15. LODE GOLD

K.H. Poulsen

INTRODUCTION

Gold is a commodity that occurs in Canada in a wide variety of both geological settings and ore deposit types. ***Byproduct*** gold from volcanogenic massive sulphide deposits, nickel-copper deposits, porphyry copper-molybdenum deposits, and the Chibougamau copper deposits accounts for approximately one-third of Canadian resources. The remainder occurs in ***gold-only*** deposits which comprise ***placers*** (5%) and bedrock sources (60%), termed ***lode gold*** deposits (e.g. Cooke, 1946). Lode gold deposits are present in all of the major tectonic subdivisions of the Canadian landmass but occur dominantly in terranes with an abundance of volcanic and clastic sedimentary rocks of low to medium metamorphic grade. Economically viable deposits are concentrated primarily in the Archean greenstone terranes of Superior and Slave provinces, with lesser numbers in the Mesozoic-Cenozoic rocks of the Cordillera, the Proterozoic greenstone sequences of Trans-Hudson Orogen and Grenville Province, and the Paleozoic sequences of the Appalachians (Fig. 15-1).

Poulsen, K.H.
1996: Lode gold: in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 323-328 (also Geological Society of America, The Geology of North America, v. P-1).

The geological classification of lode gold deposits is problematical owing to the diversity of their host rocks. There are four aspects that historically have been important in arriving at a coherent classification of these deposits.

First is the temperature-depth concept. Classification is still largely influenced by the scheme of Lindgren (1933) who divided hydrothermal ore deposits, including those of gold and silver, into thermal types such as *epithermal*, *mesothermal*, and *hypothermal*. Ore deposit geologists now fully appreciate that thermal conditions for gold and silver deposition are rather similar (200-400°C) for all of these types so that Lindgren's choice of terms was unfortunate. Nonetheless, Lindgren fully recognized that his scheme also applied in a qualitative way to the depths in the Earth's crust at which various types of deposits form

(Fig. 15-2) and it is this aspect of his classification scheme which has persisted to the present day. Thus, ***epithermal*** gold deposits are those for which there is evidence of a shallow crustal origin (less than 1 or 2 km), ***mesothermal*** deposits are those inferred to have formed at 1 to 3 km, and ***hypothermal*** deposits at 3 km to more than 5 km. The depth ranges implied for each of the three types are not firmly fixed, but are guidelines that reflect variations in lithostatic pressure, fluid pressure, crustal temperature and metamorphic facies transitions, availability of meteoric fluids, and the vertical extent of brittle and ductile fields of deformation and seismicity. For example, in areas of high heat flow such that both the brittle-ductile transition and metamorphic facies boundaries occupy elevated positions in the crust, and where a reduced permeability permits establishment of high fluid pressures, it is theoretically possible

