 4H and 4I). Compared to the W skarn-related plutons, many of those associated with Sn skarns tend to be fluoritic (Newberry, 1998; Fig. 4I).

Intrusions related to the Rossland Mo (Au) skarns and Hedley Au skarns are distinct in containing greater quantities of Ba than any of the other skarn-related plutonic rocks in British Columbia (Fig. 4J). The Hedley rocks are also noteworthy for their higher Ba/La and Sc/Nb ratios. The significance of the enhanced Ba content is unknown.

The chemical signature and terrane setting of plutons responsible for Au, Fe, and Cu skarns indicate that many were derived from oceanic crust in oceanic arc and back-arc environments. Their volcanic arc character is seen in Figure 4E, whereas plutons associated with Sn and most of the W skarns represent within-plate intrusions. Although worldwide the plutonic rocks responsible for W and Sn skarns include I, S, and A-type granites (Newberry, 1998), in British Columbia and Alaska these deposits mainly occur with I-type plutons (Figs. 4K and 4L).

7.0 A model for the origin of large-volume skarns (megaskarns)

Skarn deposits are generally hosted by envelopes of exoskarn alteration that may either be stratiform, discordant, sub-circular, pipe-like or vein-like in morphology. Many of the >1000 skarn occurrences in the Canadian Cordillera are relatively small in volume and extent, with envelopes that probably comprise an outcrop area of less than 0.4 km^2.

However, some have envelopes that extend over many square kilometers and these are referred to as megaskarns. For example, the Nickel Plate Au deposit in British Columbia has an envelope covering an area of 4 km^2, is up to 300 meters thick, and contains between 0.75 and 1.5 km^3 of altered rock (Ray et al., 1996). The Mactung W skarn (Dick and Hodgeson, 1982; Gerstner et al., 1989) is another Cordilleran megaskarn. Even more spectacular examples occur worldwide, including: the Antamina Cu-Zn skarn in Peru, which hosts a >550 Mt deposit (Redwood, 1999; Love et al., 2004); and the Ertsberg-Grassberg-Big Gossan cluster of Cu (Au) deposits and the Wabu Au (Zn) skarn in Irian Jaya, Indonesia (Rubin and Kyle, 1998; Allen et al., 1998; Meinert et al., 1997; 2005). The envelope of the garnet-dominant Wabu megaskarn has a strike length of 5 km, a thickness of 700 meters, and is estimated to contain 3.5 km^2 of alteration (J.M Allen, personal communication 2013).

Einaudi et al., (1981) proposed a model that involved the following paragenetic stages in the formation of an infiltration calcic skarn: (1) intrusion of magmas into relatively cool host rocks leading to isochemical contact metamorphism and the formation of a calc-silicate "skarnoid' or biotite-rich hornfels; (2) infiltration of magmatic hydrothermal fluids into the country rocks. This results in metasomatic garnet-pyroxene ± amphibole prograde skarn assemblages within an alteration envelope that expands until the hydrothermal system wanes; and (3) collapse of the magmatic hydrothermal system, groundwater influx and retrograde overprinting of the prograde assemblages by hydrous minerals such as chlorite, epidote, amphibole, ilvaite and prehnite. In some systems this final retrograde stage is coeval with the deposition of ore sulfides or the redistribution and upgrading of metals introduced during the earlier prograde stage.

The Einaudi et al., (1981) model implies that skarn evolution proceeds in temporally distinct steps and that most of the hydrous retrograde alteration post-dates the prograde stage. This is certainly valid for the development of a small skarn envelope but megaskarns probably formed during a more diachronous evolutionary process in which prograde and retrograde alteration migrate through space and time. The proposed model for the development of a megaskarn is as follows (Fig. 5).

Stage 1. Pluton intrusion and formation of a hornfels is followed by the outflow of high temperature hydrothermal fluids into the reactive country rocks via open conduits. This results in an expanding, but relatively small, initial exoskarn hydrothermal cell of prograde garnet ± pyroxene assemblages.

Stage 2. As the first-generation hydrothermal cell grows, the conduits become blocked due to prograde mineral growth. Pressurized fluids emerging from the pluton are then forced to follow new channels, leading to a second-generation prograde cell (or cells) adjacent to the initial cell or some distance from it. As the initial skarn cell wanes and cools, inflowing groundwater results in barren retrograde overprinting of earlier prograde skarn.

Stage 3. Ultimately, the conduits responsible for the second-generation cells also become blocked, leading to a third generation of prograde growth. While this latest prograde crystallization is taking place, barren retrograde alteration continues in the older hydrothermal cells.

Stage 4. Over time, the successive formation and collapse of multiple hydrothermal cells results in the incremental growth of the exoskarn envelope. This diachronous sequence of prograde and retrograde alteration continues until the entire magmatic hydrothermal system begins to shut down. During these late stages, pulses of metal-rich fluids may pass out into the exoskarn resulting in sulfide-rich deposits that in many cases are spatially associated with the youngest phases of retrograde alteration.

This diachronous megaskarn model has implications for exploration. It explains why much of the retrograde alteration in many skarns is typically barren, and cannot always be used as a reliable guide to locate ore. The model implies that a very large skarn envelope may comprise many generations of prograde and retrograde alteration. The earlier retrograde phases will commonly lack significant mineralization because they were associated with the influx of barren groundwater. In contrast, the youngest retrograde assemblages formed during the final collapse of the magmatic hydrothermal system probably have the greatest potential for hosting ore. Thus, exploration should attempt to identify the youngest conduits and their spatially related zones of young retrograde alteration. Although recognizing the original hydrothermal conduits is commonly difficult due to strong silicate overprinting, mapping mineral zoning and lateral changes in garnet-pyroxene grain size may help. Dating the retrograde minerals throughout a large and long-lived skarn could track evolutionary trends. Microprobe analyses may also provide useful clues because the hydrous minerals related to the deposit-forming event could be enhanced in certain metallic elements relative to those formed during the earlier phases of barren retrograde alteration.

8.0 Skarn deposits in the Canadian Cordillera

8.1 Introduction

At least seven major classes of metallic skarn deposits, as defined by Burt (1972, 1977), are recognized in the Canadian Cordillera: Fe, Cu, Au, Mo, Pb-Zn, W, and Sn. In addition, a few skarns are enriched in U and REEs, and others are potential sources of industrial minerals such as fluorite, wollastonite, garnet, borates, rhodonite, tremolite, and marble; (Figs. 2A and 2B).

Many Fe, Cu, Mo, and W skarn deposits form close to their related plutons, whereas the ore in some Au, Sn, and Pb-Zn skarns tends to develop in the outer parts of the exoskarn envelope (Tables 2 and 3). In some cases, late, metalliferous hydrothermal fluids migrate considerable distances to produce

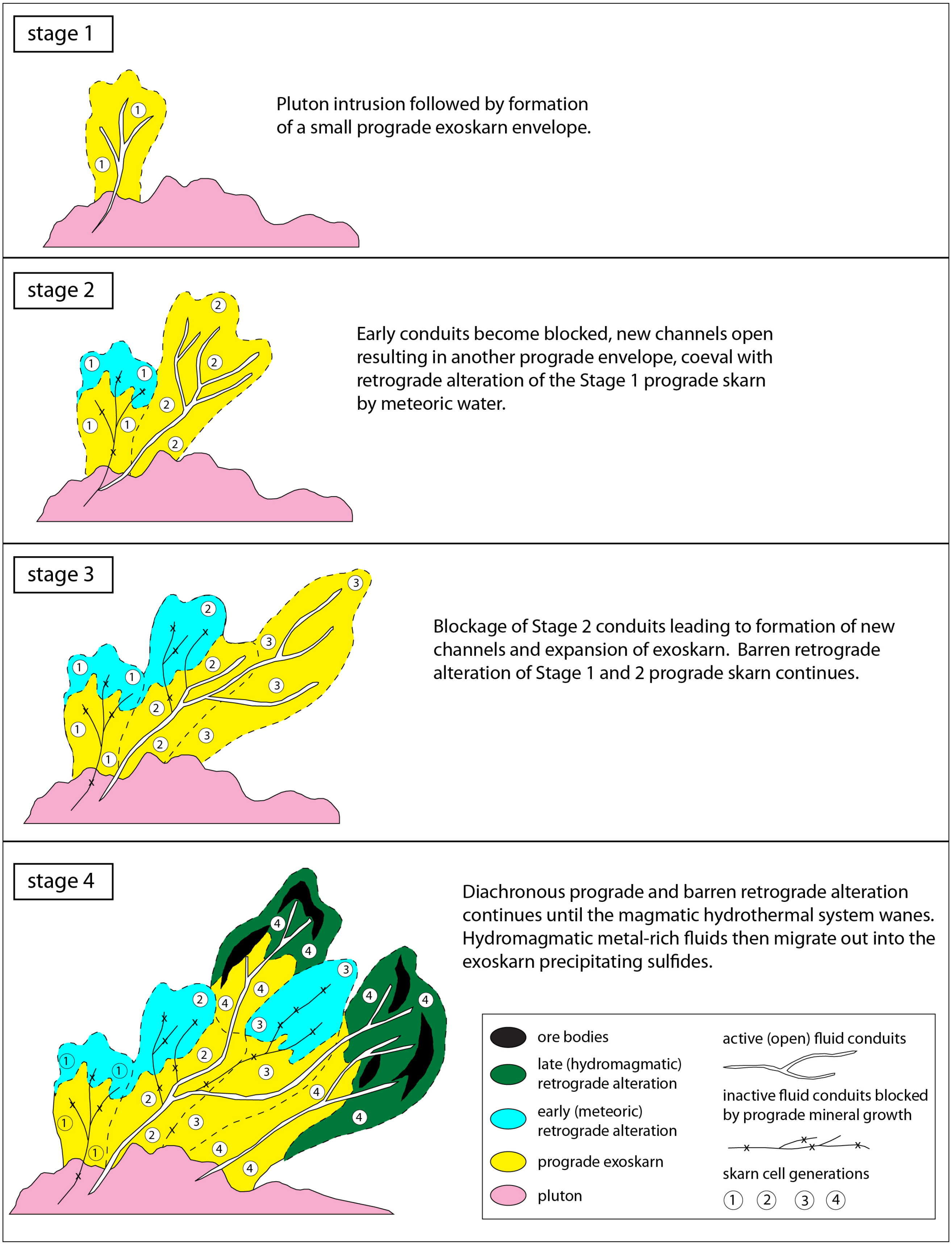

Fig. 5. Model for the diachronous development of a megaskarn.

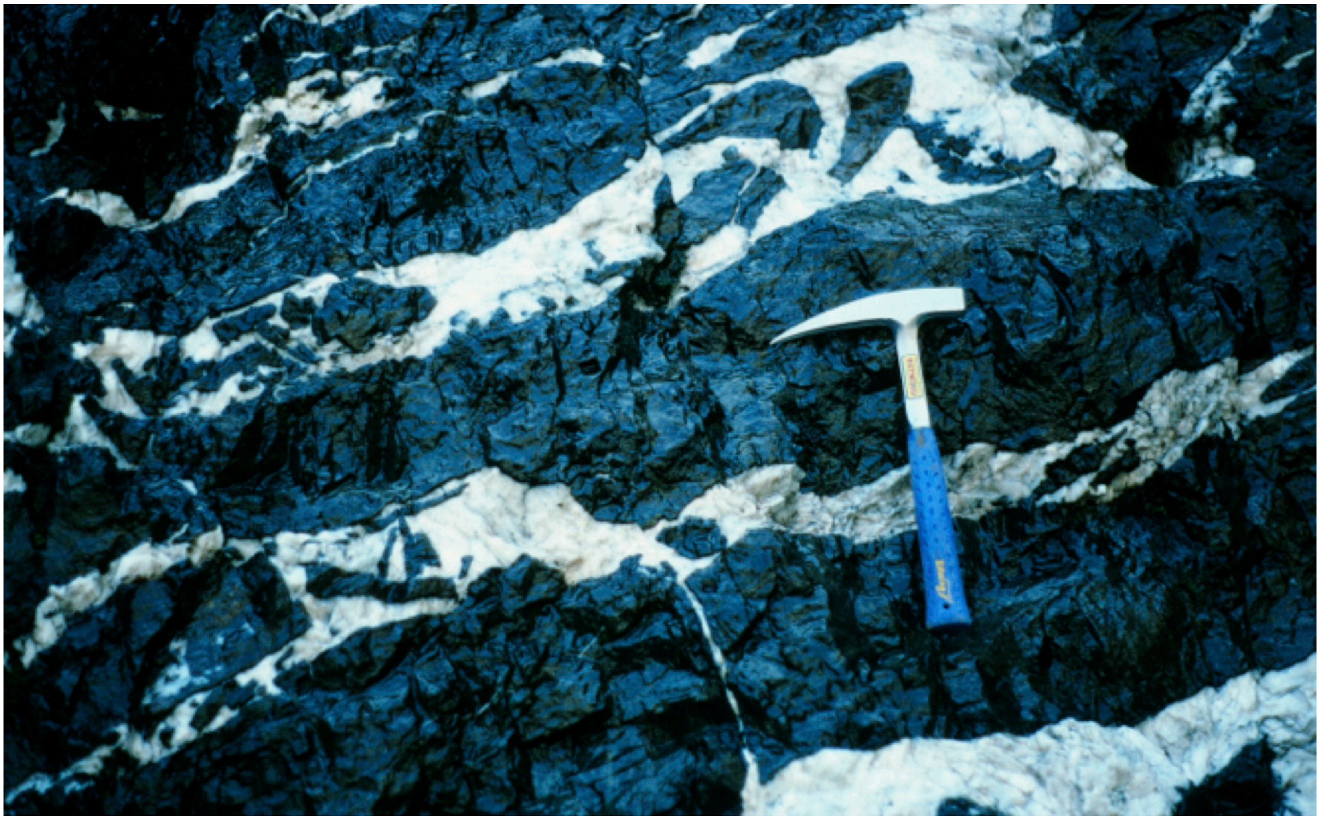

Photo 1. Hydrothermal breccia; massive magnetite with a quartz-feldspar-calcite cement, Merry Widow Mine, northern Vancouver Island, British Columbia.

ore deposits beyond the main exoskarn halo. Depending on the lithology, porosity, and permeability of the host rocks and the chemistry of the fluids, the distal magmatic fluids generate either sulfide-poor, low temperature Carlin-type Au orebodies (Sillitoe and Bonham, 1990) or sulfide-rich veins, replacement bodies or mantos that contain Pb, Zn, Ag, Au, or Cu and are often enriched in Fe and Mn (Einaudi et al., 1981; Megaw, 1998).

Although skarn envelopes and their contained deposits commonly display a complex morphology and mineralogy, each deposit class tends to have certain identifying characteristics (Tables 2 and 3). The chemistry and mineralogy of both the skarn gangue assemblage and the ore are influenced by factors such as host rock lithology, depth of formation, and the composition and oxidation state of the related intrusion and hydrothermal fluids. Dolomitic rocks are favorable hosts for some Fe and Sn skarns, but tend to inhibit W skarns (Zharikov, 1970; Einaudi et al., 1981). Calcareous siltstones, tuffs, or volcanic rocks are more commonly altered to pyroxene, actinolite, or epidote-rich assemblages, whereas limestones generally result in skarns with predominantly grossular garnet. The oxidation state of the hydrothermal fluids and the oxidizing or reducing capacity of the host rocks also influences skarn mineralogy and metal chemistry (Meinert, 1992). Reduced fluids or host rocks tend to produce high pyrrhotite-pyrite ratios, magnetite rather than hematite, and low Fe^{3+}/Fe^{2+} ratios in the silicates; they may also influence the garnet-pyroxene ratios in the exoskarn.

Skarn deposits in the Canadian Cordillera formed at a range of depths. Shallow subvolcanic regimes are indicated in Cu skarns associated with the high-level Copper Mountain, Mount Polley, and Galore Creek alkaline Cu-Au porphyries (Preto, 1972; Dawson and Kirkham, 1996; Rees, 2013). At shallow depths, the exoskarn envelopes tend to be extensive and are strongly controlled by brittle structures and may include hydrothermal breccias. They also have more oxidized mineral assemblages than skarns formed at depth and may display intense retrograde alteration due to convecting groundwater. Deeper level systems (e.g., some W and Sn skarns) are characterized by higher temperature mineral assemblages and relatively reduced states (Newberry, 1983; Newberry and Swanson, 1986; Newberry et al., 1997), as well as higher metamorphic grade, ductile deformation, and less endoskarn and retrograde alteration.

Vital for the formation of a megaskarn deposit are host rocks that are both chemically reactive and physically capable of maintaining long-lived permeability. Conduit structures such as faults, dike and sill margins, bedding and lithologic contacts commonly focus hydrothermal fluids and control skarn development. Mineralogical and chemical zoning can be mapped in a skarn envelope; this data may be used to locate protolith contacts, proximal and distal parts of the exoskarn envelope, original hydrothermal conduits and any associated orebodies.

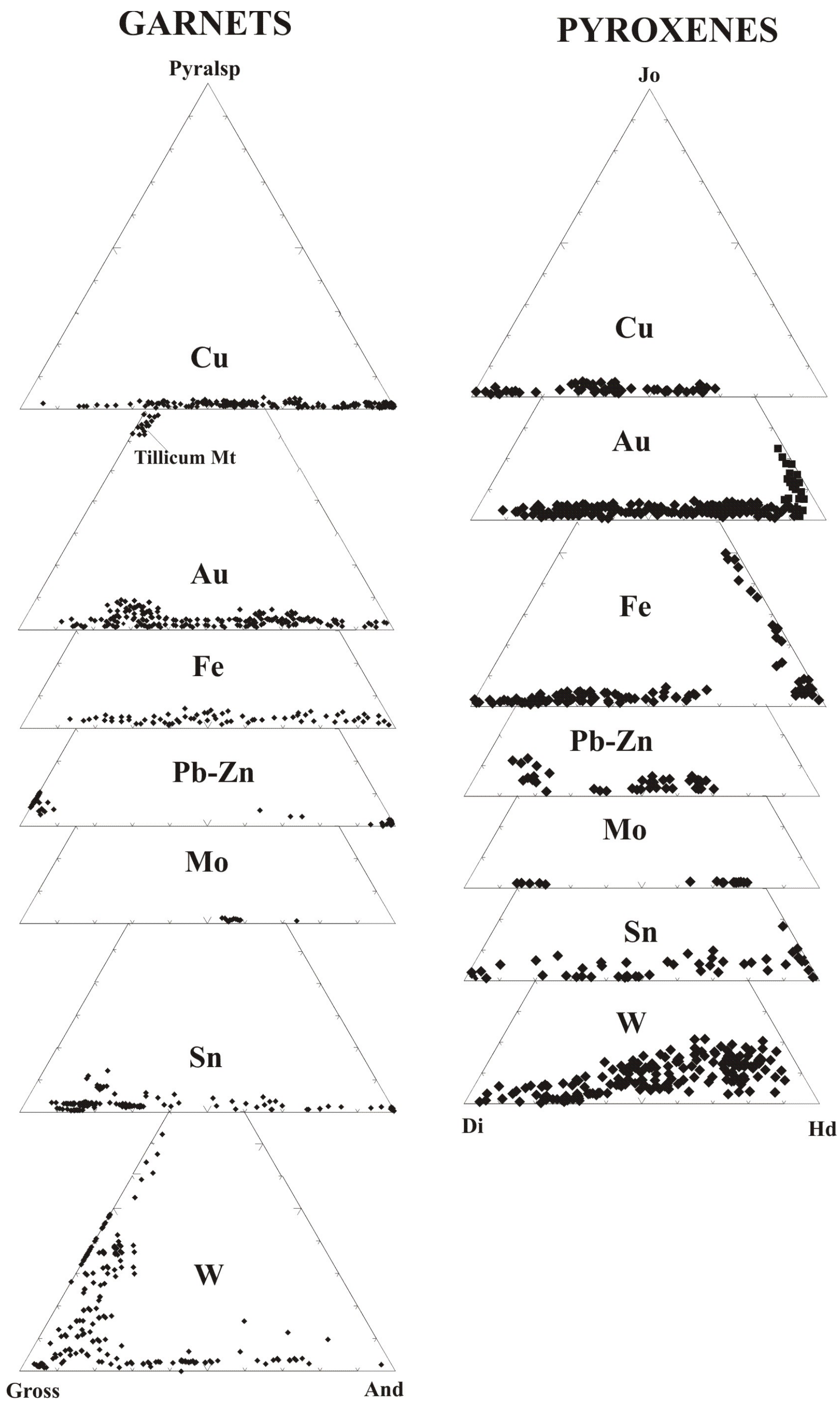

Fig. 6. Mole percent compositions of garnets and pyroxene in the skarn deposit classes in British Columbia, Yukon, and NWT. Data from Dick (1980), Dick and Hodgson (1982, 1983), (Meinert (1984), Brown and Nesbitt (1987), Ettlinger and Ray (1989), Ettlinger (1990), Ettlinger et al. (1992), Ray and Dawson (1994), Ray and Webster (1997; 2007), and Ray et al. (2000).

8.2 Iron (magnetite) skarns

Worldwide, Fe skarn deposits can be broadly separated into two types (Gross, 1996): (1) stratiform deposits developed by the dynamo-thermal metamorphism of an iron-rich protolith; and (2) contact metasomatic or replacement deposits developed at plutonic contacts with calcareous sedimentary and volcanic rocks. All of the significant Fe skarns in the Canadian Cordillera are of the latter type and represent island-arc-related calcic skarns as defined by Einaudi et al. (1981).

Overviews on Fe skarns in British Columbia have been presented by Sangster (1969), Meinert (1984), and Ray and

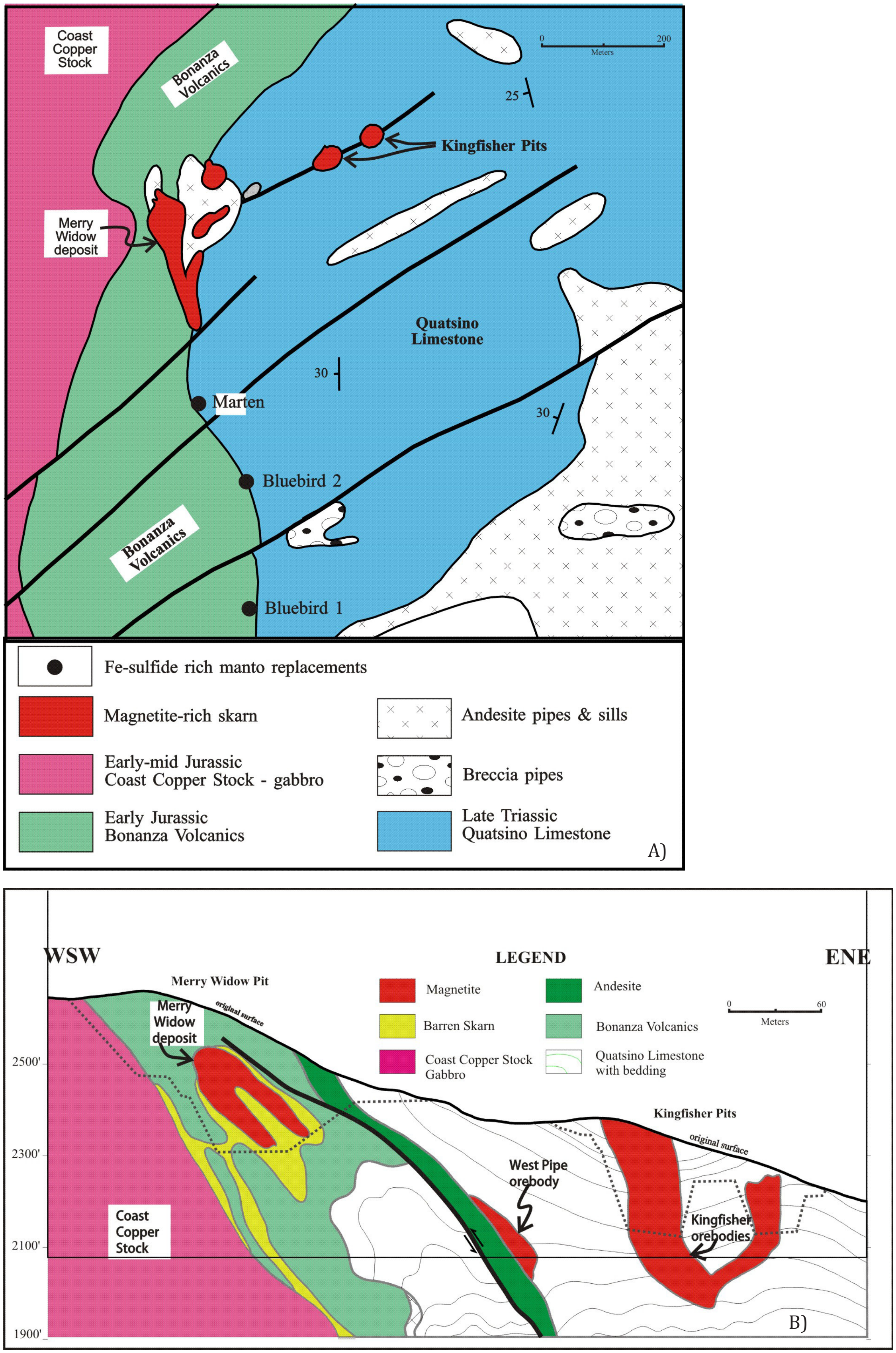

Fig. 7. (A) Geology of the Merry Widow Fe skarn deposit, BC (from Ray and Webster, 1991). (B) WSW-ENE section across the Merry Widow and Kingfisher magnetite deposits (adapted after Haug, 1977).

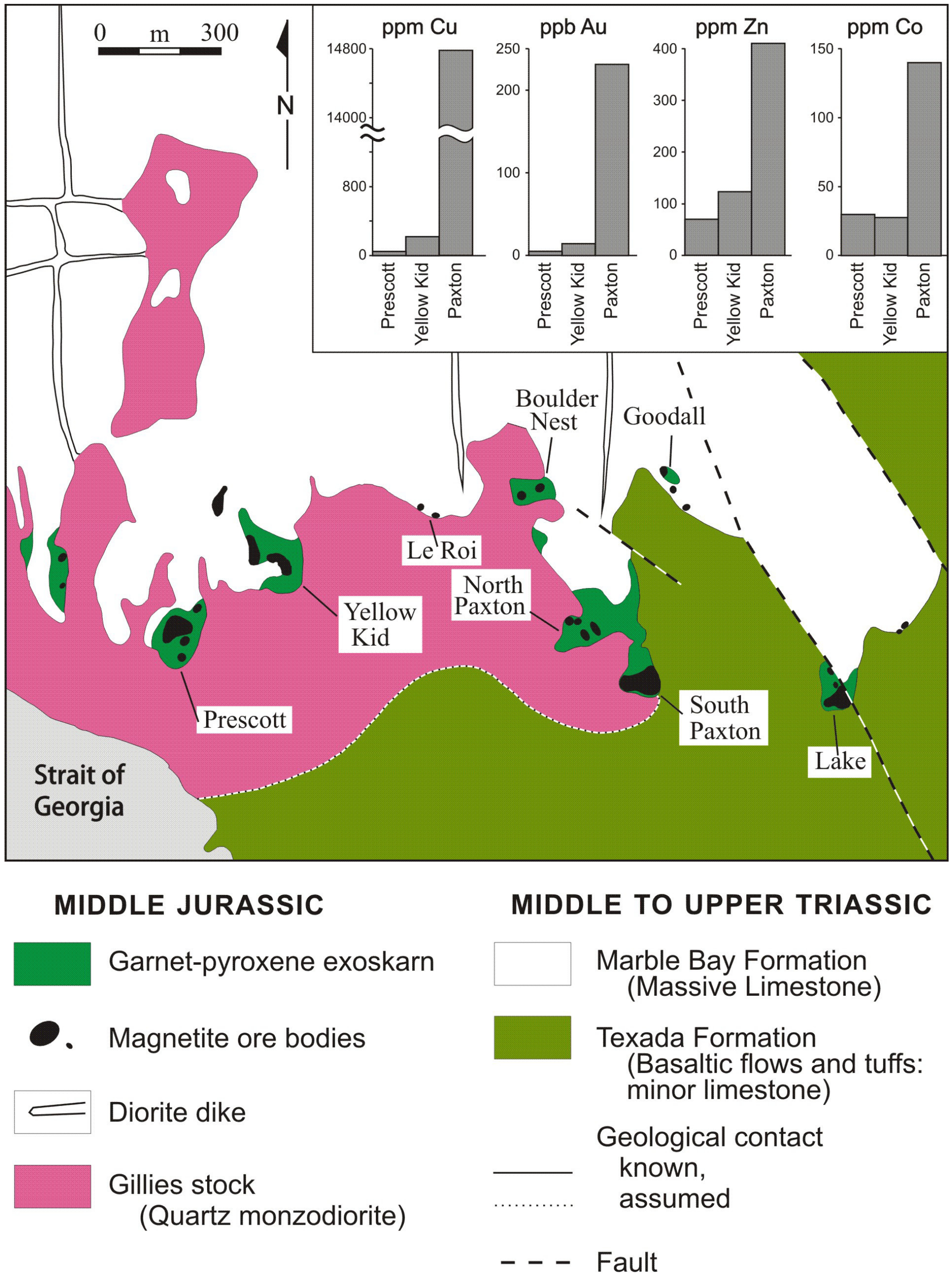

Fig. 8. Geology of the Texada Iron camp, Texada Island, B.C., showing distribution of the Fe skarn deposits along the margin of the Gillies stock. Inset bar charts show easterly increases in Cu, Au, Zn, and Co in the Fe skarn deposits. Geology and chemical data from Bacon (1957), Webster and Ray (1990a, 1990b) and Ray and Webster (1997).

Webster (1997); major deposits are listed in Figure 1. Although none are currently being mined, they have accounted for nearly 90 % of the historical iron (magnetite) production from skarn in British Columbia (Ray and Webster, 1997).

The Fe skarns are characterized by veins, pods, and lenses of generally massive magnetite (Photo 1; Table 2) that generally have low vanadium and titanium contents. For example, the magnetite at the Merry Widow deposit averages 0.03 percent TiO_2 and 0.01 percent V_2O_3 (Ray and Webster, 2007). The deposits are often associated with extensive epidote-pyroxene or albite-scapolite endoskarn alteration (Table 3) and a Fe-rich, calc-silicate gangue in the carbonate or volcanic exoskarn. The exoskarn assemblages may consist of prograde Fe-rich garnet and pyroxene with retrograde chlorite, epidote and actinolite; these minerals reflect an intermediate oxidation state (Einaudi et al., 1981).

A compilation of microprobe data (Fig. 6) shows that Fe skarns are characterized by low Mn grandite garnets that range from Ad 10-99, whereas some pyroxenes contain up to 50 mole percent johannsenite. In this feature the Fe skarn pyroxenes are similar in composition to those in some Au skarns, although they differ in lacking pyroxenes of Hd 70-95 composition.

Most of the economically significant Fe skarns in the Canadian Cordillera lie in the Wrangellia Terrane (Fig. 1) where they are associated with sub-alkaline, metaluminous island-arc-related, Early to mid Jurassic intrusions of gabbro-diorite-quartz diorite composition (Figs. 3C and 4A-4E; Woodsworth et al., 1991; Anderson and Reichenbach, 1991). On Vancouver Island, most deposits are hosted by limestones of the Upper Triassic Quatsino Formation (Figs. 7A and 7B), and the equivalent Marble Bay and Kunga formations on Texada and the Queen Charlotte Islands, respectively (Fig. 8). They may also be partly hosted by basaltic flows and tuffs of the stratigraphically underlying Karmutsen or Texada formations (Meinert, 1984).

Many deposits are strongly controlled by both the pluton margins and stratigraphy in the country rocks (Figs. 7A, 7B and 8). The Merry Widow and Texada Island skarns are hosted mainly by Triassic limestones of the Quatsino and Marble Bay formations, respectively. However, the former deposit lies at the top of the limestone unit (Figs. 7A and 7B; Haug, 1977; Ray and Webster, 1991), whereas the Texada Island skarns are concentrated at the base of the limestone, along its contact with underlying volcanic rocks (Fig. 8; Webster and Ray, 1990a, 1990b). The Kingfisher deposits (Figs. 7A and 7B), which lie close to the Merry Widow mine, have morphological, textural, and mineralogical features that distinguish them from other Fe skarns in Wrangellia. They form pipe-like replacement orebodies that have some fault control, and they sharply crosscut limestone host rocks that show little evidence of skarn alteration (Haug and Farquharson, 1976). The magnetite at the Kingfisher differs from that at the nearby Merry Widow in being colloform-textured (Stevenson and Jeffrey, 1964; Sangster, 1965). It is cut by phlogopite veinlets, and has anomalously high fluorine abundances (up to 1800 ppm F; Ray and Webster, 1997).

Some Fe skarns are associated with small Zn-Pb or Fe-sulfide rich mantos and replacements that generally lie well outboard from the main magnetite deposits. Many of the Fe-sulfide bodies contain anomalous amounts of Cu, Au, and As; examples include the stratigraphically controlled Marten, Bluebird 1, and Bluebird 2 occurrences, which lie up to 600 meters from the Merry Widow deposit (Fig. 7A).

The magnetite-rich ores in the Fe skarns generally have a low Cu, Au, and sulfide content (< 100 ppb Au and < 1000 ppm Cu; Ray et al., 1996). However, many deposits contain variable amounts of late pyrrhotite, pyrite, and chalcopyrite, either as local disseminations in the magnetite ore or as more distal veins and pods. The sulfide-rich ore may be sporadically enriched in Au, Ag, and Cu (up to 32 ppm, 200 ppm and 17 % respectively (Ettlinger and Ray, 1989), and contain anomalous amounts of Co and Zn. A positive correlation between Cu, Au, Ag, and S is apparent in these deposits (Ray and Webster, 1995). Many sulfide-rich Fe skarns have recently been explored for their Au potential, but without economic success due to low tonnage and inconsistent grades.

A metal zoning exists in some Fe skarn deposits or camps. In the Merry Widow area, a vertical zoning probably occurs between the Cu ± Au ± magnetite-bearing Old Sport deposit, which lies along the base of the Quatsino limestone, and the overlying magnetite-dominant Merry Widow deposit at the top of the Quatsino unit. In contrast, the Texada Island Fe skarns display lateral zoning in which an easterly increase in sulfides along the margin of the Gillies stock is accompanied by increased amounts of Cu, Au, Ag, Zn, and Co (Fig. 8).

8.3 Copper skarns

Copper skarn occurrences are widely distributed throughout the Canadian Cordillera. Most lie in the Wrangellia and Quesnellia terranes of British Columbia, and the northern Stikine terrane in the Yukon (Tables 1A and 1B). However, most of the larger deposits are hosted by Upper Triassic island-arc rocks of the Quesnellia and Stikine terranes (Fig. 1). The Cu skarns can be broadly separated into two types: (1) those associated with alkaline porphyry Cu-Au-bearing stocks, in which the peripheral skarns are commonly hosted by coeval mafic volcanic rocks; and (2) those related to generally barren calc-alkaline plutons of diorite-quartz monzodiorite-granodiorite composition (Ray and Dawson, 1998). The latter type is generally hosted by calcareous sedimentary rocks.

Copper skarns associated with alkalic porphyry systems, such as at the Ingerbelle, Galore, and Mount Polley deposits (Fig. 1; Watson, 1969; Preto, 1972; Ennes et al., 1995; Fraser et al., 1995; Rees, 2013) tend to be of low grade (<0.7 % Cu). Their exoskarns contain predominantly epidote-actinolite-biotite-K feldspar assemblages in which garnet is uncommon, which partly reflects their mafic volcanic host rocks. At Galore Creek, skarn ore constitutes some of the reserves, which total 284 Mt grading 0.67 % Cu and 0.35 g/t Au (Enns et al., 1995). This skarn includes an assemblage of orthoclase and biotite in high-K volcaniclastic host rocks, but changes to a calcic assemblage of andradite, diopside, epidote and vesuvianite in calcareous host rocks (Enns et al., 1995; Dawson and Kirkham, 1996).

Copper skarns related to unmineralized calc-alkaline plutons tend to be more numerous, smaller (<30 Mt), and with higher grades (> 1 % Cu). They are commonly associated with grandite garnet (Ad 5-100), diopsidic pyroxene (Hd 0-70) (Fig. 6) and epidote-rich exoskarn envelopes. The intrusive rocks are metaluminous; although compositions vary, quartz diorite to granodiorite is most common (Figs. 4A to 4D). Almost all are arc-type intrusions (Fig. 4E). They are generally the most oxidized plutonic rocks of any skarn class (Fig. 4F), reflecting their development at a high structural level. Typical examples in British Columbia include former mines in the Greenwood camp, such as the Motherlode, Emma, Greyhound, Oro Denoro, Rawhide, Snowshoe, Idaho, and Phoenix deposits (Photo 2; Figs. 1 and 9; Church, 1986). Other important Cu skarns include the Jurassic Old Sport on Vancouver Island, and a cluster of probable Cretaceous Cu-Au skarns on Texada

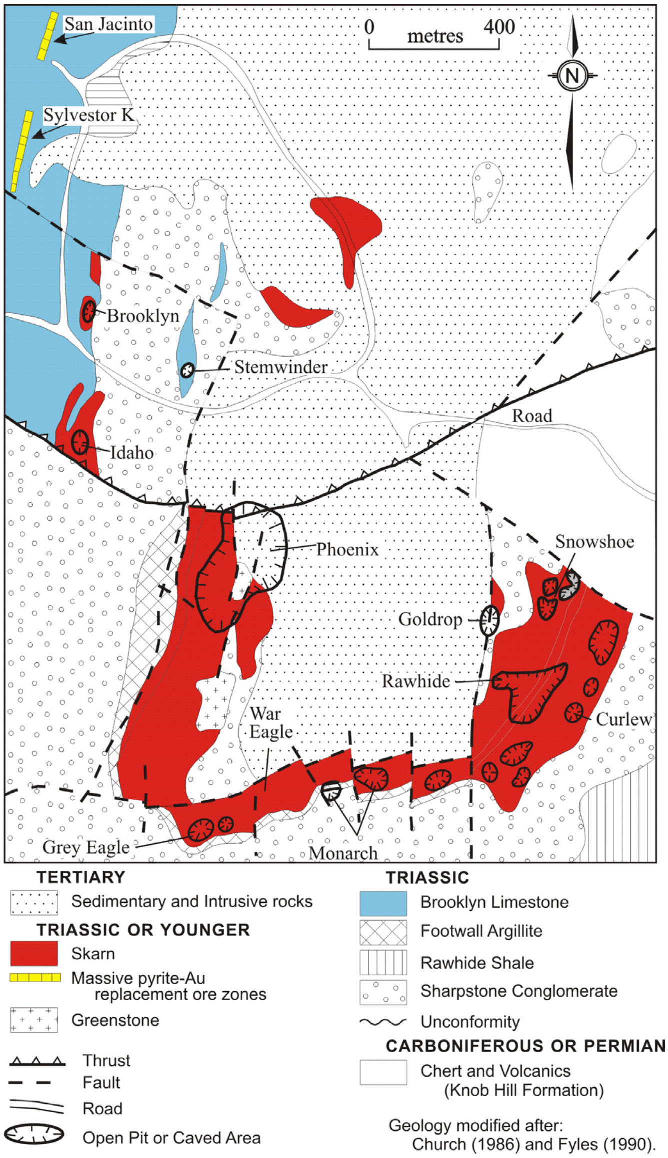

Fig. 9. Geology of the Phoenix Mine area, Greenwood camp, southern B.C., showing the distribution of the Cu (Au) skarn deposits (adapted after Church, 1986; Fyles, 1990).

Photo 2. Phoenix Cu-Au open pit mine, Greenwood, southern British Columbia.