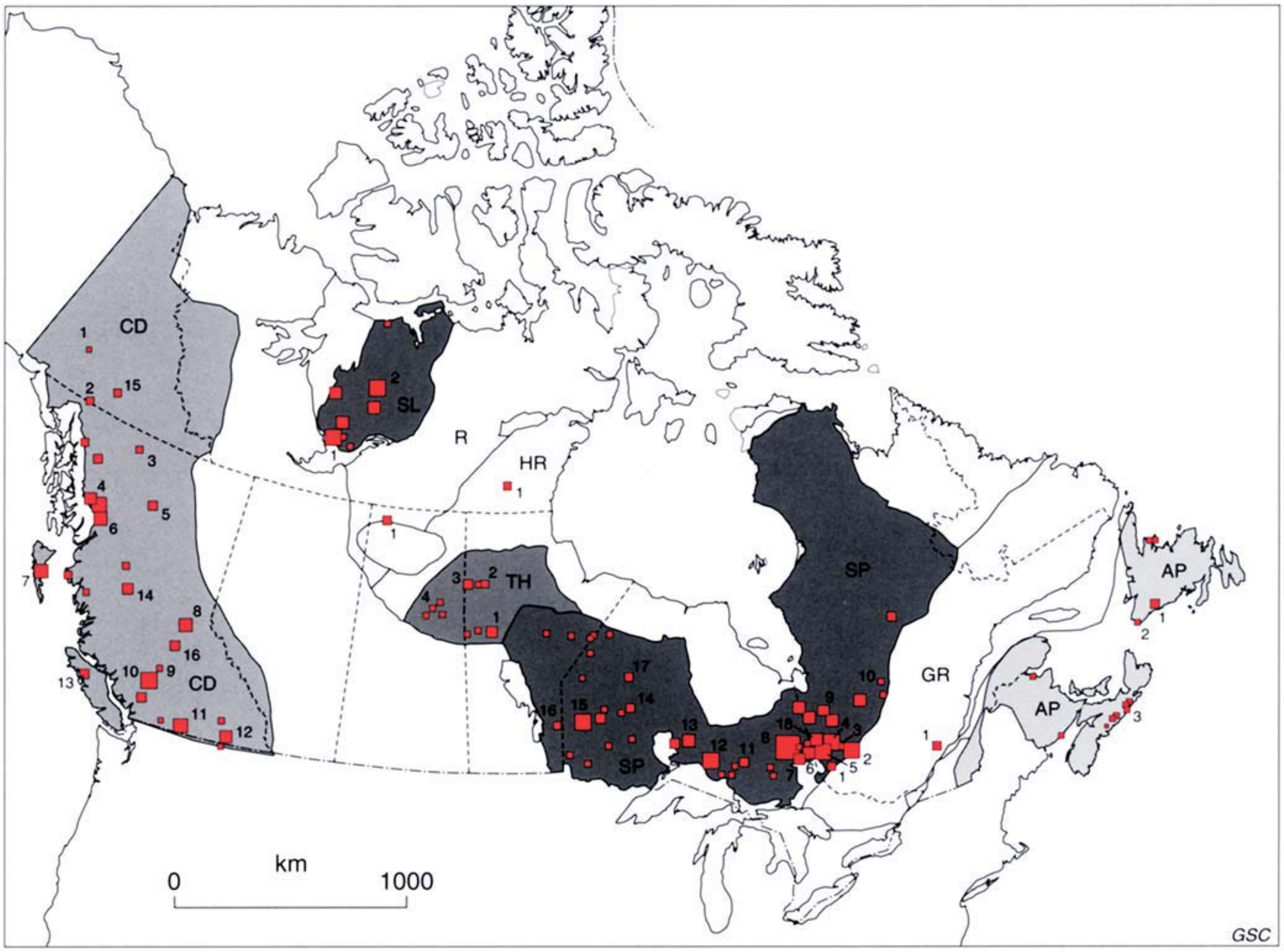

Figure 15-1. Map of Canadian lode gold deposits with respect to major tectonic domains. The smallest symbol size represents deposits that are estimated to contain less than 10 t Au; the next largest symbols, deposits containing 10 to 100 t; the second largest symbols, deposits and districts containing 100 to 1000 t; and the largest symbol size, the giant Timmins district containing more than 1000 t Au. Selected deposits and districts include: Appalachians Orogen (AP) – Hope Brook (1), Cape Ray (2), Goldenville (3); Grenville (GR) – Montauban (1); Superior Province (SP) – Belleterre (1), Val d'Or (2), Cadillac-Malartic (3), Bousquet (4), Noranda (5), Kirkland Lake-Larder Lake (6), Matachewan (7), Timmins (8), Agnico-Eagle (9), Chibougamau district (Norbeau) (10), Renabie (11), Hemlo (12), Geraldton (13), Pickle Lake (14), Red Lake (15), Bissett (16), North Cariboo Lake (17), Beattie (18); Trans-Hudson Orogen (TH) – Snow Lake (1), Farley Lake (2), MacLellan (3), LaRonge (4); Hearne Province (HR) – Cullaton Lake (1); Rae Province (R) – Box (1): Slave Province (SL) – Yellowknife (1), Lupin (2); Cordilleran Orogen (CD) – Brewery Creek (1), Mount Skukum (2), Cassiar (3), Iskut River (4), Toodoggone (5), Premier- Stewart (6), Cinola (7), Cariboo (8), Blackdome (9), Bridge River (10), Hedley (11), Rossland (12), Zeballos (13), Equity Silver (14), Ketza River (15), QR (16).

that the depth interval encompassing both "epithermal" and "mesothermal" conditions could be substantially compressed to 2 or 3 km. Burial and uplift histories are also important factors in assigning gold deposits to a particular depth zone because they can result in the superposition of a style of mineralization that characterizes one zone onto a style that characterizes deeper or shallower conditions.

Second is the vein-replacement distinction. There has been a historical distinction between vein deposits and those in which gold is disseminated, along with sulphide minerals, throughout the matrix of a particular host rock. Some lode gold deposits are particularly rich in sulphide minerals (10-70%) and these sulphides are not distributed in any particular relationship to associated veins. Such deposits have been termed "replacement" deposits in the past (e.g. Cooke, 1946). This term is no longer widely used because it was also used historically to describe magmatic nickel sulphide deposits and volcanic exhalative massive sulphide deposits which are not now believed to have formed entirely by replacement processes. Nonetheless, replacement is still a relevant process in the formation of many hydrothermal ore deposits (e.g. mantos and "zone refinement" in massive sulphide deposits) and is of particular importance in many gold deposit types.

Third is the concordance-discordance distinction. In the past two decades, increasing emphasis has been placed on the geometric relationships between gold orebodies and their host rocks. Thus concordance or discordance of orebodies is an important parameter because many other ore deposit types, such as volcanogenic massive sulphide and magmatic nickel deposits, once portrayed as being of "mesothermal" and "replacement" origins, are now regarded to have formed syngenetically. Many gold deposits are stratabound at a large scale but composed of discordant orebodies at a smaller scale.

Fourth is the compositional aspect. For many decades, geologists have noted the fact that gold deposits differ from one another in their relative contents of gold and silver and that, in the case of many epithermal deposits, the ratio of these two elements changes with depth. A corollary is that some gold deposits contain significant base metals,