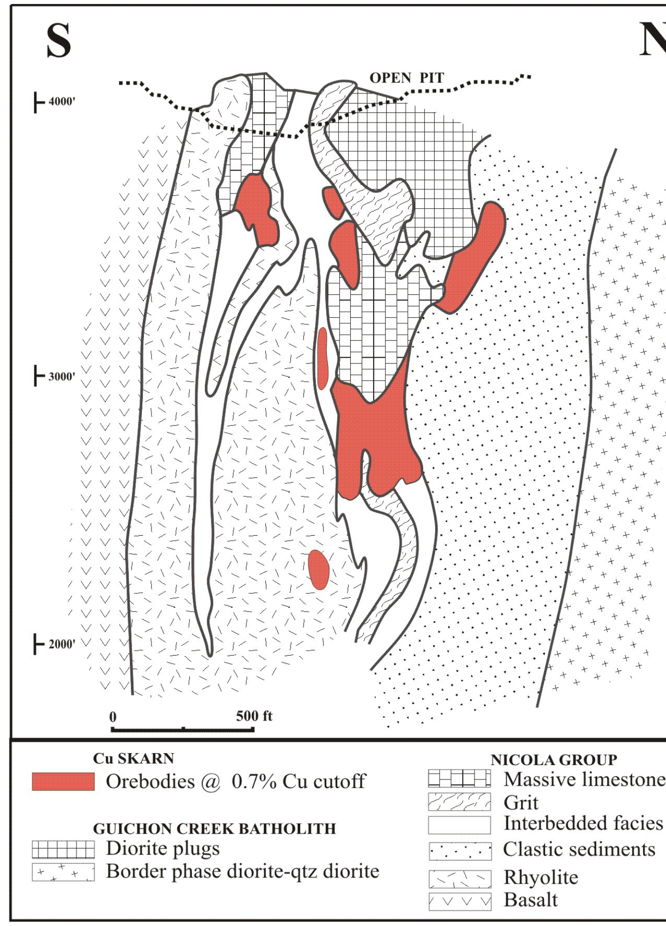

Fig. 10. Simplified north-south section across the Craigmont Cu skarn deposit, southern BC. After Morrison (1980).

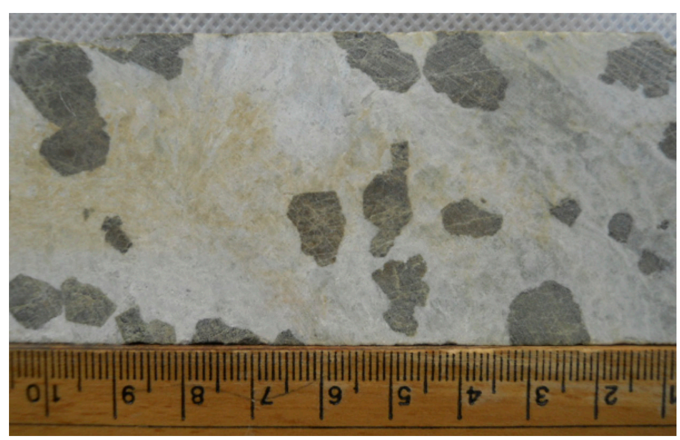

Photo 3. Drill core showing garnet-pyroxene-wollastonite skarn from a distal part of the Little Billie Cu-Au skarn, Texada Island, British Columbia.

Island, including the Marble Bay, Cornell, and Little Billie deposits (Photo 3; Ettlinger and Ray, 1989; Webster and Ray, 1990a and 1990b).

The precise origin of the large (29 Mt) Craigmont Cu skarn in southern British Columbia (Figs. 1 and 10) is uncertain. The deposit lies immediately adjacent to the southern margin of the calc-alkaline Guichon Creek Batholith which, farther north, hosts several economically important Cu-Mo porphyry deposits, including the Highland Valley cluster (Casselman et al., 1995; McMillan et al., 1996). The host rocks comprise steeply dipping Triassic Nicola Group limestones, silicilastic sedimentary rocks, rhyolites, and basalts (Morrison, 1980; McMillan, 1978; Fig. 10), although the mineralization is generally hosted by interbedded carbonates, limey sandstones and siltstones that lie adjacent to a barren limestone reef complex. The proximity of the skarn to the Guichon Creek Batholith (Fig. 10) suggests a genetic relationship, but Morrison (1980) considered that the metals were derived from Nicola Group volcanic rocks rather than the intrusion. Furthermore, the rhyolite-basalt bimodal volcanic package and a basal mineralized stringer zone raise the possibility of volcanic massive sulfide (VMS) mineralization with a skarn overprint. However, because VMS-type mineralization is extremely rare in the entire Nicola Group, a skarn origin seems more likely.

The Yukon has at least 96 Cu skarn occurrences (Table 1B; Fig. 2B) but the most economically important are clustered in the Whitehorse Copper Belt (Figs. 1, 11, 12 and 13; Tenney, 1981; Morrison, 1981; Watson, 1984; Meinert, 1986; MacKay et al., 1993). More than 30 separate Cu skarns are in the belt, at least 10 of which have been mined; these include the War Eagle, Cowley Park, Keewenaw, Arctic Chief, and Big Chief deposits (Photo 5; Fig. 11). Most of the Whitehorse deposits lie in limestones or dolostones near the western margin of the Cretaceous Whitehorse Batholith, commonly in embayments or roof pendants. The Keewenaw deposit (Fig.11) is unusual in being hosted by the batholith, whereas at the War Eagle mine, intrusive rocks have not been identified. Typical examples of skarns developed in embayments are at the Big Chief, Little Chief, and Middle Chief deposits, which lie within a steeply dipping package of Triassic limestone, dolostone, sandstone, and siltstone (Figs. 12A and 12B).

Over half of the Cu skarn occurrences in British Columbia, whether related to calc-alkaline or alkaline plutonism, are Early

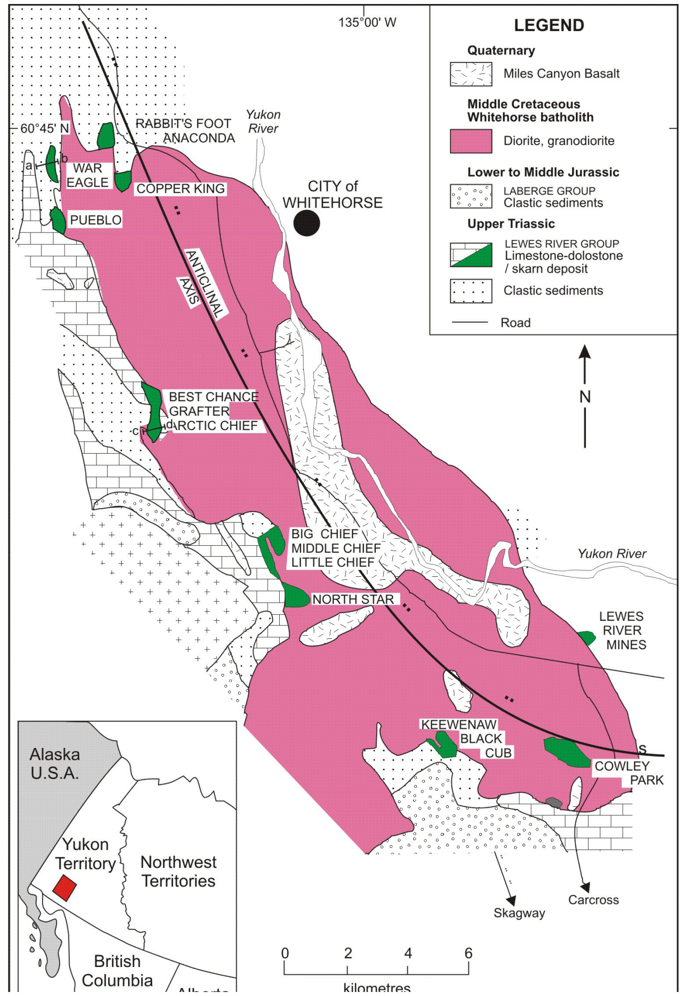

Fig. 11. Regional geology of the Whitehorse Copper belt, Yukon, showing the distribution of the Cu skarn deposits around the margin of the Whitehorse Batholith. Adapted after Morrison (1981), Watson (1984) and Dawson and Kirkham (1996).

Photo 4: Massive garnet ± pyroxene skarn cut by quartz, calcite and chalcopyrite veins. Queen Victoria Cu Mine, southern British Columbia.

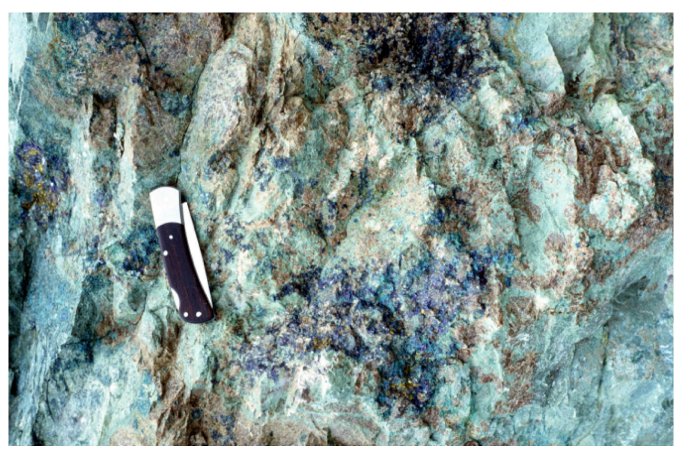

Photo 5: Garnet-pyroxene exoskarn with chalcopyrite, bornite and azurite. Arctic Chief Mine, Whitehorse Copper Belt, Yukon.

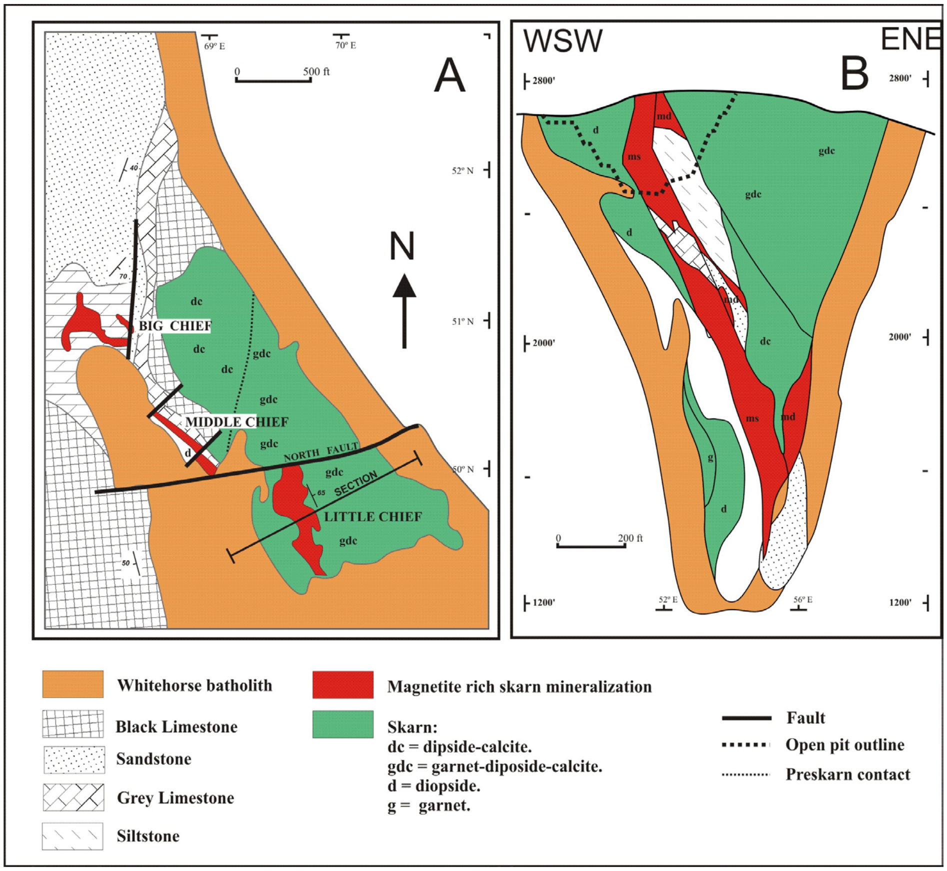

Fig. 12. (A) Geology of the Big Chief, Middle Chief, and Little Chief Cu deposits, Whitehorse Copper Belt, Yukon, illustrating skarn development in an embayment of the Whitehorse Batholith. Adapted after Morrison (1981). (B) ENE-WSW cross section across the Little Chief Cu-Fe skarn deposit. Adapted after Morrison (1981).

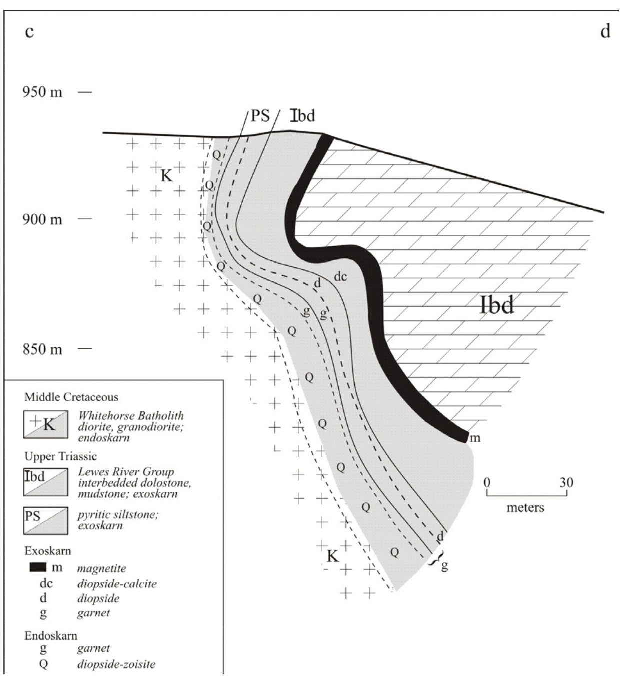

Fig. 13. Cross section of the Arctic Chief magnesian Cu skarn deposit, looking north. Note mineral zoning from proximal endoskarn to distal magnetite-rich mineralization. After Morrison (1981), Watson (1984) and Dawson and Kirkham (1996).

to mid Jurassic in age (Ray et al., 1995). The province contains at least 47 Cu skarns of Cretaceous age and another 16 that are Eocene. Important Cretaceous examples include some deposits in the Greenwood camp, and those in the Whitehorse Copper Belt (Fig. 1; Morrison, 1981; Tenney, 1981; Church, 1986). The Eocene suite includes the Lustdust property in central British Columbia (Figs. 1 and 14), which represents a zoned skarn-manto-vein system developed along strike for 2.5 km. (Megaw, 2000, 2001; Ray et al., 2002; Dunne and Ray, 2002). The skarn is unusual in being hosted by oceanic Cache Creek terrane rocks; the proximal Cu-Au skarns are developed adjacent to a small, high-level monzonite-diorite stock that has been dated at 51 Ma by U-Pb zircon methods (Ray et al., 2002).

Many Cu skarns formed at high structural levels and are marked by high pyrite-pyrrhotite ratios and oxidized mineral assemblages. Good examples include the Greenwood camp deposits (Fig. 9) and some of the Whitehorse Copper Belt skarns. Mineral zoning is common, with pyrite-chalcopyrite-magnetite near plutonic contacts grading outwards to bornite-chalcopyrite-wollastonite assemblages near the marble contacts. This zoning reflects a decreasing Fe content and increasing oxidation-sulfidation states with both time and towards the periphery of the skarn system (Burt, 1972; Einaudi et al., 1981). However, in some of the Whitehorse deposits the zoning is different and magnetite is distal (Morrison, 1981).

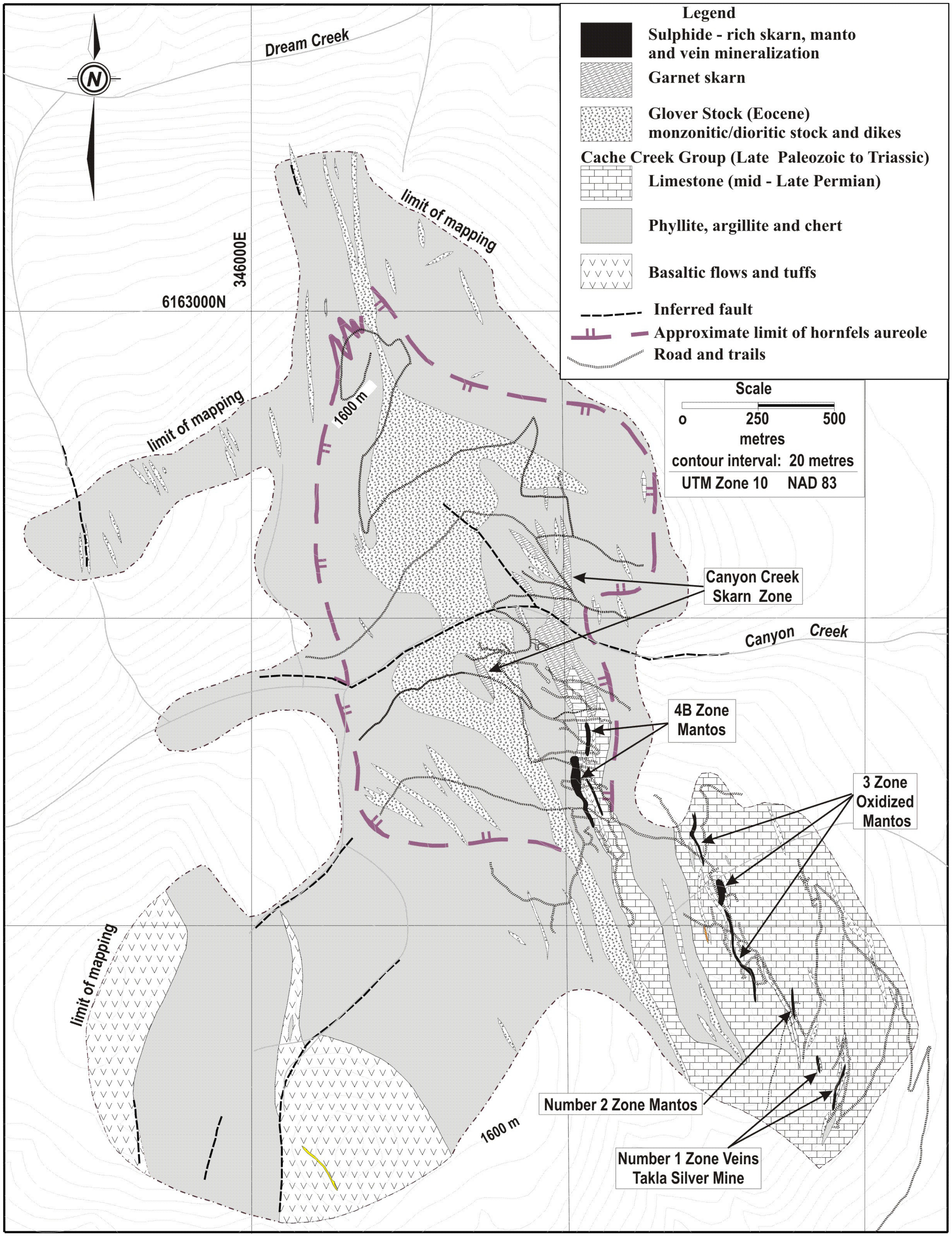

Fig. 14. Geology of the zoned skarn-manto-vein Lustdust property in central BC. Note the locations of the proximal Canyon Creek Cu-Au skarn, the intermediate Zn-Cu-Au-Ag mantos (2, 3 and 4B zones), and the distal sulfosalt-bearing Au-Ag-Pb-Zn veins (1 Zone). Geology after Evans (1998), Megaw (2000, 2001), Ray et al. (2002), Ray and Webster (2002).

At the Arctic Chief magnesian Cu skarn for example (Fig. 13) the proximal to distal zoning is: (1) diopside-zoisite endoskarn, (2) garnet endoskarn, (3) garnet-rich exoskarn, (4) diopside-rich exoskarn, (5) diopside-calcite exoskarn, (6) magnetite-rich mineralization, (7) marble, (8) limestone.

Copper skarn deposits formed at deeper levels tend to have more reduced mineral assemblages, low pyrite-pyrrhotite ratios, and are commonly enriched in W, Mo, Bi, Zn, As, and Au. Mineralization formed near the periphery of the system is commonly enriched in sphalerite, pyrrhotite, tennantite, and galena. Retrograde alteration assemblages include sulfides with actinolite, carbonates, clay, silica, Fe oxides, chlorite, epidote, sericite, K-feldspar, montmorillonite, and talc (Table 3). Copper skarns associated with unmineralized stocks generally lack the intense stockworking and quartz veining that is more typical of porphyry systems. Instead their retrograde alteration assemblages, together with significant concentrations of base and precious metals, are commonly restricted to widely spaced fractures, contact zones, and vug fillings.

Ores at the Craigmont, Maid of Erin, and Blue Grouse deposits (Fig. 1), have very low Au contents and correspondingly high Cu-Au ratios (Ray et al., 1996). However some deposits such as the Phoenix, Motherlode, Marble Bay, Little Billie (Photo 3) and Old Sport skarns in British Columbia, and some of the Whitehorse Copper deposits in the Yukon, have sufficiently high Au contents to merit its recovery. The Phoenix Mine area (Photo 2) in the Greenwood camp of southern British Columbia (Figs. 1 and 9) contains a major concentration of productive Cu (Au) skarn deposits that are characterized by garnet-epidote-chlorite alteration (Church 1986; Ettlinger and Ray, 1989; Fyles 1990). Unlike the Whitehorse Copper Belt skarns, which are strongly controlled by intrusive margins (Fig. 11), the Cu skarns in the Phoenix area do not lie close to any known major intrusion. Instead, they are stratigraphically controlled by Triassic carbonate units, and skarn is developed discontinuously over a 1.8 km by 1.4 km area (Fig. 9). Although large intrusions responsible for the Phoenix skarns have not been positively identified, a small body of endoskarn-altered microdiorite-greenstone is present in the Phoenix Mine open pit (Photo 2; Paxton, 1971; Fig. 9). This body is surrounded by a zone of massive garnet exoskarn that passes laterally outwards to garnet skarn which is strongly retrograde altered to epidote and chlorite. The intrusion is thought to have played a role in skarn development.

Some Cu skarns are associated with distal, massive sulfide replacements that may be Au-rich. Possible examples include narrow Au-bearing pyritic zones (Jacinto and Sylvestor K) that are a short distance northwest of the skarns in the Phoenix Mine area (Fig. 9). Their origin is debatable; they may represent either massive Au mantos and replacements related to the Phoenix system (Church 1986; Ray and Webster, 1997) or older VMS-type orebodies (M. Rasmussen, personal comm. 1997).

8.4 Gold skarns

Gold skarns are those in which Au is the primary or predominant economic metal (Meinert, 1989; Ray et al., 1990). They tend to have characteristics that distinguish them from Au-rich Cu, Fe, Mo, and Zn-Pb skarns (Dawson, 1996b), in which the gold may represent an important byproduct (Orris et al., 1987; Theodore et al., 1991).

Worldwide, many Au skarns occur at destructive plate margins, where they are related to plutons derived from oceanic crust, and they commonly exhibit a temporal and spatial association with Cu porphyry belts (Ray et al., 1990). In the Canadian Cordillera, many of the most economically important Au skarns, such as those in the Hedley camp (Fig. 1; Nickel Plate, Canty, French, Good Hope), are Early to mid Jurassic in age (Fig. 3B). These are related to syn- to post-tectonic plutons that cut Triassic calcareous sequences deposited in island-arc or back-arc settings (Ray et al., 1996). They occur mainly in Quesnellia terrane carbonate and siliciclastic rocks that have a significant marine volcanic component.

The Hedley skarns (Figs. 15A, B) are hosted by a Late Triassic package that is marked by abrupt, structurally controlled, east to west sedimentary facies changes (Ray et al., 1995). These facies include a thin sequence of shallow-marine carbonate-bank sediments in the east, an intermediate thicker unit of well-bedded calcareous siltstone and lesser limestone in the central part of the area (Photo 6), and a thick sequence of organic, deeper-water argillites further west (Fig. 15A). The mafic intrusions that produced the Hedley Au skarns were partly controlled by the pre-existing syn-sedimentary growth faults, and the economic skarns were preferentially developed in the central and eastern packages of calcareous siltstones and carbonates (Figs. 15A, B). The intrusions include the Toronto Stock (Photo 7) and its related dike-sill swarm (Photos 8 and 9) which are spatially associated with the Nickel Plate deposit; other minor bodies further east lie close to the much smaller Canty, and French deposits (Photo 10).

The intrusions related to the Hedley Au skarns are I-type, porphyritic, sub-alkaline, and of largely gabbro-diorite-quartz diorite composition (Photo 7; Ray et al., 1995, 1996; Fig. 4). They are the most Fe and Al-rich igneous rocks of any skarn deposit class (Fig. 4G). They also tend to be undifferentiated, relatively depleted in LIL-elements such as Rb, Ce, Nb, and La, and enriched in Cr, Sc, Sr, and V (Ray et al., 1995). In British Columbia, a negative spatial association apparently exists on a regional terrane scale between Au and Fe skarns, even though both classes are related to arc plutonism; most Au skarns occur in Quesnellia whereas Fe skarns are concentrated in Wrangellia (Fig. 1).

Worldwide, Au skarns include calcic and magnesian varieties; the latter, which are hosted by dolostones and Mg-rich volcanics rocks, are relatively uncommon worldwide and have not been identified in the Canadian Cordillera. Examples elsewhere include the Savage Lode and Butte Highlands deposits in Western Australia and Montana, respectively (Mueller 1991; Ettlinger et al., 1995).

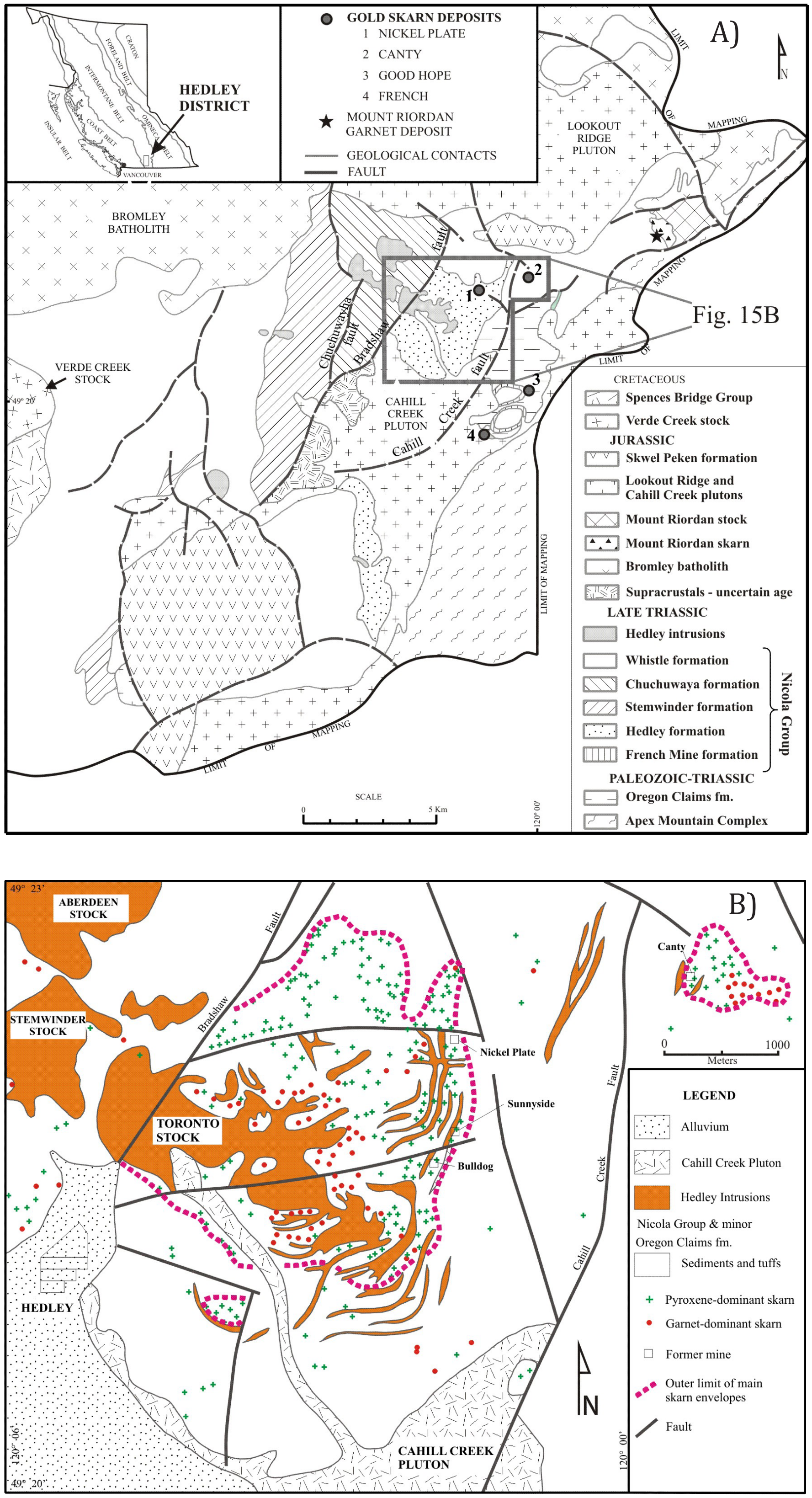

Fig. 15. (A) Geology of the Hedley Gold Skarn District, southern British Columbia (adapted after Bostock, 1930, 1940; Billingsley and Hume, 1941; Dolmage and Brown, 1945; Ray and Dawson, 1994; Ray et al., 1996). (B) Geology of the Nickel Plate and Canty Au skarn deposits, Hedley, B.C., showing the distribution of, and mineral zoning in, exoskarn envelopes (after Ray et al., 1996). Note that most of the large Nickel Plate alteration envelope comprises pyroxene skarn but a relatively narrow zone of garnet-rich skarn is developed close to the Toronto Stock.

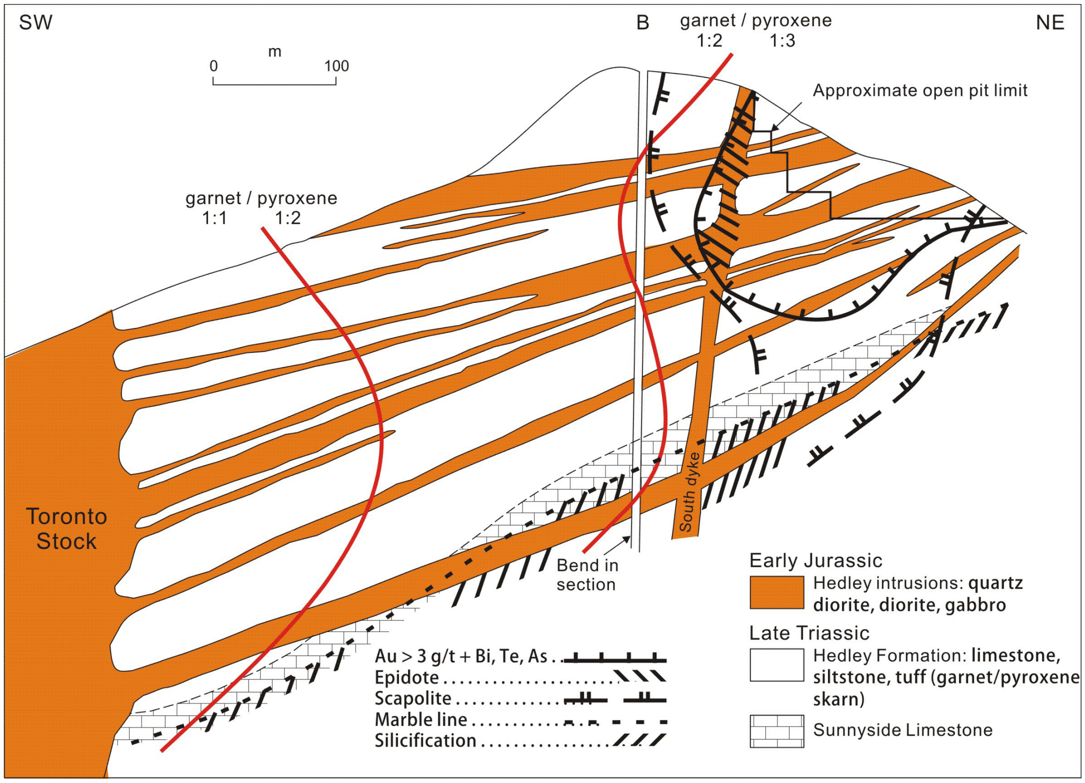

Fig. 16. Schematic SW-NE cross section through the Nickel Plate Au skarn deposit, Hedley, B.C. (after Ettlinger et al., 1992). Note the decreasing garnet/pyroxene ratios with increasing distance from the Toronto Stock, and that the open pit gold-bearing ore lies in the distal, pyroxene and scapolite-rich skarn.

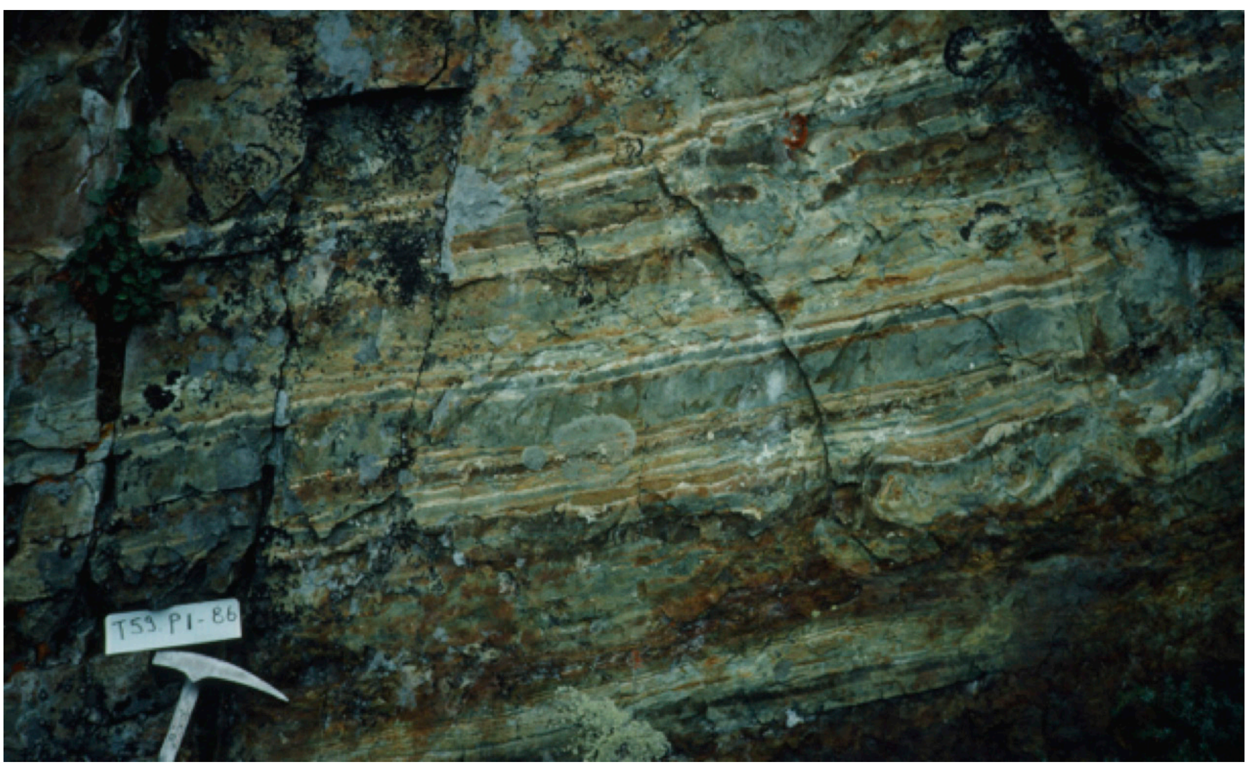

Photo 6. Bedded calcareous siltstone and thin limestone (grey) partly altered to garnet-pyroxene skarn (brown). Nickel Plate Au Mine, Hedley, British Columbia.

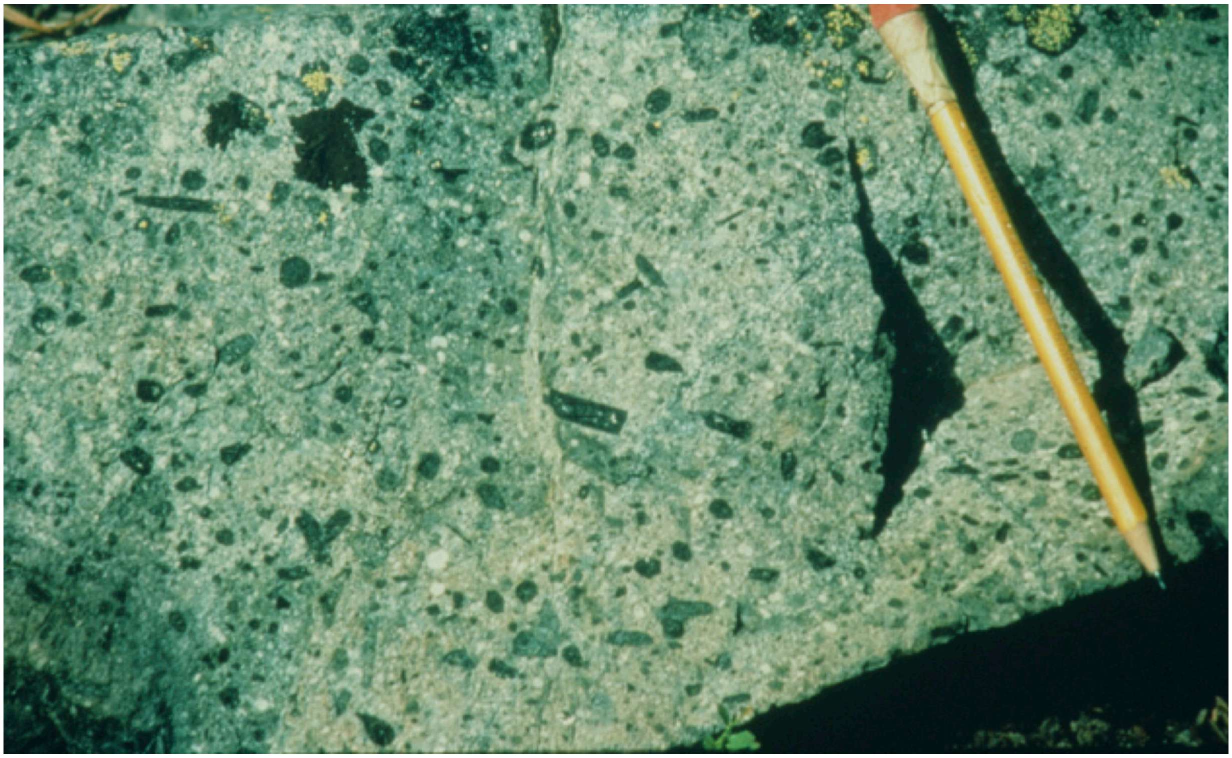

Photo 7. Partly bleached and endoskarn-altered Toronto Stock gabbro with igneous pyroxene and hornblende phenocrysts. Nickel Plate Au Mine, Hedley, British Columbia.

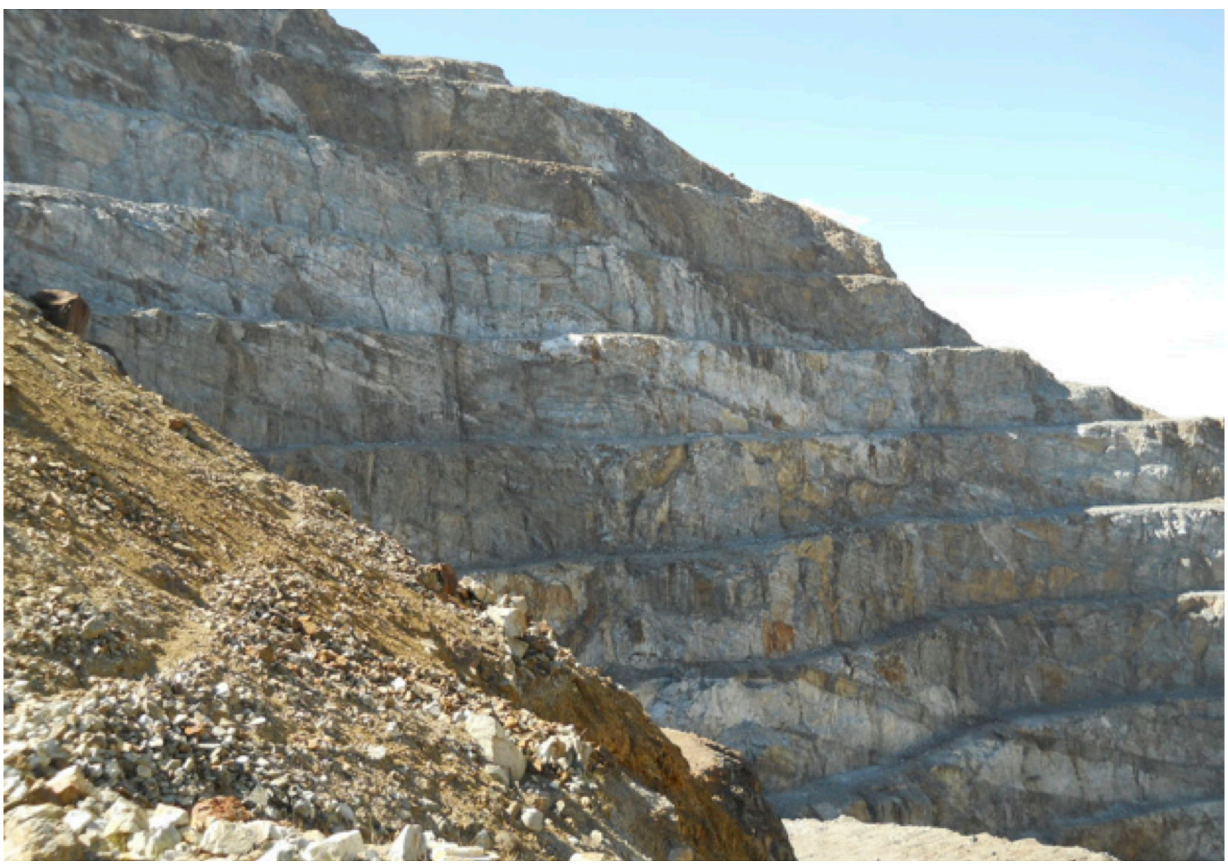

Photo 8. Nickel Plate open pit showing gently dipping pale endoskarn sills with intervening dark exoskarn ore, Hedley, British Columbia.