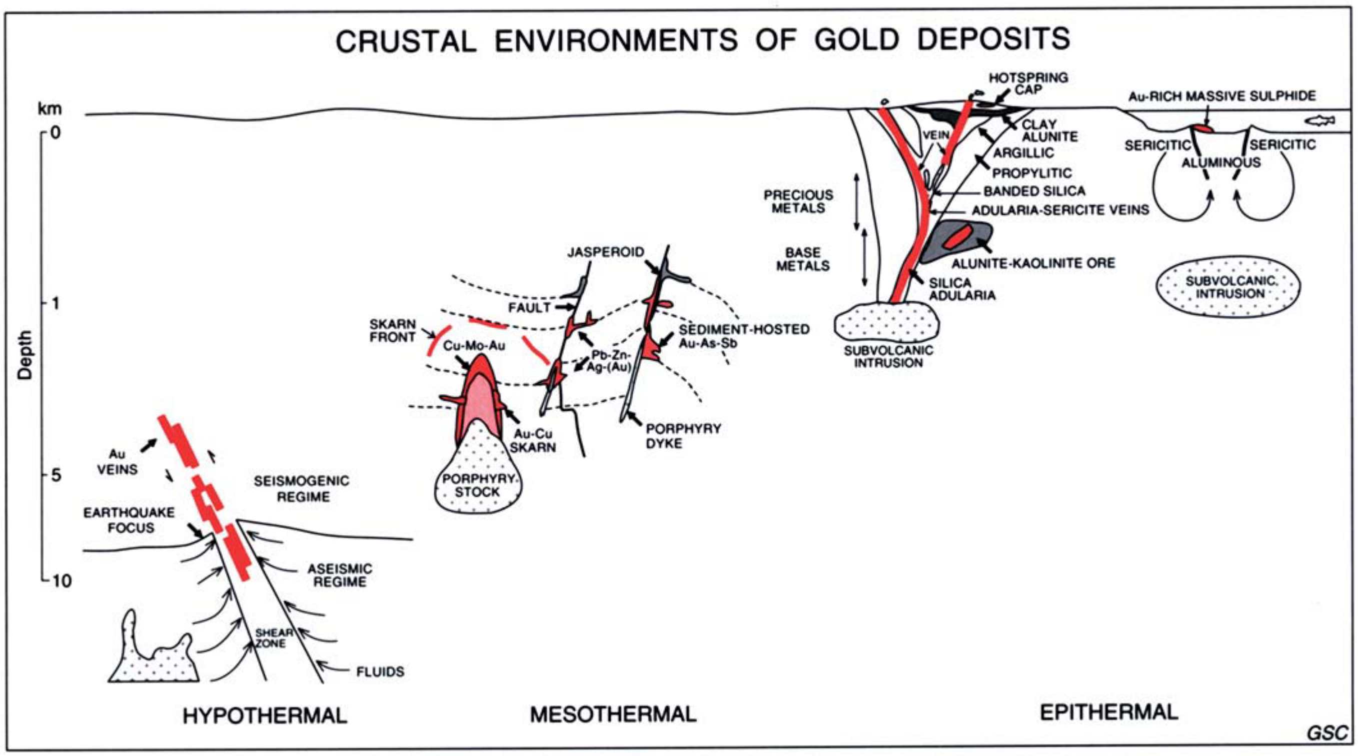

Figure 15-2. Schematic models of the crustal settings of gold deposits. For the deeper "hypothermal" environment a steep shear zone is illustrated to transect the boundary between seismogenic and aseismic crust and as a control on fluid (curved arrows) movement (after Sibson et al., 1988); for a shallower "mesothermal" environment the relative positions of porphyry Cu-Mo-Au, Au-skarn, and distal "Carlin-type" Au-As-Sb mineralization are illustrated (after Sillitoe and Bonham, 1990); for a shallow "epithermal" environment the relative position of subaerial hotspring mineralization is illustrated with respect to deeper epithermal veins (after Buchanan as reproduced in Panteleyev, 1986) as well as a hypothetical shallow marine environment corresponding to the formation of gold-rich volcanogenic massive sulphides.

whereas many base metal deposits yield significant byproduct gold. The definition of what constitutes a "gold deposit" in economic terms depends both on relative abundance of gold, silver, and base metals and on the prevailing prices of these commodities. Figure 15.3 shows the compositional ranges for common geologically-defined types of hydrothermal ore deposits as well as for individual examples. Note the wide variation in gold:silver ratios, lower values favouring epithermal, porphyry, and massive sulphide deposits, as well as the overlap of some deposit types (massive sulphide, porphyry, skarn) into the economically defined fields of both gold and base metal deposits.

Although there are many classification schemes that embody combinations of the above concepts, as well as parameters such as types of host rocks and alteration, lode gold deposits possess such a diversity of characteristics that there is little consensus among geologists as to their division into unique geological types. Most classifications (e.g. Boyle, 1979) emphasize aspects of the structure and geological setting of deposits with a decided emphasis on the nature of host rocks, whereas others, such as the classical scheme of Lindgren (1933), rely on inferred genetic variables such as depth and temperature. The most common current practice is to identify gold deposits with a "typical" deposit or geological setting (Table 15-1). This approach is practical and useful for some purposes but suffers from several weaknesses: a) many important deposits differ sufficiently from the type example to require constant definition of new types; b) the use of this approach also tends to obscure common processes that may link more than one deposit type; and, c) objective classification of deposits, particularly those that have attributes of more than one typical example, is difficult in highly deformed and metamorphosed terranes. The scheme is nonetheless satisfactory for the broad recognition of groups of deposits having like characteristics.

The summaries of Canadian lode gold deposits in this volume are organized less on the basis of a unified classification scheme than on broad groupings of deposits that illustrate common geological problems. The treatment

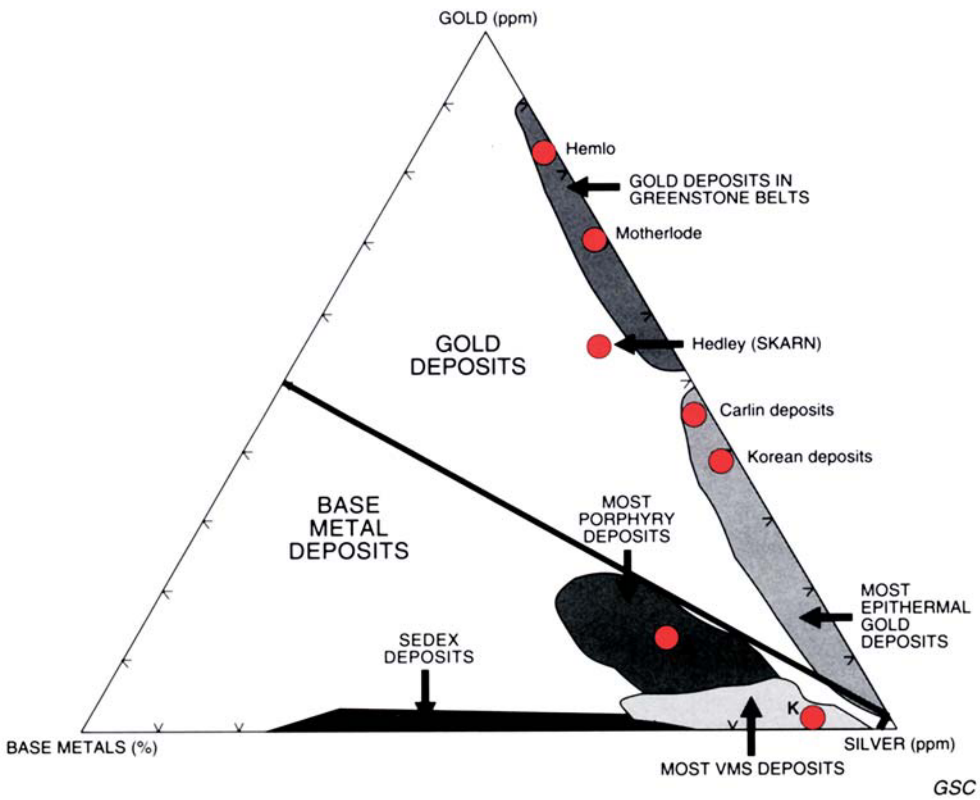

Figure 15-3. Ternary representation of the relative abundance of Au (ppm), Ag (ppm), and base metals (%) in a variety of ore deposit types world-wide: specific examples of individual gold-bearing deposits are shown for comparison. Note that the boundaries of the field defining "gold deposits" in an economic sense are elastic (a function of prevailing metal prices) but the plotted positions for specific deposits are fixed only by their bulk composition. "B" identifies the Bingham Canyon, U.S.A. porphyry deposit and "K" the Kidd Creek, Ontario massive sulphide deposit. "Gold deposits in greenstone belts" refers to deposits discussed below as subtypes 15.2, 15.3, and 15.4.

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emphasizes the geological setting and the nature of the ore constituting the deposits; where possible, widely used and accepted nomenclature has been retained. Clearly, the gold deposits, as defined in economic terms, are of diverse geological types. Some are treated in separate sections of this volume, together with their related deposit types: examples include placers (see subtype 1.2), paleoplacers (see subtype 1.1), volcanic-associated massive sulphide gold deposits (see subtype 6.4), gold-bearing porphyry deposits (see Type 19), and skarn gold (see subtype 20.3). Others, as summarized below, are described as separate subtypes of "Lode gold" (15) deposits.

"Epithermal gold" (subtype 15.1) deposits account for approximately 5% of Canada's lode gold production and reserves. Most contain more silver than gold (Fig. 15-3). Deposits of this type occur mainly in extensional settings

Table 15-1. Common type of lode gold deposits with Canadian examples.

Type	Characteristics	Typical example	World examples	Canadian examples	References
SHALLOW ENVIRONMENTS					
a) Witwatersrand type	quartz arenite-conglomerate; paleoplacers	Witwatersrand, South Africa	Jacobina, Brazil; Tarkwa, Ghana	minor occurrences in Huronian rocks, Ont.	Minter, 1991
b) Hotspring type	gold disseminated in sinters	McLaughlin, California	Round Mountain, Nevada	Cinola, B.C.	Bonham, 1989
c) Submarine exhalative type	stratabound sulphides; shallow(?) felsic volcanic association; Cu, Pb, Zn, Ag common	Boliden, Sweden	Mount Lyell; Mount Morgan, Australia	Eskay Creek, B.C.; Montauban, Bousquet, Agnico-Eagle, Horne, Que.	Hannington and Scott, 1989
d) Alunite-kaolinite (Acid-Sulphate) type	advanced argillic alteration; vein and disseminated; high-sulphur mineral assemblages (i.e. enargite)	Goldfield, Nevada	El Indio, Chile	rare - minor development at Island Copper, B.C.	Heald et al., 1987; Berger and Henley, 1989
e) Adularia-sericite (Bonanza) type	crustiform veins; chalcedonic quartz; vertical metal zonation; calderas	Creede, Colorado	Thames, New Zealand; Hishikari, Japan	Blackdome, Lawyers, B.C.; Grew Creek, Y.T.	Heald et al., 1987; Berger and Henley, 1989
MODERATELY DEEP ENVIRIONMENTS					
a) Porphyry type	mainly intrusion-hosted; stockwork and disseminated; K-silicate alteration, Cu-Bi association	Lepanto, Philippines	Yu Erya, China	Fish Lake, Kemess, B.C.; Young-Davidson, Ross, Ont.; Doyon, Douay, Que.	Sillitoe, 1991
b) Breccia pipe type	magmatic-hydrothermal and phreatomagmatic breccias; pipes and cylindrical sheeted fractures	Kidston, Australia	Golden Sunlight, Montana	Sunbeam Kirkland, Man.; Chadbourne, Que.	Sillitoe, 1991
c) Skarn type	Al-rich skarn assemblages adjacent to diorite-granodiorite; As, Bi, Te association	Fortitude, Nevada	Red Dome, Australia; Suan, Korea	Hedley, Tillicum, B.C.; Akasaba, Que.	Meinert, 1989
d) Manto type	i) carbonate replacement ii) noncarbonate replacement	i) Cove, Nevada ii) Porgera, Papua New Guinea	i) Foley Ridge, South Dakota; ii) Andacollo, Chile	i) Ketza River, Y.T.; Mosquito Creek, B.C. ii) Equity Silver, QR, B.C.; Brewery Creek, Y.T.; Hemlo, Ont.; Beattie, Que.; Hope Brook, Nfld.	Sillitoe, 1991
e) Carlin type	sediment-hosted disseminated micrometre-size Au; As-Sb-Hg association	Carlin, Nevada	Mercur, Utah; Guizhou, China	rare	Berger and Bagby, 1991
f) Korean type	intrusion-related, fault-controlled quartz veins and disseminated zones	Shandong Province, China	Charters Towers, Australia	Venus, Y.T.; Zeballos, B.C.	Shelton et al., 1988
DEEP ENVIRONMENTS					
a) Motherlode type	shear zone-related, volcanic-hosted ribboned quartz veins; carbonatization	Mother Lode district, California	Kalgoorlie-Norseman, Australia	Bralorne, B.C.; Giant-Con, N.W.T.; Noracme, Man.; Kerr Addison, McIntyre-Hollinger, Ont.; Sigma-Lamaque, Que.; Deer Cove, Nfld.	Knopf, 1929
b) Grass Valley type	shear zone-related, plutonic-hosted ribboned quartz veins; sericitization and carbonatization	Grass Valley district, California	Alleghaney d istrict, California	Star Lake, Contact Lake, Sask.; Renabie, Ont.; Silidor, Ferderber, Que.	Johnston, 1944
c) Bendigo type	fold and fault-controlled, turbidite-hosted quartz veins; arsenopyrite common	Victoria Goldfields, Australia	Otago, New Zealand; Ashanti, Ghana; Murantau, Uzbekistan	Camlaren, N.W.T.; Pamour, Little Long Lac, Ont.; Meguma, N.S.	Boyle, 1986
d) Homestake type	vein-related, iron-formation-hosted; sulphidic alteration; arsenopyrite common	Homestake, South Dakota	Jardine, Montana; Cuiaba, Brazil; Hill 50, Australia	Lupin, N.W.T.; Farley, Man.; Central Patricia, McLeod-Cockshutt, Ont.	Phillips et al., 1984; Caddy et al., 1991