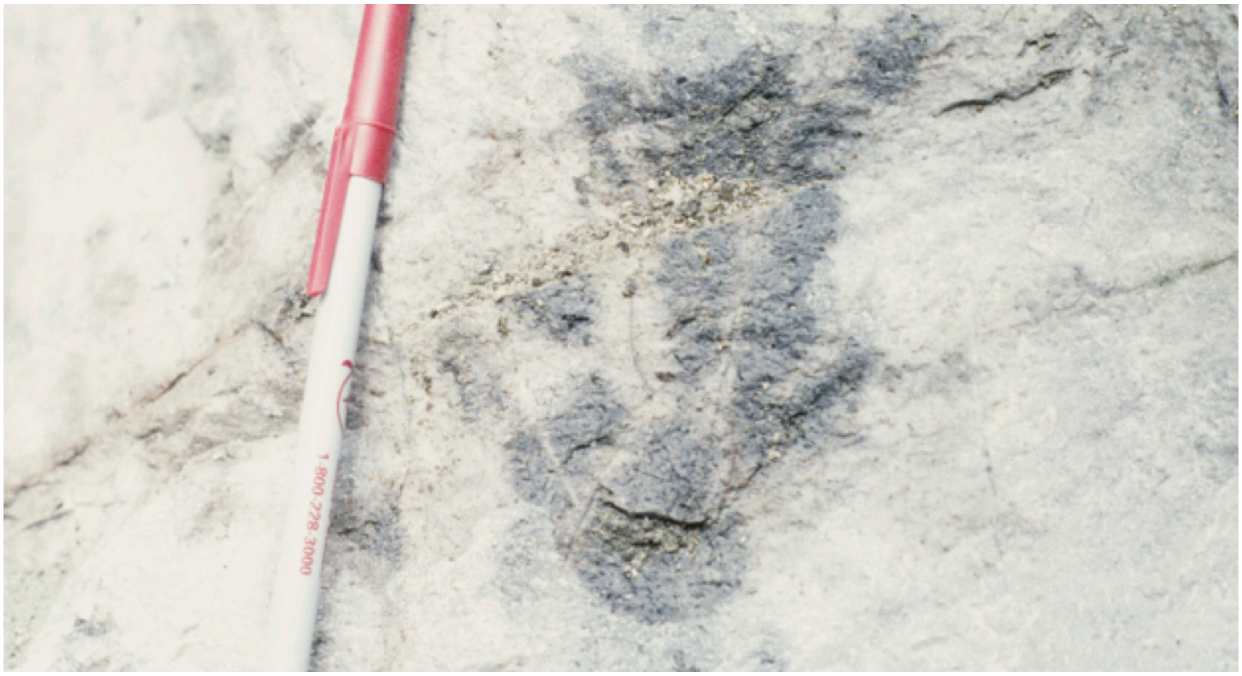

Photo 9. Strongly bleached endoskarn sill (white) with small remnant patches of less altered gabbro (grey). Note the alteration is fracture-controlled. Nickel Plate Au Mine open-pit, Hedley, British Columbia.

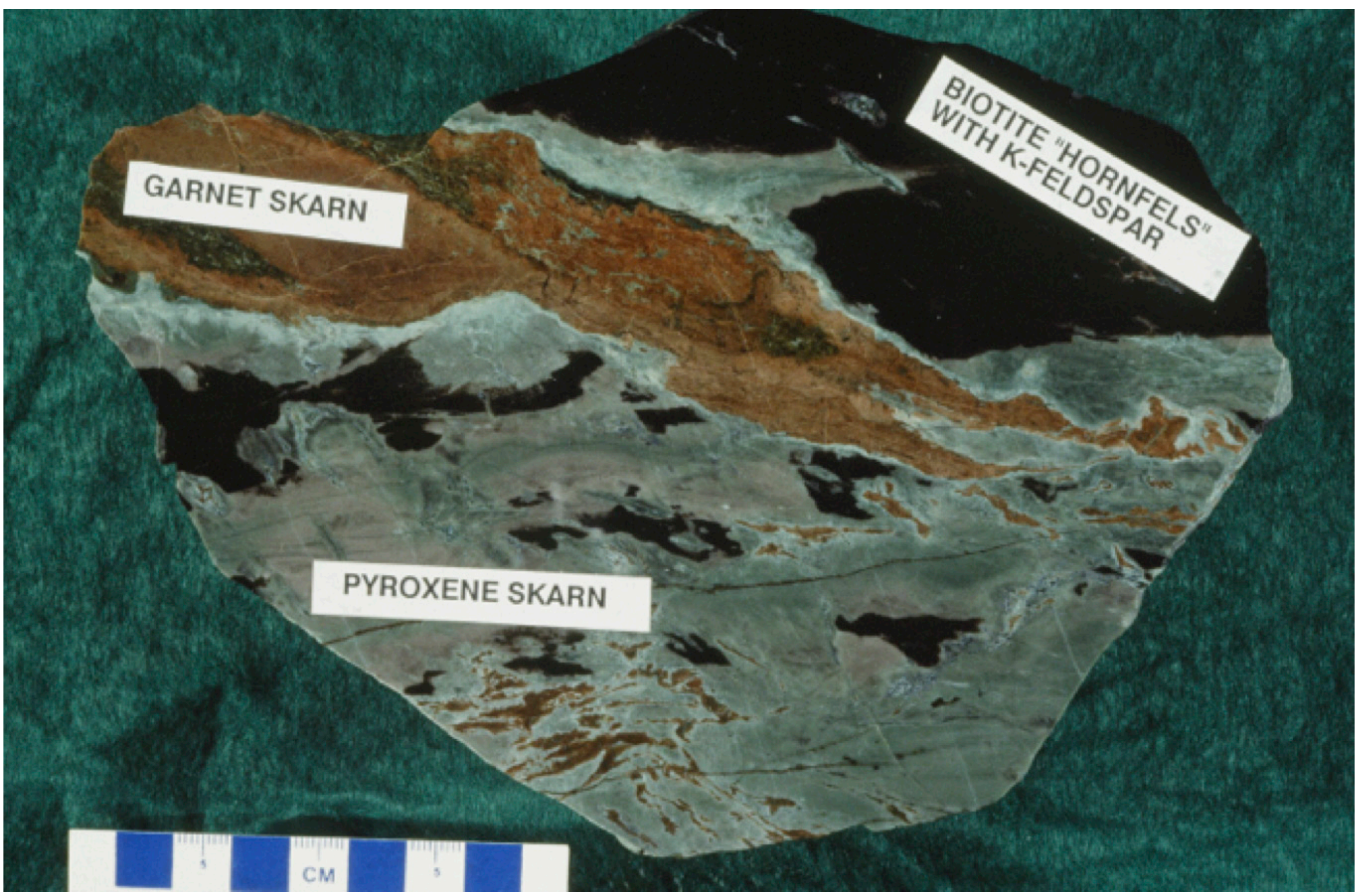

Photo 10. Early biotite “hornfels” (black) partially replaced by pyroxene exoskarn (pale green), which is cut by garnet vein (brown). Note that where the pyroxene replaces the “hornfels” a reaction rim of pink K-feldspar is produced. French Au Mine, Hedley, British Columbia.

In contrast to the Hedley skarns, the Au skarns at Banks Island, British Columbia, and at Ketza River, Yukon (Fig. 1), are hosted by the Alexander and Cassiar terranes respectively; these are associated with Cretaceous granitoid plutons (Dawson, 1996b). The Marn and Horn Au skarns in the Yukon (Brown and Nesbitt, 1987; Yukon MINFILE) are also Cretaceous, but are hosted by Permian limestones in the Selwyn Basin.

All of the Au skarns in the Canadian Cordillera contain predominantly calcic skarn assemblages. Most are hosted by calcareous sedimentary rocks, although a few, such as the QR deposit, are hosted by Ca-rich mafic tuffs and flows (Fox and Cameron, 1995). On the basis of their dominant gangue mineralogy, most of the Cordilleran Au skarns can be broadly separated into pyroxene-rich, garnet-rich, or epidote-rich types (Table 3). These contrasting mineral assemblages partly reflect differences in host rocks, variations in pluton and fluid chemistry, and oxidation and sulfidation conditions.

Pyroxene-rich Au skarns have low garnet/pyroxene and pyrite/pyrrhotite ratios and they contain grandite garnet, generally hedenbergitic pyroxene, and Fe-rich biotite (Table 3; Fig. 6). The related intrusions are commonly gabbros, diorites and granodiorites with high total Ti contents and low Fe_2O_3/FeO ratios (Ray et al., 1995; 1996). The sulfide-rich orebodies tend to lie in the outer parts of the exoskarn envelopes (Table 2). Examples include the Marn skarn in the Yukon (Fig. 1; Brown and Nesbitt, 1987) and the Nickel Plate, Canty, French, and Good Hope deposits at Hedley, in British Columbia (Figs. 15A and 15B; Billingsley and Hume, 1941; Dolmage and Brown, 1945; Ettlinger, 1990; Ray and Dawson, 1994). They favour calcareous siltstone host rocks and the skarn mineralogies (e.g., high pyrrhotite content and the presence of Fe-rich biotite and hedenbergitic pyroxene) suggest that the hydrothermal systems were relatively reduced.

Large, economic garnet-rich Au skarns have not yet been identified in the Canadian Cordillera, although the Guder skarn in the Yukon (Fig. 1) may be of this type and there is potential elsewhere. Foreign examples include the McCoy and Wabu skarns in Nevada and Indonesia, respectively (Brooks, 1994; Allen et al., 1995). They are characterized by high garnet/pyroxene and pyrite/pyrrhotite ratios, and by the presence of diopside, pyrite, magnetite and hematite (Table 3). Orebodies are generally sulfide-poor and may form both proximal and distal to the intrusions. They can be Cu-poor (<200 ppm Cu) and magnetite-rich, and locally contain anomalous Zn (>1000 ppm) and Bi. The magnetite-rich parts of some deposits are associated with well-developed hydrothermal breccias, as seen at Wabu, Indonesia (Allen et al., 1995; personal communication 2012). Garnet-rich Au skarns favor high-level, relatively oxidized hydrothermal systems and are commonly hosted by successions with predominantly carbonate rocks.

Epidote-rich Au skarns are uncommon. The QR (Quesnel River) skarn (Photo 11; Fig. 1; Fox and Cameron, 1995) is the only economic deposit known in the Canadian Cordillera, although two deposits in Montana (McLaren and the Diamond Hill) may be of this type (Johnson and Meinert, 1994; P.S. Mulholland and T. Stepp, personal communication, 1998). The QR skarn is related to a high-level, oxidized alkalic porphyry system and is hosted mainly by epidotized and chloritized mafic flows and tuffs in which garnet is rare (Photo 12). The ore has high pyrite-pyrrhotite ratios and is locally rich in chalcopyrite.

Photo 11. Open pit, Quesnel River (QR) Gold Mine, south-central British Columbia.

To the naked eye, the ore in most types of Au skarn is indistinguishable from waste rock. Gold occurs mostly as micron-sized inclusions in sulfides or at sulfide and/or silicate grain boundaries. In the pyroxene-rich and garnet-rich types, it is commonly associated with Bi minerals (including Bi tellurides) and arsenopyrite; some deposits display sporadic enrichment in Co (Table 3). Compared to the ore in other skarn classes (Fig. 19), Au skarn mineralization in many deposits (e.g. Nickel Plate) has low base-metal/Au ratios (Cu/Au <2000; Cu/Ag <1000; Zn/Au < 100, Ag/Au < 1; Ray and Webster, 1995; Ray, 1996). Furthermore, a correlation between copper and gold in many pyroxene-rich and garnet-rich Au skarns is lacking, unlike many Fe and some Cu skarns where a positive Cu:Au correlation exists. Thus, the gold potential of a skarn prospect might be overlooked if Cu sulfide rich outcrops are preferentially sampled and other sulfide-bearing or sulfide-lean assemblages are ignored. A positive Au:Cu correlation is seen in the epidote-rich QR skarn (Fox and Cameron, 1995), and the Marn skarn (Brown and Nesbitt, 1987).

Mineral and metal zoning is common in many Au skarns. At the Nickel Plate deposit, coarse-grained, predominantly garnet skarn close to the Toronto Stock quickly grades distally out to fine-grained pyroxene-rich skarn (Photo 13; Ettlinger et al., 1992; Figs. 15B and 16). Mineralization in the proximal garnet skarn is marked by sporadic chalcopyrite and malachite with high Cu/Au ratios. By contrast the distal pyroxene skarn hosts orebodies characterized by low Cu/Au ratios (Figs. 16 and 19; Ettlinger et al., 1992). Although the Nickel Plate orebodies lie in the distal pyroxene-rich portion of the skarn envelope, on a local scale the highest grade mineralization is commonly hosted by thin zones of garnet-dominant skarn that developed adjacent to the sills and dikes.

As noted at Nickel Plate by Billingsley and Hume (1941), the arsenopyrite, pyrrhotite, and scapolite-rich ore bodies tend

Photo 12. Gold-bearing ore of massive epidotised volcanic rocks with disseminated pyrite, blebs and veinlets of calcite-quartz, and trace garnet. Quesnel River (QR) Gold Mine, south-central British Columbia.

Photo 13. Polished 20 cm long slab of gold and sulfide-rich ore showing pyroxene (green), pyrrhotite (upper left yellow) and gold-bearing arsenopyrite (white). Nickel Plate Au Mine, Hedley, British Columbia.

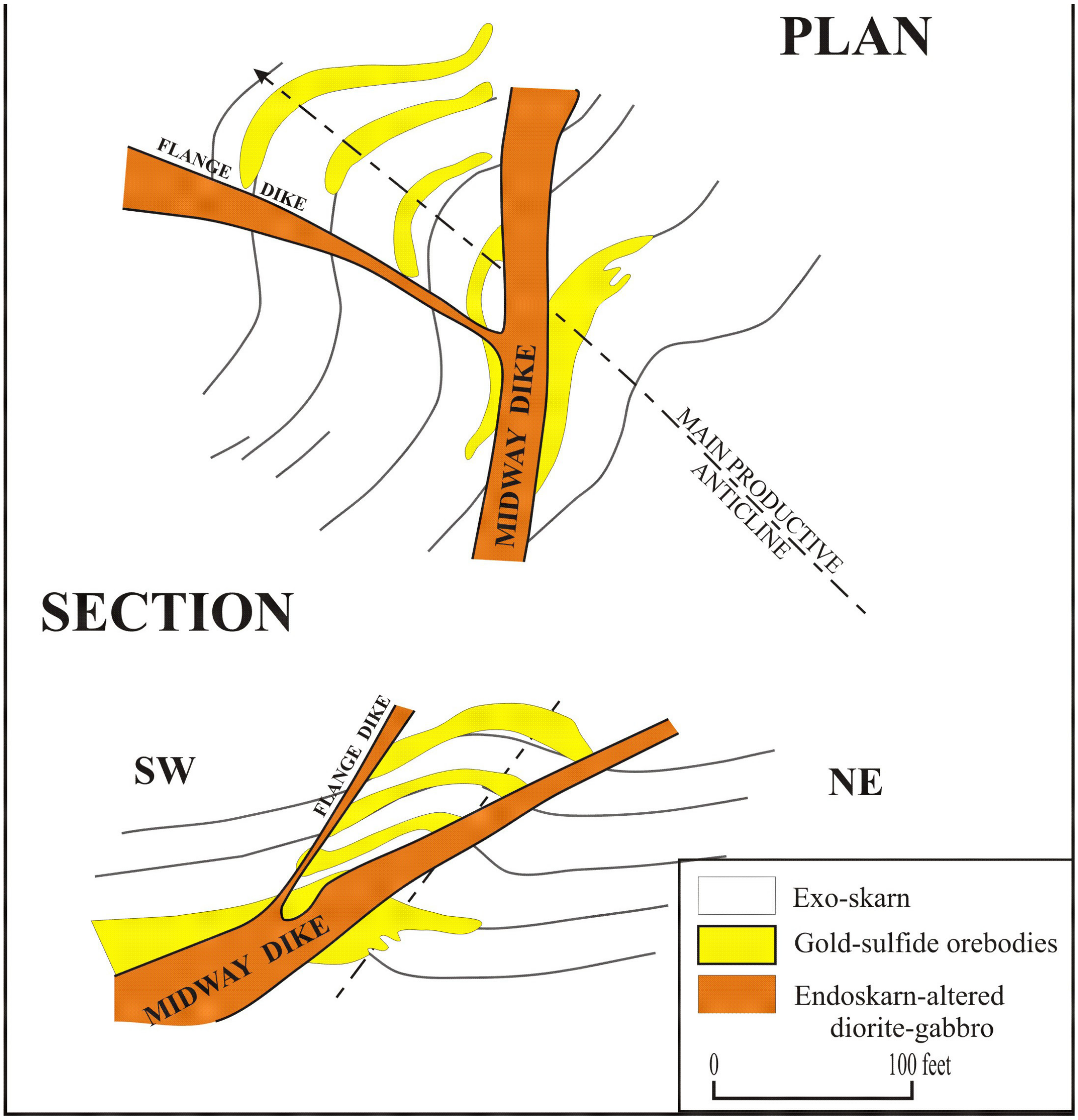

Fig. 17. Schematic plan and cross section through parts of the Nickel Plate orebodies, as presented by Billingsley and Hume (1941). Note that the ore bodies are controlled by structural traps such as antiformal fold hinges and dike-sill intersections.

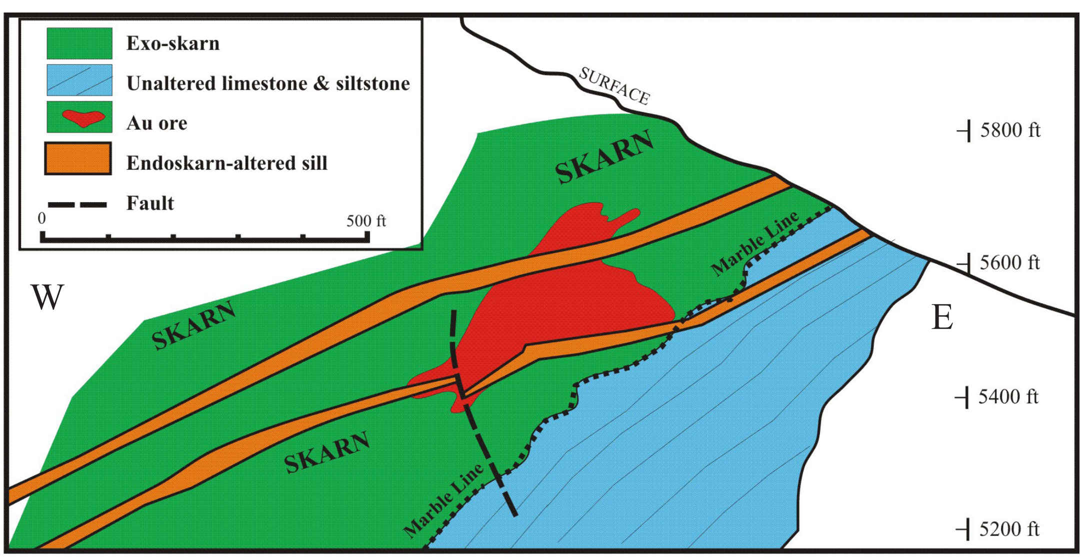

Fig. 18. W-E cross section through the "Sunnyside" orebody, Nickel Plate Au skarn deposit. Note that the mineralization forms close to and above the 'marble line', which represents the lower and outer limits of the skarn envelope. Adapted after Billingsley and Hume (1941).

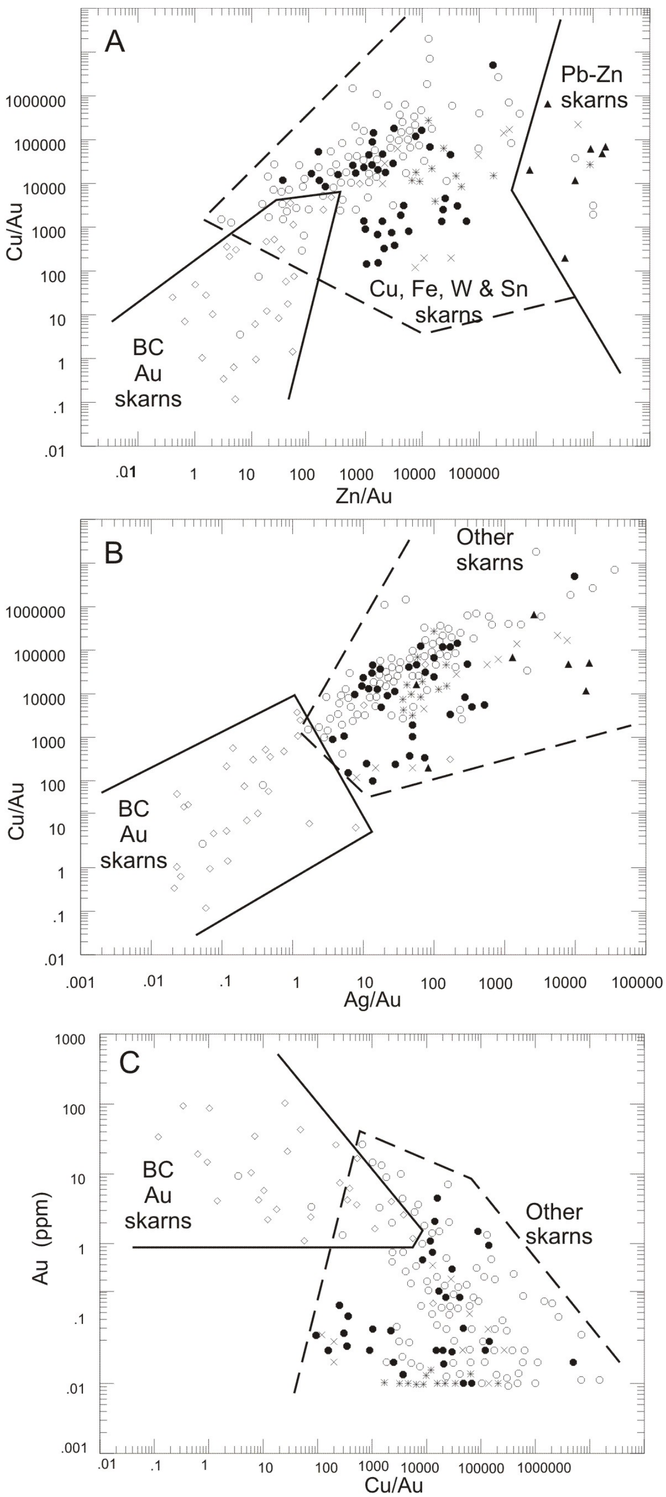

Fig. 19. Plots (using assay data from Ray and Webster 1997) comparing the metal ratios of Au, Fe, Cu, W, Sn, and Pb-Zn skarns in British Columbia. (Hedley Au skarns = open diamonds; Fe skarns = solid dots; Cu skarns = open circles; W skarns = asterisks; Sn skarns = crosses; Pb-Zn skarns = triangles). Skarn field classes are drawn around main clustering of points. Note the comparatively low metal ratios in the Hedley Au skarns. (A) Cu/Au versus Zn/Au, (B) Cu/Au versus Ag/Au, and (C) Au (in ppm) versus Cu/Au.

to form in structural traps such as sill-dike intersections and antiformal hinges (Fig. 17). The richest orebodies were found close to the lower parts of the pyroxene skarn envelope, within 30 to 70 meters of the “marble line” (Billingsley and Hume, 1941), which represents the contact between skarn and the underlying marble (Fig. 18). Thus, a vertical as well as lateral zoning is apparent at Nickel Plate. From top to bottom this zoning comprises: (1) coarse grained calcite ± quartz veins cutting calc silicate hornfels; (2) barren, fine-grained pyroxene-quartz-potassium feldspar ± biotite skarnoid, sometimes referred to as the "Upper siliceous beds" (Billingsley and Hume, 1941), (3) generally barren pyroxene ± garnet exoskarn and lesser amounts of endoskarn sills and dikes; (4) sulfide-gold mineralization hosted by pyroxene ± garnet ± scapolite exoskarn; (5) barren marble, silicified marble and biotite hornfels and (6) unaltered siltstones and limestones.

The Ketza River deposit in the Yukon also displays a district-wide zoning in which Au-rich pyrrhotite-chalcopyrite manto orebodies apparently grade outward across 1 - 3 km to Ag-Pb-Zn replacements (Cathro, 1990). Mineral zoning is also seen at the epidote-rich QR deposits, where the richest ore lies within 50 meters of the distal epidote skarn front (Fox and Cameron, 1995).

An unusual type of Au skarn, the Heino-Money deposit, is in the Tillicum Mountain area of southern British Columbia (Fig. 1). It is related to small monzodioritic stocks and sills of uncertain age and is hosted by a roof pendent of metasedimentary and lesser metavolcanic rocks of the Jurassic Rossland Group (Ray and Spence, 1986; Ettlinger and Ray, 1989). The skarn, which appears to be pre- or syn the regional deformation and metamorphism, is characterized by pyroxene-garnet-quartz-potassic feldspar assemblages, and is locally marked by thin quartz stringers and veinlets that may have developed during regional metamorphism and deformation (Photo 14). The garnets are highly unusual compared to most Au skarns in being sub-calcic with between 45 and 55 mole percent pyralspite (Fig. 6; Ettlinger and Ray, 1989). Generally, the mineralization is not sulfide-rich but is associated with bismuth minerals and tellurides (Meinert, 1998). In most other Au skarns in British Columbia, gold is of micron-size and invisible to the naked eye. However, the Tillicum Mountain mineralization is unusual in having visible gold, commonly in the quartz veinlets. Meinert (1998) classified the mineralization as part of a group of Au skarns found in “mesothermal” regional metamorphic terranes that include the Archean-hosted deposits in Western Australia (Mueller, 1991).

8.5 Molybdenum skarns

Worldwide, Mo skarns are usually smaller and of less economic importance than porphyry Mo deposits (Einaudi et al., 1981). They are separable into two types: polymetallic (containing molybdenite with other W, Zn, Pb, Bi, Sn, Co, or U-rich minerals), and "molybdenite-only" (containing mainly molybdenite with few or no other sulfides).

British Columbia has 22 Mo skarn occurrences and the

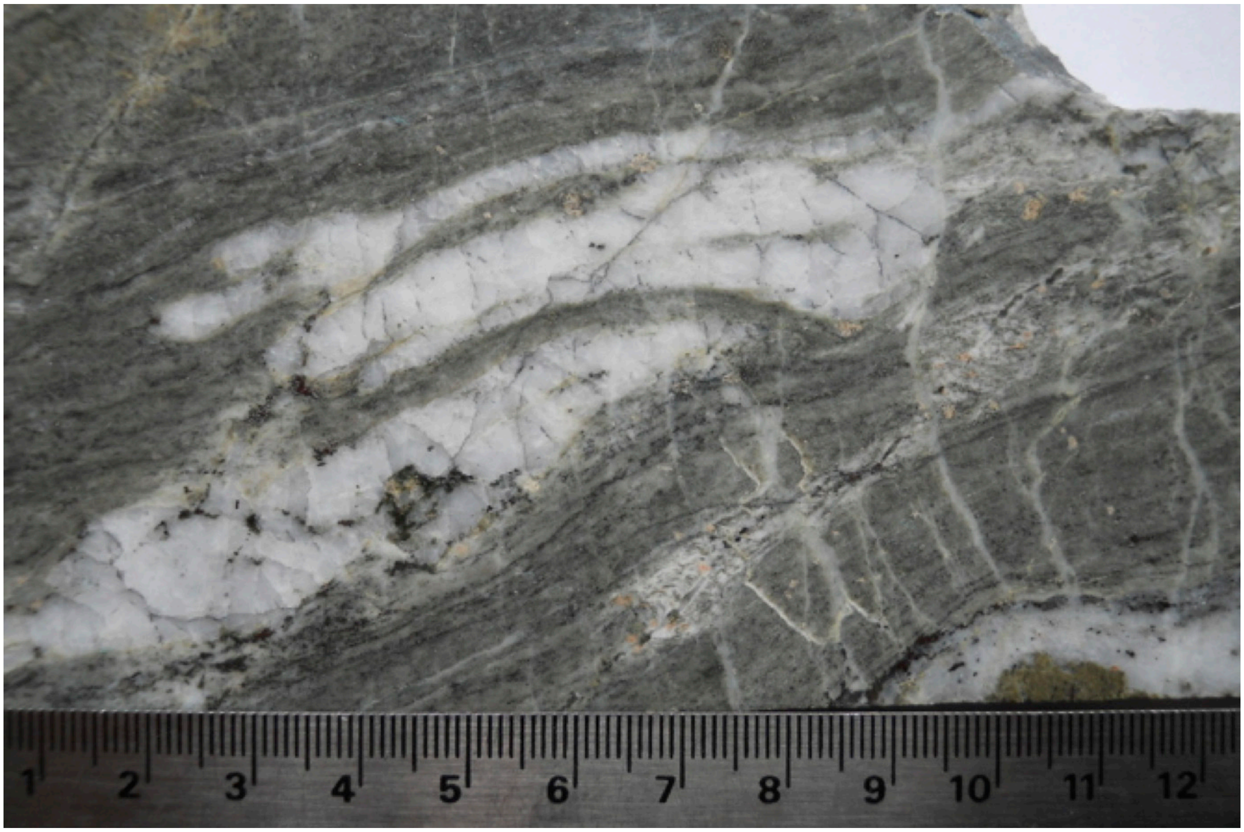

Photo 14. Polished slab of ore from the Heino-Money deposit, Tillicum Mountain, southern British Columbia. Gold-bearing quartz veins in foliated garnet-pyroxene-K-feldspar exoskarn.

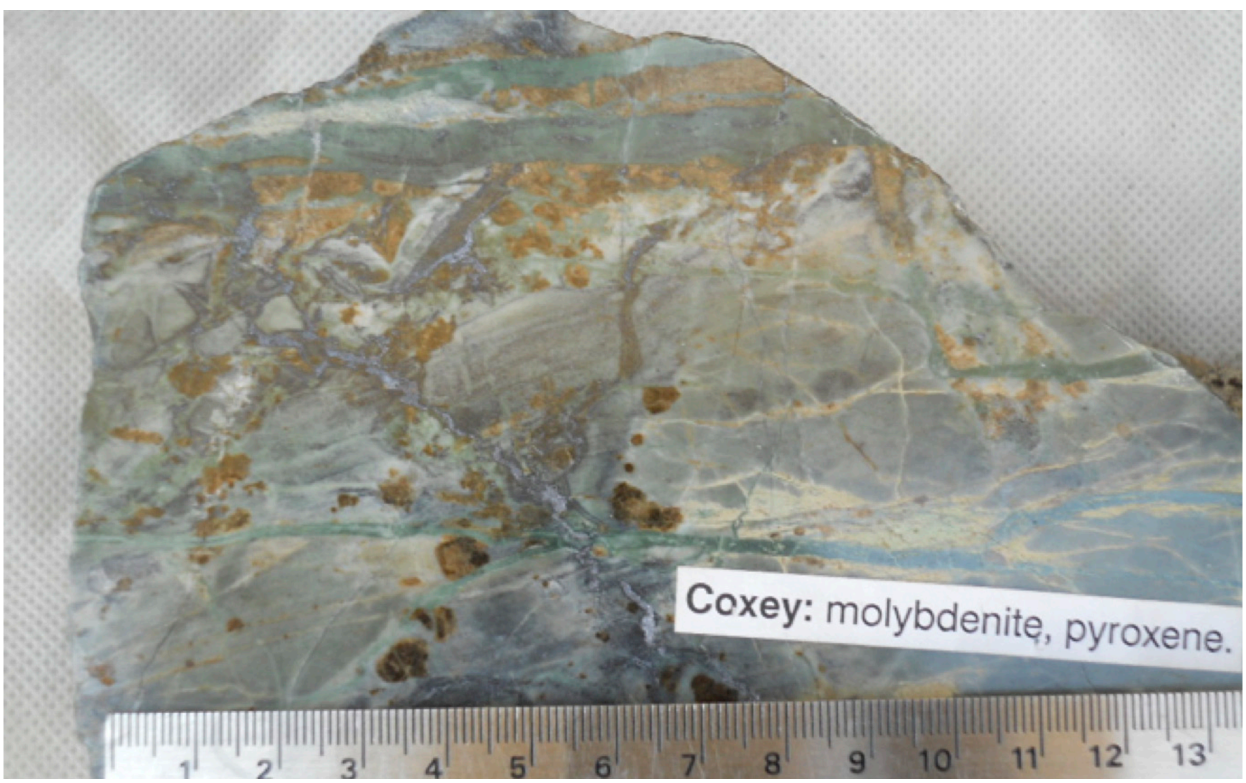

Photo 15. Pyroxene-quartz-vesuvianite-chlorite exoskarn (pale green) with scattered subhedral garnet (brown) cut by molybdenite veins. Coxey Mo Skarn, Rossland, southern British Columbia.

Yukon has 7 (Fig. 2). Of these, only the Coxey-Novelty-Giant deposits at Rossland (Fig. 1) have been mined (Fyles, 1984; Webster et al., 1992; Hoy and Dunne, 1997, 2001). Many Mo skarns in the Canadian Cordillera are hosted by cratonic, pericratonic, and displaced continental margin rocks of the Kootenay and Cassiar terranes, and Ancestral North America (Tables 1A, 1B). The Rossland Mo skarns are associated with arc-related, sub alkaline stocks and dikes of Early to mid Jurassic age that are largely of quartz monzonite to adamellite composition (Fig. 4).

The Coxey-Novelty-Giant Mo skarns at Rossland lie at the western end of an east- trending belt of mineralization that is associated with a Jurassic sub-volcanic intrusion, the Rossland Monzonite (Höy et al., 1992, 1997; Höy, 1998; Höy and Dunne, 2001). Also associated with this intrusion, at deeper structural levels, are the Au-Cu sulfide veins of the Rossland camp, which are locally enveloped by barren skarn (Höy and Dunne, 2001). Shallow-level dikes and small porphyritic stocks at the Coxey-Novelty-Giant deposits locally display spectacular explosion breccia textures. These intrusions, like those associated with the Hedley Au skarns, are enriched in Ba (Fig. 4J). However, they have much higher K_2O/Na_2O ratios than the plutons related to Cu, Fe, or Au skarns in British Columbia (Ray and Dawson, 1998), which possibly relates to the shoshonitic character of the Rossland volcanic sequence (Höy et al., 1992; Höy, 1998).

The Coxey Mo skarn contains biotite hornfels that is overprinted by pyroxene-garnet-vesuvianite prograde skarn (Photo 15) and epidote-actinolite-chlorite retrograde assemblages (Webster et al., 1992; Ray and Webster, 1997). The grandite garnets range from Ad 53-73, and the low-Mn pyroxenes from Hd 63-78 (Fig. 6). The Coxey ore consists primarily of molybdenite (Photo 15) with minor scheelite, pyrite, and pyrrhotite. The hydrothermally brecciated intrusions and adjacent brecciated sedimentary rocks are locally mineralized. In contrast to the Coxey orebodies, scheelite has not been reported in the nearby Novelty Mo skarn. The Novelty and Giant deposits are highly unusual Mo skarns in having significant quantities of Au. Apart from the abundant molybdenite, mineralogically they resemble some Au skarns in containing abundant arsenopyrite, and minor pyrrhotite, chalcopyrite, cobaltite, bismuthinite, native bismuth and gold, (Fyles, 1984; Webster et al., 1992). Grab samples from the Novelty and Giant skarns contained highly anomalous quantities of Au, Bi, Ni, As, Co, Te, and Se (Ray and Webster, 1997); the nearby Novelty mineralization also includes uraninite. The Coxey, Novelty and Giant deposits probably lie within a large exoskarn envelope that is mineralogically and chemically zoned.

Several deposits in Lower Paleozoic limestones of the Cassiar Terrane in the northern Cordillera are composite porphyry-skarn types in which Mo- and W-bearing veinlets are concentrated in the border phases of the pluton. Molybdenite also overprints scheelite-rich calc-silicate skarns at the Logtung, Boya, and Mount Haskin W and Sn properties (Fig. 20; Dick, 1980; Dawson et al., 1991; Noble et al., 1995; Kirkham and Sinclair, 1996).

8.6 Tungsten skarns

The northern Canadian Cordillera has several W-bearing megaskarn deposits that define an arcuate belt flanking the Selwyn Basin (Fig. 1). They include the Canada Tungsten (Cantung) Mine in the NWT and the Macmillan Tungsten (Mactung) deposit in the Yukon (Dick, 1976; 1980; Dick and Hodgson, 1982; Figs. 1, 20 and 21). However, significant mining has occurred only at Cantung in the NWT (Fig. 21), and at the Emerald Tungsten and Dimac deposits in British Columbia (Figs.1 and 22; Photos 16, 17 and 18).

Most W skarns in the Canadian Cordillera are associated with mid-Cretaceous intrusions of the Omineca Crystalline Belt (Figs. 1, 3D and 3E) and are mainly hosted by Upper Proterozoic to Lower Paleozoic rocks of the cratonic shelf and its displaced equivalents (e.g., Cassiar, Kootenay, Yukon-Tanana, Selwyn Basin, and Dorsey terranes; Tables 1A, 1B). Relatively thick and pure limestone beds in Lower Cambrian carbonate-pelite sequences are particularly favorable host rocks. Dolomitic carbonate rocks, although common in these settings, tend to be less favorable sites for W skarn development, hence magnesian W skarns are rare.

The associated plutonic rocks are generally of adamellite-quartz monzonite-granodiorite-granite composition (Figs. 4A and 4B) and leucocratic. Studies elsewhere (Newberry et al., 1990; Newberry, 1998) and plots (Figs. 4K and 4L) indicate the intrusive rocks are mostly evolved, I-type granites-granodiorites of either the ilmenite or magnetite series. The Nb, Y, and Rb content of the stocks in the Emerald Tungsten camp (Fig. 4E) show they represent "within-plate" plutons (as defined by Pearce et al., 1984), although the intrusions at the Dimac deposit are of "volcanic arc" character (Ray and Webster, 1997). Granitic rocks related to W skarns tend to be more differentiated (Fig. 4H), more contaminated with sedimentary material, and have crystallized in more reduced and deeper structural levels than those associated with Cu skarns (Newberry and Swanson, 1986; Newberry, 1998). They are commonly coarse grained, porphyritic, and unaltered, but border phases may display variable amounts of argillic, greisen, or tourmaline alteration. Stockwork quartz-scheelite-molybdenite veining is generally not extensive, and breccia pipes, intrusive and shatter breccias and other features indicating high-level emplacement are generally absent.