in Mesozoic and Tertiary rocks in the Canadian Cordillera. Important examples include Mount Skukum in Yukon Territory, and the Blackdome, Cinola, and Toodoggone deposits in British Columbia (Fig. 15-1). The discussion covers those epithermal deposits that are generally regarded to be of alunite-kaolinite, adularia-sericite, and hotspring types, as well as "transitional" or "deep epithermal" veins and Carlin-type sediment-hosted gold-arsenic-antimony deposits, although the latter are not particularly important in Canada.

"Quartz-carbonate vein gold" (subtype 15.2) deposits typify metamorphic terranes of all ages and account for approximately 80% of the production from Canadian lode gold deposits. By contrast with epithermal deposits, they contain little silver relative to gold (Fig. 15-3). The Canadian Shield, and Superior Province in particular, contains the most significant producers (Fig. 15-1). Typical examples of these deposits include Goldenville, Nova Scotia; Sigma-Lamaque at Val d'Or, Quebec; Dome and Campbell Red Lake, Ontario; San Antonio at Bissett, Manitoba; Star Lake, Saskatchewan; and Bralorne-Pioneer and Cariboo-Island Mountain, British Columbia. The deposits consist of simple to complex vein systems with significant vertical extent (in some cases greater than 2 km), hosted by deformed and metamorphosed volcanic, plutonic, and clastic sedimentary rocks in compressional tectonic settings. Sulphide-rich vein deposits such as at Chibougamau, Quebec and Rossland, British Columbia overlap in some attributes with these deposits.

"Iron-formation-hosted stratabound gold" (subtype 15.3) deposits represent approximately 5% of Canada's total lode gold production and reserves. These occur only within the Canadian Shield (Fig. 15-1) and important Canadian examples include the McLeod Cockshutt-Hardrock deposit at Geraldton and Central Patricia deposit at Pickle Lake in Ontario, the Farley deposit in Manitoba, and the Lupin deposit in the Northwest Territories. All of these deposits occur in complexly folded iron-formation containing quartz veins, and ore commonly consists of disseminated to massive sulphides adjacent to veins. They are a special subtype of the quartz-carbonate veins but are treated separately because they embody aspects of two ore deposit classes, the host iron-formations and their contained gold mineralization. Due to the inherent exhalative nature of the iron formations, there is a possibility that some deposits in this category owe their gold enrichment to prevein processes.

"Disseminated and replacement gold" (subtype 15.4) deposits represent approximately 10% of Canada's historical production and reserves. Important examples include the Hope Brook deposit in Newfoundland, the Hemlo and Madsen (Red Lake) deposits in Ontario, the MacLellan deposit in Manitoba, and the Equity Silver deposit and the sulphide lodes of the Island Mountain mine in the Cariboo district of British Columbia (Fig. 15-1). The Ketza River manto deposits, as well as several intrusion-related disseminated deposits in Superior Province (e.g. Beattie and Lac Shortt in Quebec), also belong to this general category. All of these deposits comprise auriferous bodies of disseminated to massive sulphides, typically pyrite or pyrrhotite, in which ore distribution is not dictated by the presence of vein quartz and, with a few exceptions, they have low contents of base metals and a gold content exceeding that of silver (Fig. 15-3).

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Contents

15.1 EPITHERMAL GOLD DEPOSITS

15.1a Quartz-(kaolinite)-alunite deposits
15.1b Adularia-sericite deposits

Bruce E. Taylor

INTRODUCTION

Current usage of the term "epithermal (gold) deposit" encompasses a somewhat broader range of physico-chemical conditions than originally envisioned by Lindgren (1922, 1933) in his depth-temperature zoning concept of deposit classification according to environment. Although still generally accepted as "shallow" (e.g., <1500 m), the depth of formation is perhaps the most difficult characteristic of epithermal deposits to quantify. Mesothermal deposits ("transitional" deposits of Panteleyev, 1986), which may form as deep as perhaps 3000 m, and in close association with intrusions, have many characteristics in common with epithermal deposits, including aspects of their origin. Indicated temperatures of formation for epithermal deposits range from about 100°C for hot spring or steam-heated deposits to about 350-400°C for deeper vein and replacement deposits. However, it is the marked variations in temperature and pressure which best characterize the ore-forming epithermal environment. Pronounced changes in the physical, thermal, and chemical properties of the hydrothermal solutions occur over short distances, promoting ore deposition.

During the past decade, classification and terminology of epithermal deposits have evolved substantially, as has our understanding of these deposits. This is evidenced by a rapidly-growing body of literature covering geological aspects and genetic hypotheses, such as discussed and further cited in recent papers by Hayba et al. (1985), Berger and Henley (1989), White and Hedenquist (1990), Panteleyev (1991), and Sillitoe (1993); see also the accompanying list of references.

Alteration and ore mineral assemblages are used here to distinguish two principal subtypes of deposits: quartz-(kaolinite)-alunite (QAL; subtype 15.1a) and adularia-sericite (ADS; subtype 15.1b; Hayba et al., 1985; Heald et al., 1987). The descriptive mineralogical terms quartz-(kaolinite)-alunite (QAL) and adularia-sericite (ADL) are preferred here, although the former deposits have been variously termed "high-sulphur" (Bonham, 1988), "acid-sulphate" (Heald et al., 1987), "high-sulphidation" (Hedenquist, 1987), or kaolinite-alunite (Berger and Henley, 1989) deposits. Adularia-sericite-subtype deposits have also been named "low-sulphur" (Bonham, 1988), or "low-sulphidation" (Hedenquist, 1987). Differing levels of acidity and oxidation state (adularia-sericite: near-neutral, intermediate to reduced; quartz-(kaolinite)-alunite: acidic, oxidized), largely distinguish the ("end-member") hydrothermal environments of these two general deposit types. In this context, the "high/low sulphur" or "high/low sulphidation" terminology (not to be confused with high/low sulphide contents) can be misleading, as discussed later.