Based on mineralogy, depth of formation, and skarn and intrusion chemistry, Newberry (1998) separated W-bearing skarns into two broad groups, “W-skarns” and “W-F skarns”. The former include both “reduced” and “oxidized” types, and the latter can be further subdivided into those that are Mo-poor and Mo-rich (see Table 1 of Newberry, 1998). The reduced W skarn group contains W-Cu-Bi-Au-bearing metal assemblages and includes many of the important western Canadian examples such as Mactung, Cantung, and Lened, and the deposits of the Emerald Tungsten camp (Fig. 1). The oxidized group of W skarns is less well represented; it tends to contain W and Mo

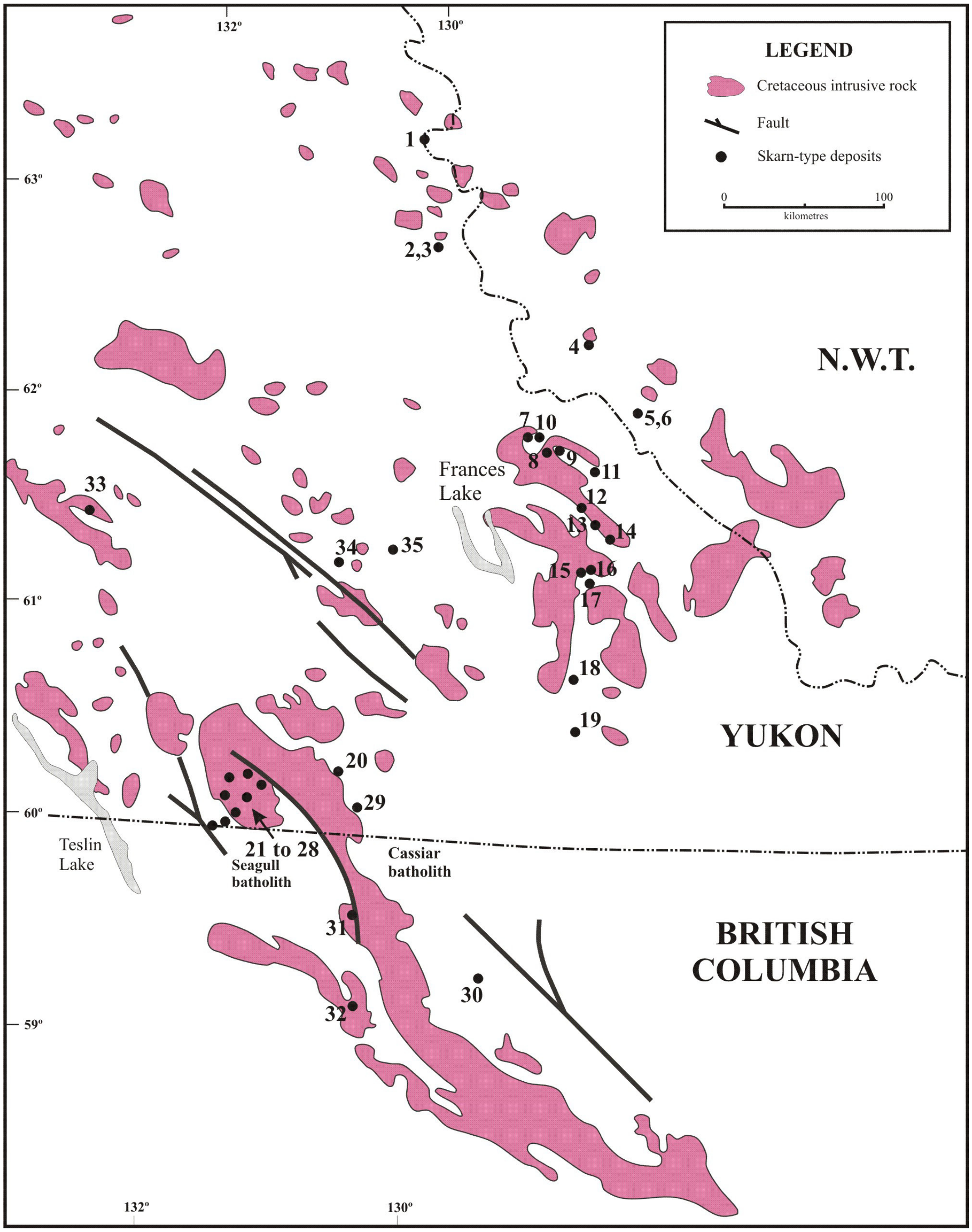

Fig. 20. Cretaceous W-Cu, Sn-W and Zn-bearing skarns and related mineralization in northern BC, southern Yukon, and adjoining part of the NWT. Adapted after Dick (1980).

1. Mactung W-Cu
2. Clea W-Cu (Zn-Sn)
3. Omo W-Cu (Zn-Sn)
4. Lened W-Cu
5. CanTung W-Cu (Sn)
6. Baker W-Cu (Zn)
7. Woah W (Mo-Zn)
8. Tai, Broten W (Mo-Zn)
9. Tanya W-Cu
10. Zeus Zn (Pb-W-Cu)
11. Cali W-Cu
12. Ron Pb-Zn
13. Fir Tree Zn-Pb (W-Ag)
14. Black Jack Zn-Pb (W-Ag)
15. Max W (Cu-Pb-Zn-Ag)
16. Glenna Zn-Pb (Ag)
17. Miko Zn-Pb (Ag-W)
18. Bailey W-Cu
19. Hundere Pb-Zn (Ag)
20. Nite W (Mo-Zn)
21. Bar Zn-Pb (Cu-Ag-Sn)
22. Atom Zn (Pb-Cu-Ag-Bi)
23. Bom, Munson Zn-Pb (Ag-Sn-Cu-W)
24. Unnamed W-Sn (Zn)
25. Unnamed W (Cu-Sn)
26. JC Sn-Cu (Zn-W)
27. Unnamed Sn-Cu (Zn-W)
28. Logtung W-Mo (vein stockwork and skarn)
29. Fiddler W-Sn (vein)
30. Mt. Haskins W-Mo-Pb-Zn (vein stockwork and skarn)
31. Blue Light W (Sn)
32. Ash Mt. Area Sn (in calc-silicates)
33. Stormy W-Mo
34. Grass Lakes area W (Sn-Au)
35. Myda W (Sn)

with lesser amounts of Cu, Zn, Ag and Bi-bearing minerals.

Calcic W skarns contain scheelite, commonly with pyrrhotite and either chalcopyrite or molybdenite, unevenly distributed in an assemblage of prograde pyroxene-garnet and retrograde hornblende, actinolite, and biotite. The pyroxenes range compositionally from Hd 5-95 (Fig. 6), although closer to the ore zones they tend to be more hedenbergitic (Hd 70-95) and may contain significant johannsenite (Jo 0-22). Compared to the garnets in other skarn classes, those in W skarns tend to have the widest ranges of grossularite-andradite-pyralspite compositions (Fig. 6). Like those in some Pb-Zn and Sn skarns, the garnets in many W skarns are highly subcalcic. The strongly subcalcic nature of garnets in British Columbia's largest W skarn deposits at the Emerald Tungsten camp (Ray and Webster, 1997) supports the conclusions of Newberry (1983) that a relationship exists between subcalcic garnets, reduced oxidation states, and the size and grade of W skarn deposits.

A typical calcic assemblage includes a coeval 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 in pelitic hornfels. Cooling of the system and influx of meteoric water initiates hydrous retrograde alteration. This

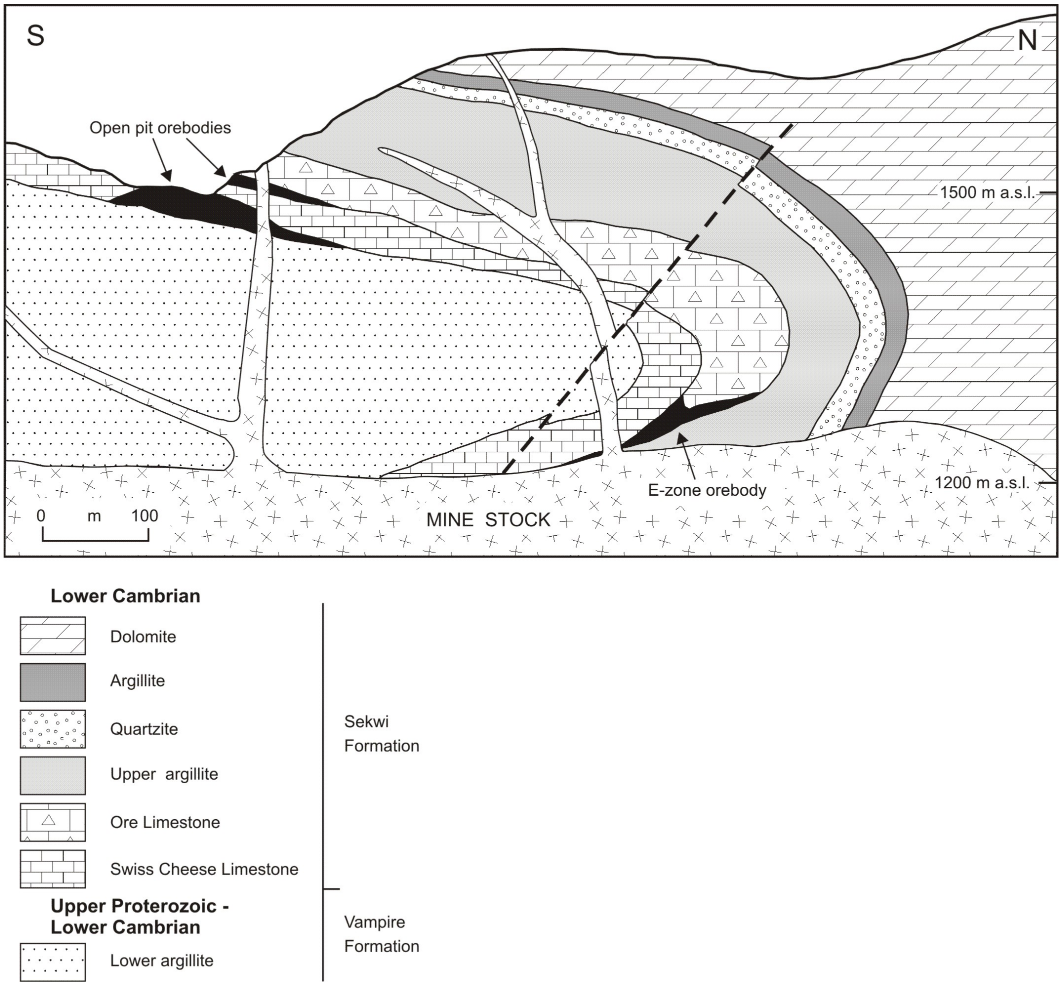

Fig. 21. Schematic cross section through the Canada Tungsten (Cantung) pit and E-zone orebodies (after Cummings and Bruce, 1977; Gordey and Anderson, 1993).

is accompanied by the deposition of most sulfides, and either primary deposition of scheelite or its redistribution, with both depletion and upgrading (Dick, 1976; 1980; Dawson, 1996c). Extensive areas of biotite hornfels are commonly associated with the larger W skarn deposits, which has been used as an exploration guide (Dick, 1980). Mineral zoning may be well developed and typically consists of sphalerite peripheral to scheelite-rich skarn.

The scheelite-bearing ore at the Emerald Tungsten camp (Fig. 22) generally comprises sulfide-poor and garnet-rich skarn with minor fluorite and powellite (Ray and Webster, 1995). However, some pyrrhotite, arsenopyrite, and quartz-rich zones lack scheelite and instead contain anomalous Au (up to 9 g/t), with enrichment in Bi, Sb, Te, and Se, and rare telluride and selenide minerals (Ray and Webster, 1997). These Au-bearing quartz and sulfide-rich veins commonly lie structurally above the garnet-scheelite skarns (L. Dandy, personal communication, 2003), although some zones are close to the margins of the stocks. It is still uncertain if the Au-Bi-bearing quartz-sulfide veins are related to, and a more distal part of, the W skarn system or were introduced later, although the former seems more likely.

The Jersey and Emerald Pb-Zn deposits lie adjacent to the Emerald, Feeney, and Dodger W skarns (Fig. 22). They occur within the same anticlinal structure and are underlain by the same granitoid stock and calc-silicate skarn horizon that hosts the W skarns. These features, plus their calc-silicate gangue led Dawson (1996a) to interpret them as distal equivalents to the proximal W-Mo (Au) skarns. Alternatively, these Pb-Zn deposits may be unrelated to the W skarns and could instead represent deformed mantos of pre-Cretaceous age (T. Hoy, personal communication, 2003).

8.7 Lead-zinc skarns

Many Pb-Zn skarns have a distinctive Mn- and Fe-rich mineralogy, a pronounced structural control along conduits and contacts, and tend to form some considerable distance from the magmatic source (Tables 2 and 3; Einaudi et al., 1981). In many deposits a continuum is recognized from endoskarn and proximal exoskarn, through to distal manto and chimney deposits that are more stratigraphically or structurally controlled. With increasing distance from the intrusion, sulfides progressively

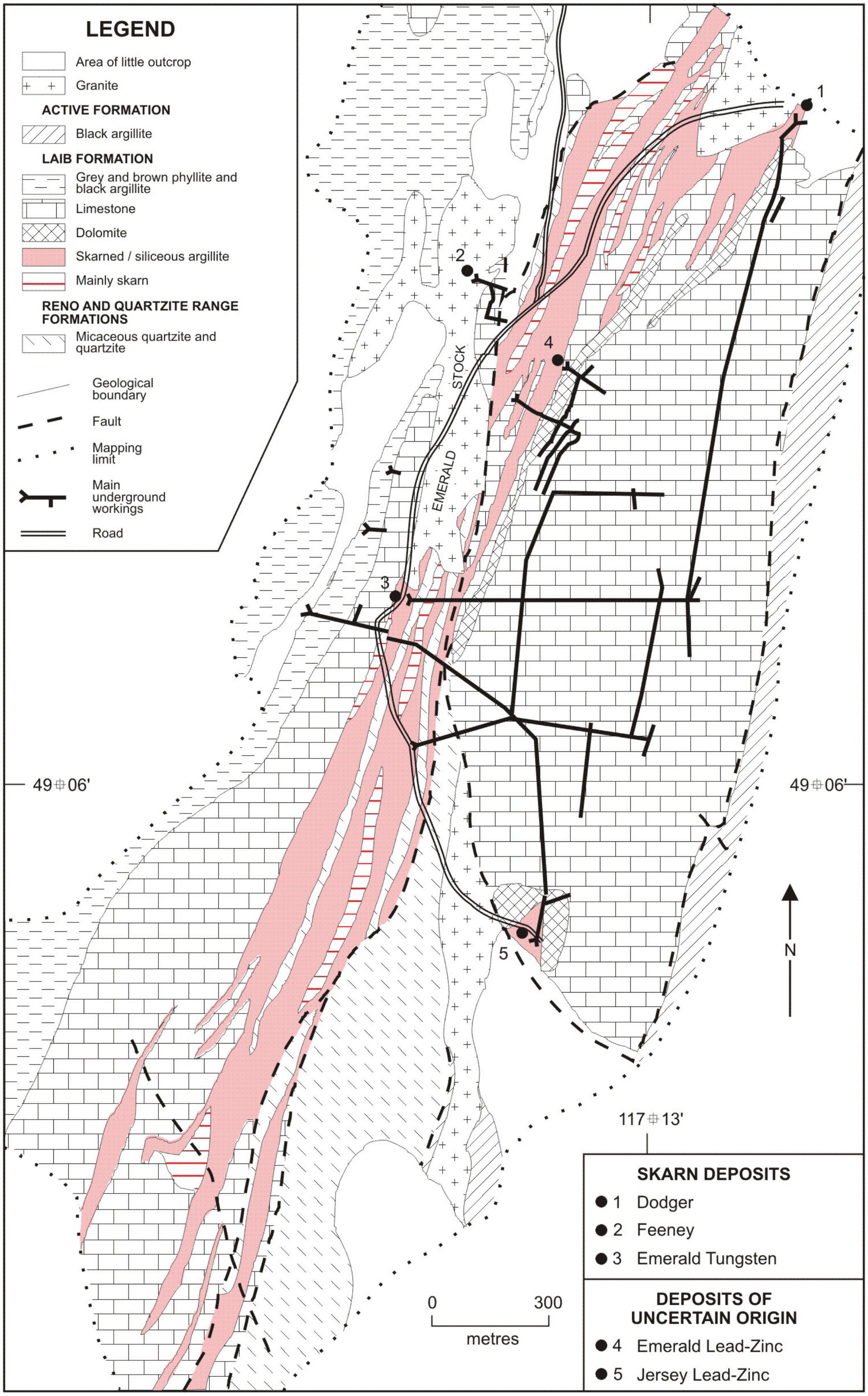

Fig. 22. Geology of the Emerald Tungsten camp showing location of the W skarn deposits and Pb-Zn orebodies (geology after Fyles and Hewlett, 1959).

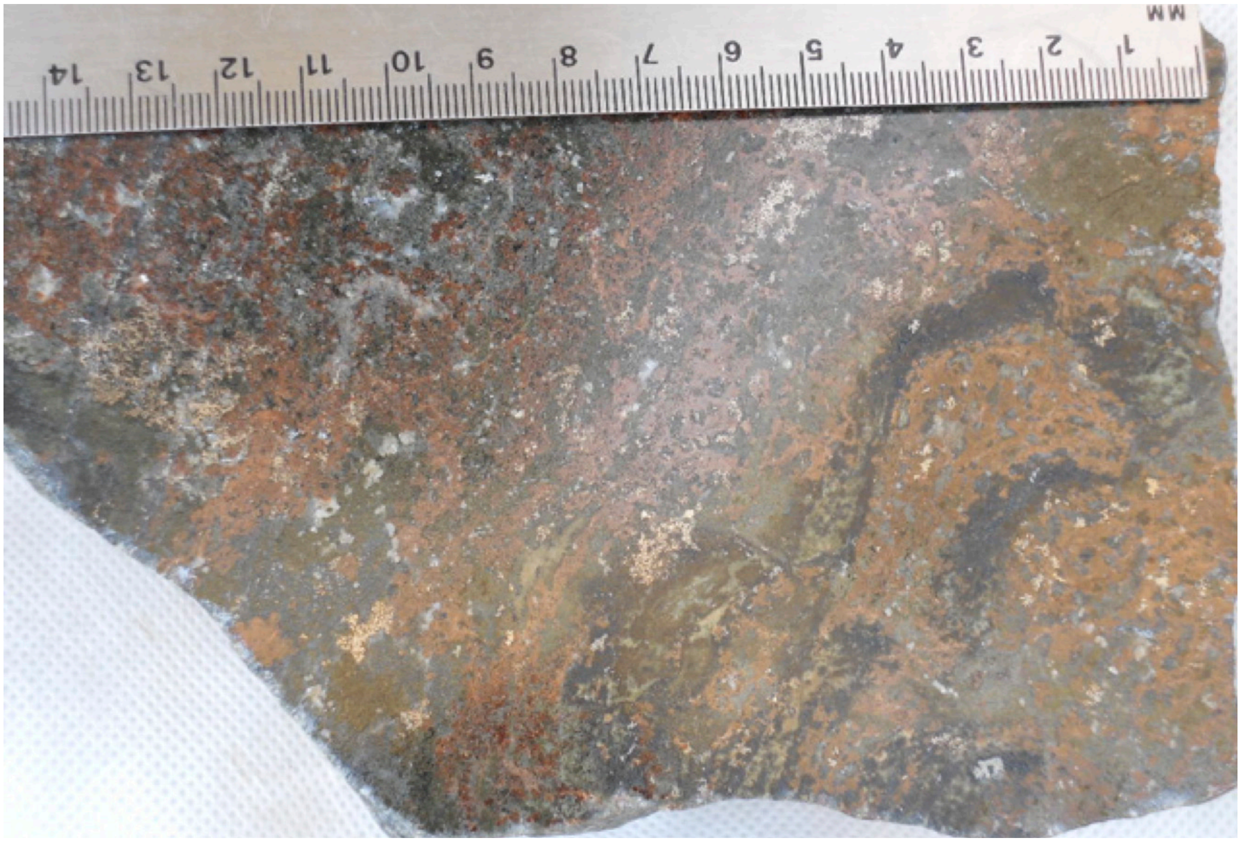

Photo 16. Massive garnet-pyrrhotite exoskarn (dark red) with scattered scheelite (white), pyroxene, amphibole and chlorite (black). Emerald-Tungsten Mine, southeast British Columbia.

Photo 17. Layered garnet-pyroxene-scheelite-idocrase exoskarn. Dimac (Silence Lake) Mine, Clearwater, central British Columbia.

Photo 18. Coarse-grained garnet-quartz-scheelite exoskarn. Dimac (Silence Lake) Mine, Clearwater, central British Columbia.

increase and the calc-silicate gangue decreases. Ultimately, distal carbonate-hosted veins or "carbonate-replacement deposits" contain Mn-rich silicates and a carbonate gangue (Nelson, 1991; Dawson 1996a; Megaw, 1998).

Because some distally developed mantos, chimneys, and other sulfide replacement deposits in the Canadian Cordillera lack a marked skarn gangue, their precise origin and relationship to skarn systems are uncertain. Significant Pb-Zn skarn and/or mantos in the Cordillera include the Sa Dena Hes and Quartz Lake deposits in the Yukon (Fig. 1; Dawson, 1964; Vaillancourt, 1982), the Prairie Creek mantos in the NWT, and the Bluebell, Midway, Ingenika, and Piedmont orebodies in British Columbia (Höy, 1980; Bradford, 1988; Nelson, 1991; Webster et al., 1992). The Mineral King, Jersey, and Emerald Lead-Zinc (Fig. 22; Fyles, 1960; Fyles and Hewlett, 1959) deposits may also be of this type, as may be small deposits such as the Magno D., Contact, Lucky Lake, and Roy in the northern Cordillera, which lie adjacent to the Cassiar, Seagull and Mount Billings batholiths (McDougall, 1954; Aho, 1969; Dawson and Dick, 1978; Webster et al., 1992; Dawson, 1996a).

Lead-zinc skarn deposits in the Canadian Cordillera range from less than 1 Mt to 8 Mt of ore at average grades of 10 to 15 % Zn-Pb, with Zn being predominant; silver grades average between 30 and 300 g/t. By comparison, the larger Ag-rich skarn and manto deposits in northern Mexico average more than 10 Mt of Zn-Pb metal (Dawson, 1996a), and many are mined for Ag alone. Some Pb-Zn skarns contain Cu at grades averaging 0.2 to 2 % Cu, and several Cordilleran deposits, such as the Midway, Silver Hart, Roy, and Magno D., contain minor W, Au, Cd and Sn (Dawson 1996a).

Many Zn-Pb skarns in the Canadian Cordillera occur within the same Upper Proterozoic to mid-Paleozoic shelf sedimentary rocks that host many W skarns. The host sedimentary strata in the eastern Cordillera are underlain by thick successions of predominantly siliciclastic sequences deposited on crystalline Precambrian rocks. On Vancouver Island, however, the small Pb-Zn skarn occurrences are generally in Paleozoic and lower Mesozoic oceanic arc-type volcanic and carbonate rocks.

Intrusive rocks associated with Zn-Pb skarns are commonly late orogenic to post-orogenic, although a few may be synorogenic. They are mostly calc-alkaline felsic to intermediate batholiths, stocks, dikes, and sills, and they span a wide range of compositions from high-silica leucogranite, topaz granite and syenite through to diorite. However, small stocks of quartz monzonite composition are the most common intrusive type. In comparison to plutons associated with many W, Cu, and Au skarns, they show a broader range of composition, morphology, and depth of emplacement. Age of intrusion and accompanying mineralization ranges from mid-Cretaceous to early Tertiary in the eastern Cordillera, but is Jurassic on Vancouver Island.

The Sa Dena Hes mine at Mount Hundere, near Watson Lake, Yukon (Fig. 1; Abbott, 1977) is an example of a large Pb-Zn manto and replacement without any exposed igneous source rocks. Abundant prograde actinolite-hedenbergite-grossularite and retrograde quartz-fluorite skarn assemblages over several manto orebodies are interpreted to reflect the presence of buried plutons (Dawson and Dick, 1978).

8.8 Tin skarns

At least 19 Sn skarns are known in the Canadian Cordillera but none have been mined, due to their small size and subeconomic grade. Much of the tin metal is in silicates such as malayaite, garnet, amphibole, epidote, and titanite, and is thus not economically recoverable. Deposits occur peripheral to the Seagull Batholith in southern Yukon, the Surprise Lake Batholith near Atlin, B.C., and at Ash Mountain west of Cassiar, B.C (Fig. 20). They are of Middle to Late Cretaceous age (Fig. 3F) and are mostly hosted by pericratonic carbonate-bearing rocks in the Cassiar and Yukon-Tanana terranes, and oceanic sedimentary and mafic rocks in the Cache Creek Terrane (Tables 1A, 1B).

Plutons associated with Sn skarns are generally late-to post-orogenic stocks of highly evolved, two-mica leucogranite. They include rocks of I, S and A-type (Newberry, 1998; Figs. 4K and 4L). They are characteristically peraluminous, highly differentiated, and have elevated contents of Rb, Nb, Y, F, Cl, B, Be and U (Figs. 4D and 4E). Unlike the plutons related to many W skarns, those associated with some Sn skarns are highly fluoritic (Fig. 4I). Intrusive rocks adjacent to many Sn skarns commonly contain accessory topaz and have undergone extensive greisen and tourmaline alteration.

Cordilleran Sn skarns are characterized by a suite of Sn-rich prograde silicate minerals including green andradite garnet, titanite, malayaite and epidote (Table 3). Cassiterite overprints and replaces prograde Sn-rich silicates, in conjunction with other retrograde minerals. In comparison to W skarns, Sn skarns tend to be deficient in sulfides and are apparently more oxidized, being enriched in Si, F, Cl, B, and ferric Fe. Skarns in the Seagull Batholith and Ash Mountain areas (Fig. 20) have garnet compositions intermediate to grossular and andradite, and pyroxene compositions intermediate to diopside and hedenbergite (Dick and Hodgson, 1983). The more reduced Sn-skarn systems have low sulfidation states and are characterized by high magnetite-sulfide ratios (Newberry, 1998). Many are associated with Sn ± Be greisens, and biotite hornfelsic rocks are common in some deposits.

The largest Sn skarn in the Canadian Cordillera, the JC deposit, is in the Yukon-Tanana Terrane (Figs. 1 and 20) and it has a resource estimate of 1.25 Mt grading 0.54 % Sn. It is hosted by Mississippian limestones adjacent to the mid-Cretaceous Seagull Batholith. The skarn is a multi-stage assemblage of Sn-rich silicates overprinted and replaced by cassiterite, sphalerite, and magnetite (Layne and Spooner, 1986, 1991, Layne et al., 1991).

Rarely, F-rich Sn skarns contain distinctive, thinly layered, 'wrigglite' or ribbon skarn textures (Kwak and Askins, 1981) that may superficially resemble gneissic layering (Photos 19 and 20). These are noteworthy because they are considered to develop at shallow levels, such as above cupolas of high-level granites (Kwak 1987). The small Daybreak skarn occurrence at Atlin, which is associated with the F-rich Surprise Lake Batholith, has wrigglite consisting of thin (< 1cm), alternating layers rich in either magnetite, fluorite, vesuvianite, or garnet (Photos 19 and 20; Ray et al.,1997, 2000).

8.9 Industrial mineral skarns

Skarns are a potential economic source of industrial minerals or commodities such as fluorite, wollastonite, garnet, borates, rhodonite, tremolite, marble, and bleached limestone. Skarn-related garnet and wollastonite are mined from several localities in the U.S.A. (Harben and Bates, 1990; Austin, 1991). The Canadian Cordillera also contains several important deposits (Fig. 1). In the Yukon, the Marlin deposit has produced rhodonite, and the bleached carbonate haloes at some Fe skarns on Texada Island in southern British Columbia are quarried for white ornamental limestone or marble. The Mount Riordan - Crystal Peak skarn at Hedley (Figs. 1 and 15A) is the largest and highest grade garnet skarn yet identified in the Canadian Cordillera. It contains reserves of 40 Mt grading 78% garnet (Grond et al., 1991; Ray et al., 1992).

The demand for industrial garnet in North America is growing and skarns such as the Mount Riordan deposit could be an important future source. A very low content of non-silicate minerals, particularly sulfides is essential for economic viability. The garnet should have a high specific gravity and angularity, be free of inclusions, and occur as discrete grains that can be processed easily by conventional beneficiation techniques. Massive garnet skarns suitable for industrial mineral purposes tend to favor thick carbonate sequences intruded by relatively oxidized granitic rocks.

Wollastonite is increasingly used by the plastic, chemical, and ceramic industries. Although trace wollastonite has been identified in approximately 10% of the skarns in the Canadian Cordillera, only a few occurrences have commercial potential. Most of these are in British Columbia (Fig. 1), although one (Monday) is in the Yukon. The deposits in British Columbia include the Mineral Hill (Photo 21; Goldsmith and Logan, 1987; Goldsmith and Kallock, 1988; Ray and Kilby, 1996a, b), Rossland Wollastonite, and Zippa Mountain-Isk skarns (Stinson, 1995; Jaworski and Dipple, 1996).

The CO_2 content of mineralizing fluids is important in influencing the stability of wollastonite (Greenwood, 1967). Because the wollastonite forming reaction produces CO_2, large, high grade wollastonite deposits preferentially form where the CO_2 content is low and temperatures are high. Such conditions prevail in open skarn systems that are either flushed by H_2O-rich fluids, or have dramatic periodic drops in fluid pressure. It is possible that, in part, the Rossland Wollastonite, Mineral Hill and Zippa Mountain-Isk deposits (Stinson, 1995; Jaworski and Dipple, 1996; Ray and Kilby, 1996 a,b) represent reaction-type skarns formed where high-temperature contact metamorphism was more important for wollastonite development than magmatic-hydrothermal fluids.

Photo 19. Proximal layered wrigglite-textured skarn showing crenulations and fold-like structures with magnetite (black), garnet (red) and fluorite-vesuvianite (pale). Daybreak Sn occurrence, northern British Columbia.

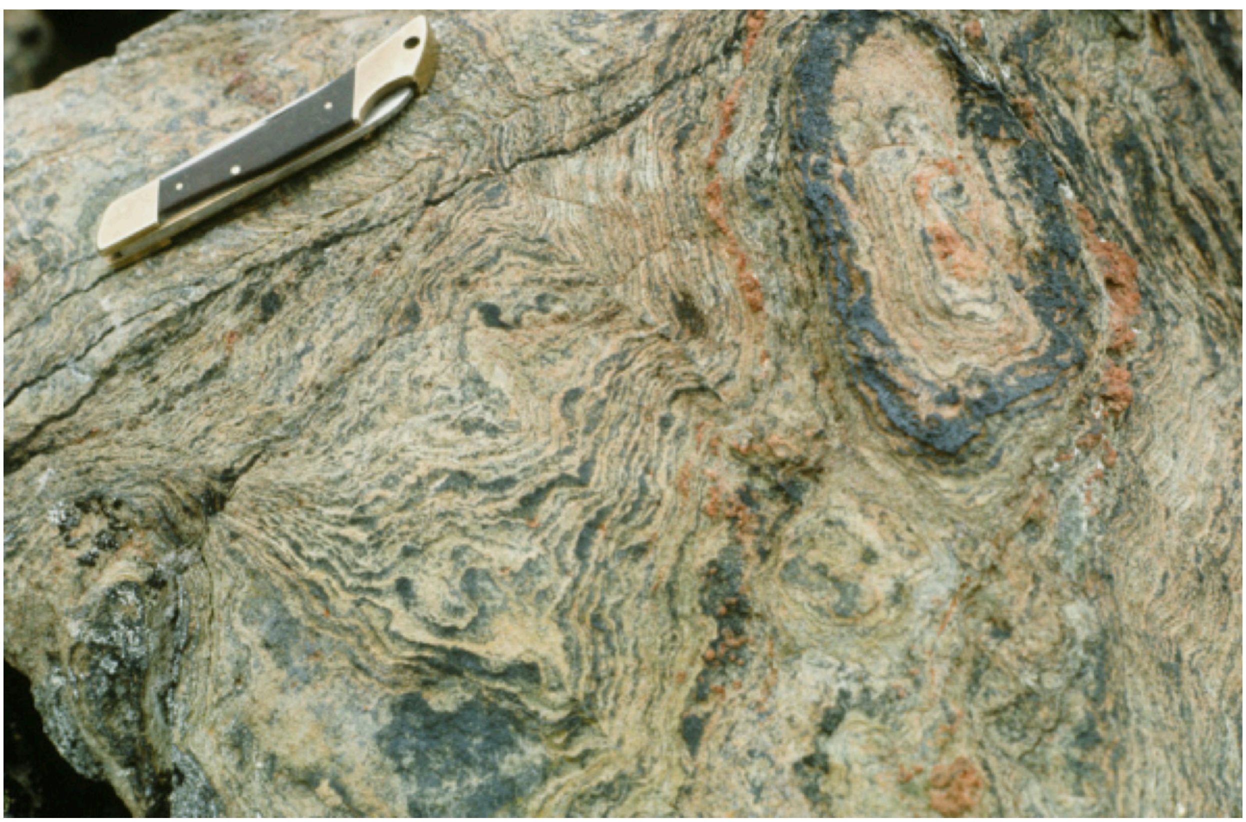

Photo 20. Layered wrigglite skarn, Daybreak Sn occurrence, northern British Columbia.

Photo 21. Mineral Hill industrial mineral (wollastonite) skarn, southern British Columbia. Garnet vein cutting radiating crystals of coarse massive wollastonite. Note the vein is haloed by bleached marble and very fine grained wollastonite.

9.0 Discussion

The size, diversity, past metal production, and current reserves of some skarns in the Canadian Cordillera indicate potential for future discoveries. Most of the major Cu and Au skarns in the Canadian Cordillera are hosted in terranes dominated by island-arc rocks. However, the Butte Highlands Au skarn in Montana (Ettlinger et al., 1995), the Big Gossan Cu-Au skarn in Indonesia (c. 37 Mt of 2.69 % Cu and 1 g/t Au; Meinert et al., 1997), and the Antamina Cu-Zn deposit in Peru (>550 Mt of 1.24 % Cu and 1.03 % Zn; Redwood, 1999; Redwood, personal communication, 2003) are hosted by platformal Ca and Mg-carbonates which indicates that similar successions in the eastern Canadian Cordillera should be explored for these deposits.

Some Cu-Au and Au skarn camps exhibit chemical and mineralogical zoning. Examples include the Hedley Au and Lustdust Cu-Au skarns in British Columbia (Ettlinger et al., 1992; Ray et al., 2002). There are many other occurrences throughout the Cordillera where proximal Cu- and garnet-rich skarns grade laterally to distal pyroxene-dominant skarns. In most cases these pyroxene skarns appear to be barren but they could perhaps contain micron gold. Thus, some of the mined-out proximal Cu skarns in the Cordillera, such as the Craigmont and Maid of Erin deposits or those in the Whitehorse Copper and Greenwood camps may warrant re-evaluation for their distal Au skarn potential. Furthermore, using the magmatic-hydrothermal model presented by Sillitoe and Bonham (1990), the carbonate host rocks lying outboard from many Cu-Au-bearing skarns should be explored for epithermal-Carlin-type Au mineralization.

Some base-and ferrous-metal skarns are also Au-bearing, which suggests that they should be re-examined as an economic source of byproduct Au. For example, the sulfide-rich Au-As-Bi-Te mineralization in parts of the Emerald Tungsten deposits and at the nearby Bunker Hill Mine (Ray and Webster, 1997) suggests that other W skarns, including those hosted by Selwyn Basin and Cassiar terrane rocks of the Yukon, may contain Au-bearing orebodies. In the Yukon, the "Tombstone Gold Belt" (Burke, 2004) includes many skarn and non-skarn Au-rich occurrences that are related to Cretaceous intrusions. Many of these skarns include W as well as Au and Bi, and some are similar in age, alteration, and chemistry to the W skarns in southern British Columbia, such as those in the Emerald Tungsten Camp (Fig. 1). Yukon examples of these

Au-bearing skarns (Emond, 1992; Emond and Lynch, 1992) include Scheelite Dome (Yukon MINFILE 115P003), Mahtin (115P007), Aurex (105M060), and the McQuesten (105M029). Similarly, the Au-rich Novelty-Giant deposits in Rossland, British Columbia (Fyles, 1984; Webster et al., 1992; Höy et al., 1992) show that other Mo-skarn occurrences in the Cordillera should be tested for Au.

Despite relatively minor historical production of Pb, Zn, and Ag from skarns, the Canadian Cordillera has potential for Pb-Zn-Ag mantos. Parts of the eastern and northern Cordillera, particularly those underlain by North American or pericratonic assemblages, have many of the favorable geological features found in other Pb-Zn-Ag manto districts in the world (e.g., northern Mexico; Megaw et al., 1988). These manto deposits are commonly erratically distributed, and lack significant alteration halos and exposed associated plutons. Thus, past exploration could have overlooked even large tonnage and high-grade orebodies.

10.0 Conclusions

The more than 1000 mineralized skarns in the Canadian Cordillera occur in a variety of different geological and tectonic environments, including volcanic island-arcs, cratonic basement, and pericratonic sedimentary rocks. They are generally hosted by diverse Ca-rich sedimentary and mafic volcanic rocks, and most are characterized by calcic alteration assemblages. Due to the lack of intrusive rocks in many of the sedimentary dolomitic or Mg-rich volcanic belts, magnesian skarns are rare in the Canadian Cordillera, although notable exceptions include some Cu skarn deposits in the Whitehorse Copper Belt.

Most of the recorded skarns are small, but some megaskarns contain several cubic kilometers of prograde and retrograde alteration. The latter are believed to develope during a long-lived diachronous hydrothermal process involving many generations of coeval prograde and retrograde alteration. This model has implications for exploration and explains why the bulk of retrograde alteration in most skarns is typically barren and is not always a reliable vector to locate ore.

The plutonic rocks related to most of the 1000 skarns range from gabbro-diorite-granodiorites formed in calk-alkaline and alkaline volcanic arcs, to highly evolved granitic rocks formed by the melting of either siliciclastic sedimentary rocks or the North American Craton. Skarn deposit classes are strongly related to pluton chemistry and plate tectonic setting. Apart from a few peripheral Cu and Au skarns formed by alkalic porphyry systems (e.g. Galore, Ingerbelle and QR), most skarns in the Canadian Cordillera are associated with calc-alkaline, sub alkaline, and I-type igneous rocks. The igneous rocks responsible for most of the Au, Fe, Cu, and Mo skarns are arc-related and metaluminous, whereas those associated with many of the W and Sn skarns have Rb, Y, and Nb contents suggesting a "within-plate" setting. Although many of the W and Sn skarn-related plutons have a similar evolved chemistry, the latter suite are commonly distinguished by their higher fluorine content.

Copper, Fe, Au, and Mo skarns are mainly hosted by island-arc packages whereas Sn and most W skarns occur either in the North American Craton or in terranes dominated by craton-derived sedimentary rocks. Most skarns in the Canadian Cordillera were formed during three distinct plutonic phases. The most important of these was related to subduction and terrane accretion during the Early to mid Jurassic, at a slightly later date than the Late Triassic to Early Jurassic age for many of the Cu porphyry deposits (Preto, 1972; Preto et al., 1979). Cretaceous and Eocene-Oligocene plutonism resulted in fewer skarns, although some Cu and W deposits (e.g., Whitehorse Copper Belt and Cantung) are economically important.

Most Cu, Fe, Au and Mo skarns in the Canadian Cordillera are Early to mid Jurassic in age, and many are hosted by island-arc rocks. However, the Cretaceous Cu skarns in the Whitehorse Copper Belt and the Greenwood camp of British Columbia are important exceptions, as is the Eocene Lustdust Cu-Au-Zn zoned skarn system, which is distinct in being hosted by oceanic Cache Creek Terrane rocks. Almost all of the W and Sn skarns are related to regional Cretaceous intrusions, some of which also contain Au-Bi mineralization. The W skarns are commonly hosted by Early Cambrian carbonate-rich sedimentary rocks that overlie ancestral North America.

There is no consistent relationship between the number of skarns in a tectonic terrane and the size and economic potential of its skarn deposits. For example, Wrangellia contains over half of the Cu skarns in British Columbia, yet its copper production has been considerably less than from those in Quesnellia, which hosts only 20% of the province's Cu skarns.

Parts of the Canadian Cordillera containing abundant intrusive rocks are not necessarily the best areas to find skarn deposits. Although the Coast Belt has the greatest concentration of plutonic rocks in the region, it has very few skarns and these have had virtually no metal production.

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