Taylor, B.E.
1996: Epithermal gold deposits; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 329-350 (also Geological Society of America, The Geology of North America, v. P-1).

Adularia-sericite and quartz-(kaolinite)-alunite deposits can be further subdivided. Two subenvironments of quartz-(kaolinite)-alunite alteration are recognized: magmatic-hydrothermal and steam-heated; either may be mineralized, or barren. Subdivision of adularia-sericite-subtype deposits by volcanic host rock (alkalic; subakalic, rhyolite; and subakalic, andesite-rhyolite) has recently been suggested by Sillitoe (1993; cf. Bonham, 1988; Mutschler and Mooney, 1993). The subakalic, andesite-rhyolite association includes sulphide-rich adularia-sericite-subtype deposits and some deep epithermal Canadian gold deposits described here.

Hot spring deposits, which may be associated with either acid-sulphate (quartz-(kaolinite)-alunite) alteration and/or argillic alteration (adularia-sericite-subtype), can constitute significant surface expressions of some geothermal systems, and form a subset of epithermal deposits. These deposits may or may not contain economic abundances of gold (±silver) in associated near-surface silicified zones, sinters, or phreatic breccias (e.g., Bonham, 1989). However, unless sinters can be positively identified, or evidence for near 100°C (boiling-limited) temperatures is available, it is difficult to distinguish a hot-spring setting per se from the general near-surface, steam-heated environment. Hot spring environments have been inferred for gold deposits in Canada hosted by both volcanic (e.g., Silver Pond; Toodoggone River, British Columbia; Diakow et al., 1993) and sedimentary (e.g., Cinola, British Columbia; Tolbert and Froc, 1988; Christie, 1989) rocks; sinters have not been identified, however.

Gold is the principal commodity of epithermal gold (±silver) deposits, and it usually occurs as free gold and alloyed with silver, but may also occur in tellurides or be included in sulphides. Copper and the other base metals, lead and zinc, may also occur with gold, especially in deposits with high silver grades. Indeed, quartz-(kaolinite)-alunite-subtype deposits are sometimes referred to as enargite-gold deposits (Ashley, 1982). Hot spring deposits,

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Table 15.1-1. Comparative mineralogical, geological, and production data for selected epithermal Au deposits in Canada and several non-Canadian, "type" examples.

District and/or deposit	Age[1] Host [Min.]	Size[2] (R+P) Ore[5]	Au[6]	Grade[3]	Ag/Au	Base metal	%S*	Mineralogy[4] Ad	Al	Cpy	En	Ss	Ags	Sp	Gn	Ba	Fl	$CO_3^=$ Rc	Cc	Ank	Host rock	Alt'n.[7] vn → w.r.	Form[8]	Selected Refs.
QUARTZ-KAOLINITE-ALUNITE (QAL) TYPE:[9] ***Volcanic host rocks***																								
Toodoggone River, B.C.	189-198;182																							
Al (Bonanza; Thesis)	[196]	0.348	3.210	9.6					X	X		X	X	X	X	X					and./dacite	Si/A	vn,	10,11,30,31,35
BV	[190-197]	0.053	0.55	10.4		x										X					andesite		vn, bx	30
Summitville, Colorado	20.2-22.0 [22.3]	83.51	3.5		1.2	X	5?		XX	XX	X	XX	X	X	X	X					qtz. latite	Vgy-Si/Qtz-Al/A	repl.,vn	28,32
Nansatsu, Japan	3.4-7.6 [2.7-5.5]		>18	3-6	0.1-1.0	x	≤10		X		X	x	X	X	X	x			X		andesite	Vgy-Si/Al-A/Ph/P	repl.	33
El Indio, Chile[10]	13.7 [8.6]	8.7	108	1.7-218	0.5-10	XX	≤30[11]		X	[X]	[XX]	X	x	[x]	[x]	X					rhyodacite	Si/Ph-A (Al-A)	vn,bx	36,37
ADULARIA-SERICITE (ADS) TYPE: ***Volcanic and plutonic host rocks***																								
Mt. Skukum, Y.T.	53.2 [50.7]	0.200	2.49	25.0	0.9		<1	X	x							x	X	x	XX	x	andesite	Si/±K/Ph/A/P	vn,bx,st	7,8,9
Mt. Nansen, Y.T.	Tertiary	0.288	3.15	11.1	39.0					X				X	X									14
Laforma, Y.T.	>140 [78?]	0.191	2.13	11.2		X				X		x		X	x	X			X	X	granodiorite	Ph	vn	34
Venus, Y.T.	L. Jur.	>0.07	>0.66	9.3	26.5	XX	15-60						x		X	X					and./dacite	Si/A	vn	5,6,16
Toodoggone River, B.C.	189-198;182																							
Lawyers	[180]	0.880	6.73	7.4	46.7	X		X	X	X		X	X	X	X	X					andesite	Si/A/P	st,bx	1,2,3,24,31,35
Baker (Chapelle)		0.055	1.05	19.5	9.1		3-15			X		X	X	X	X				X		and./basalt	Si/Ph/A/P	vn	13
Blackdome, B.C.	Eocene [>24,<51.5]	0.368	7.35	20.6	3.1	x	≤5	X		X			x	x	x				X		and./dacite	Si/K/A/P	vn,bx	4,23,26,35
Stewart-Iskut region, B.C.	210																		X					
Silbak-Premier	[194.8?]	9.622	66.24	7.0	22.6	XX	≤5[12]	X[13]		X		X	X	X	X	X		X	X	X	and./dacite	Si/K/Ph/P	vn,st,bx	21
Sulphurets (Snowfield)	[192.7]	25	0.78	2.4	0.6	X				X		X		X	X	X	X		X		bslt.-and./ andesite	K/Ph/A/P	st,vn,diss.	41
Creede, Colorado	Teritary	1.4	21.0	1.5	400	X		X	x			x	X	X	X	X	X	X						22,28
ADULARIA-SERICITE (ADS) TYPE: ***Sedimentary and/or mixed host rocks***																								
Cinola, B.C.	Tert./Cret. [14]	23.80	58.31	2.45	2	x	≤10		x	x				x	x				X		congl./s.s./shale	Si/A	diss.,bx,vn	25,27,35
Equity Silver, B.C.[14]	57.2 [>48; 57.2]	31.42	24.41	4.2	128.2	X				X		X	X	X							dacite/tuff/congl.	A	vn,st,diss.	17,18,19
Dusty Mac, B.C.	Eocene	0.093	0.60	7.2	21.5	X	≤15			x			x	x	x		X		X		s.s./sh./and. pyroclastic	Si/A	bx,st	35,40
Carlin, Nevada	Paleozoic [Tertiary]	10	109.7	11.0		x			X[15]				x	x	x	X			X		silty lms.	Si	diss.,vn	29
Hishikari, Japan	0.51-1.78/Cret. [0.8-1.0]		121.7	70	1.27	x		XX		X		x	x	X	x				X	x	shale-s.s./ and./dacite	Si/A	vn	38,39

* Principal deposits plus several others selected to represent part of the spectrum of variation in type and setting.
1. Based on reported mineral ages; Ma., exclusive of uncertainty limits. Host= age of host rocks; [Min.] = age of mineralization. 2. P = cumulative production; R = reserves; 3. Average grade in g/t; 4. characteristic; in addition to quartz (+pyrite±sericite±clays); 5. tonnes of ore x10^6; 6. grams of gold (Au) x10^6; 7. Alteration facies, vein (vn) to wall rock (w.r.): Vgy-Si; vuggy silica; Qtz, quartz; Al, alunite (advanced argillic); Si, silicification; K, potassic; Ph, phyllic (sericitic); A, argillic/advanced argillic; P, propylitic (sequence from vein to wall rock); 8. Form of deposit (in order of importance) vn, vein; bx, breccia; st, stockwork; diss., disseminated, repl., replacement; 9. Classification is based on available data; uncertain in some cases; 10. main gold deposition probably not from alunite-kaolinite type system, *sensu stricto*, see text; 11. older, alunite-associated (Cu) veins contain 30-90% sulphide. 12. base metal-rich veins and breccias contain 20 to 45% sulphide; 13. potassium feldspar; species not confirmed;14. contains metamorphosed advanced argillic mineral assemblage; low-pH conditions approached those of magmatic-hydrothermal QAL subtype deposits, 15. in oxidized ore.

Abbreviations: %S*, per cent sulphide; Ad, adularia; Al, alunite; Cpy, chalcopyrite; En, enargite; Ss, sulphosalts (e.g., tennantite-tetrahedrite); Ags, silver sulphides; Sp, sphalerite; Gn, galena; Ba, barite; Fl, fluorite; $CO_3^=$, carbonate: Rc, rhodochrosite; Cc, calcite; Ank, ankerite; XX = abundant; X = present; x = minor to rare; blank = absent or unknown; and. = andesite; bslt. = basalt; congl. = conglomerate; s.s. = sandstone; lms. = limestone; sh. = shale; Tert. = Tertiary; Cret. = Cretaceous; L. Jur. = Lower Jurassic; *NB: [ ] = not in paragenetic association with Au.*

References: 1) Schroeter, 1986; 2) Schroeter, 1985; 3) Schroeter, 1982; 4) D. Rennie, 1986, written commun.; 5) Walton, 1986; 6) Walton and Nesbitt, 1986; 7) McDonald et al., 1986; 8) McDonald and Godwin, 1986; 9) Pride and Clark, 1985; 10) Clark and Williams-Jones, 1986; 11) Schroeter, 1986; 12) Andrew et al., 1986; 13) Barr et al., 1986; 14) Morin and Downing, 1984; 15) Duke and Godwin, 1986; 16) McFall, 1981; 17) Shen and Sinclair, 1982; 18) Cyr et al., 1984; 19) Wojdak and Sinclair, 1984; 20) Love, 1989; 21) McDonald, 1990; 22) Mosier et al., 1985; 23) Faulkner, 1986; 24) Vulimiri et al., 1986; 25) Champigny and Sinclair, 1982; 26) Vivian et al., 1987; 27) Christie, 1989; 28) Heald et al., 1987; 29) Bagby and Berger, 1986; 30) Diakow et al., 1993; 31) Clark and William-Jones, 1991; 32) Stoffregen, 1987; 33) Hedenquist et al., 1994; 34) McInnes et al., 1990; 35) Anon., 1992, B.C. Geol. Survey (MINFILE/pc), 1992; 36) Jannas et al., 1990; 37) Siddeley and Araneda, 1986; 38) Izawa et al., 1990; 39) Bakken and Einaudi, 1986; 40) Church, 1973; 41) Margolis, 1993.

some other epithermal deposits, and the well-known Carlin-type deposits, exhibit a characteristic association of Hg, As, Sb, and Tl with gold.

The best examples in Canada of low-sulphide, volcanic-hosted adularia-sericite epithermal gold deposits include the Blackdome deposit and deposits in the Toodoggone River camp in British Columbia, and the Mt. Skukum deposit in Yukon Territory (Table 15.1-1). The largest adularia-sericite epithermal deposit (Silbak-Premier) is sulphide-rich, but has a low-sulphide precious metal stage (McDonald, 1990). Quartz-(kaolinite)-alunite deposits are not prominent in Canada. The Al deposit (Toodoggone River camp: Diakow et al., 1993) is the single example chosen (Table 15.1-1). A quartz-alunite bearing alteration mineral assemblage also occurs in a small area at Mt. Skukum (McDonald, 1987), and advanced argillic mineral assemblages (or metamorphic equivalents) are found in several other deposits (e.g., Snowfield: Margolis, 1993; Equity Silver: Cyr et al., 1984; Chetwynd: McKenzie, 1986), but the quartz-muscovite-pyrite±chlorite (adularia-sericite) alteration mineral assemblage is typical of the majority of deposits in Canada.

Cinola is the principal (clastic) sediment-hosted adularia-sericite epithermal gold deposit in Canada. According to Champigny and Sinclair (1982), it shares some features with Carlin-type deposits in the western United States, including close association with felsic dykes, fine grained gold in silicified rocks, Tertiary age, and high Hg contents. The deposits differ in that mudstone was silicified and replaced at Cinola, whereas decarbonated, silicified impure carbonate rocks are the host to ore at the Carlin mine (Bakken and Einaudi, 1986; Christie, 1989). The depth of formation of these deposits is controversial and not well established, however. Tolbert and Froc (1988) and Christie (1989) interpreted Cinola to be a hot spring deposit based on classic "epithermal" characteristics, such as chalcedonic silica and hydrothermal breccias, whereas Shen et al. (1982) suggested a depth of formation of 1.8 km based on fluid inclusion data. Isotopic data (discussed below) require deep circulation of meteoric waters. The commonly accepted shallow emplacement level of the Carlin-type deposits has been questioned on the basis of geological arguments (Bakken and Einaudi, 1986; Sillitoe and Bonham, 1990) and isotopic data (e.g., Taylor, 1987; Holland et al., 1988).

IMPORTANCE

Epithermal gold deposits represent a minor proportion of the gold reserves and production in Canada, where meso- and hypothermal gold deposits are the principal producers. For example, the average annual production from epithermal gold deposits in Canada during 1985-1987 was 2725 kg/a, or about 2.7% of the total annual gold produced. In British Columbia and Yukon Territory, epithermal gold deposits contributed relatively more (24%) of the total gold produced than elsewhere in Canada.

SIZE AND GRADE OF DEPOSITS

The sizes of principal Canadian epithermal gold vein deposits and selected "type" deposits elsewhere, are given in Table 15.1-1 in millions of tonnes (Mt) of ore (geological reserves plus past production) and kilograms (kg) of gold. The size estimates, which range from about 0.05 to 42 Mt of ore, give an order of magnitude basis for comparison as they depend on cut-off grades and economics. Grades and tonnages of these Canadian deposits are compared to other selected gold vein deposits and to gold-producing deposits of other types in Figure 15.1-1. The grades (grams/tonne; g/t) of Canadian epithermal gold vein deposits (most about 2.5-25 g/t), and of several deep epithermal or mesothermal vein deposits, are similar to those of most hypothermal quartz-carbonate gold vein deposits, but the epithermal deposits tend to be smaller in size. Epithermal vein deposits are distinguished from hypothermal quartz-carbonate vein deposits by higher silver:gold ratios (>1:1; see Fig. 15-3). Although variable, silver:gold ratios tend to be higher in adularia-sericite-subtype deposits than in quartz-(kaolinite)-alunite-subtype deposits (Table 15.1-1). The Canadian deposits are comparable to the smaller deposits in major epithermal terranes (e.g., western Pacific: Sillitoe, 1989; central Andes: Erickson and Cunningham, 1993).

At Cinola and in areas of the Sulphurets district of British Columbia, ore comprises disseminated gold in silicified and/or finely veined rocks; grades are typically lower, but tonnage larger, than in other vein-type epithermal deposits (Table 15.1-1). The Cinola deposit contains 58 310 kg of Au, based on a reported grade of 2.45 g/t and 23.80 Mt of ore, which compares to the median gold grade of 2.5 g/t and 5.1 Mt size of Carlin-type deposits in Nevada (Bagby et al., 1986). The Cinola deposit is potentially the second largest epithermal gold deposit in Canada (Table 15.1-1).

Variable Ag:Au ratios characterize deposits as shown in Table 15.1-1. Lower values of Ag:Au are shown in Table 15.1-1 for several quartz-(kaolinite)-alunite deposits, but this ratio varies widely on a world-wide basis (e.g., 0.5, Kasuga, Japan: Hedenquist et al., 1994; >>500, Cerro Rico de Potosi: Erickson and Cunningham, 1993). Both differing magmatic metal budgets (Sillitoe, 1993) and depth of formation (Hayba et al., 1985) have been suggested to influence this ratio. Very silver-rich quartz-(kaolinite)-alunite deposits like those found in Bolivia and Peru (e.g., Erickson and Cunningham, 1993) are not presently known in Canada. The deep epithermal (mesothermal) Equity Silver deposit (e.g., Cyr et al., 1984; Wojdak and Sinclair, 1984; Table 15.1-1) represents the closest analogue to a magmatic-hydrothermal quartz-(kaolinite)-alunite deposit in Canada (silver-rich; contact-metamorphosed); alunite has not been reported. At the Lawyers deposit, the ratio varies northward, from less than 20 to more than 80, and higher Ag:Au ratios are also found at deeper levels of the deposit (Vulimiri et al., 1986; average = 46.7).

Quartz-(kaolinite)-alunite deposits of magmatic-hydrothermal origin (see Rye et al., 1992; discussed below) are restricted to areas in close proximity to (above) a related source of magmatic heat and volatiles. Altered rocks of the Summitville, Colorado deposit outcrop over an area of 1.5 by 1.0 km, and produced about 3500 kg of gold (Heald et al., 1987). Shallow, steam-heated environments may produce wide-spread altered areas, typically (but not always) barren; bulk-tonnage mining of these zones may be possible if they are mineralized. For example, mineralized areas altered to quartz+clay+alunite(+barite+dickite) at the Al deposit, Toodoggone River area, measure about 250 m by as much as 1.5 km (Diakow et al., 1993). Fault-controlled, quartz-(kaolinite)-alunite alteration zones occur topographically above the Mt. Skukum deposit, in an area measuring roughly 200 by 250 m (McDonald, 1987).

Adularia-sericite-subtype deposits in some cases cover large areas, even though alteration mineral assemblages are restricted to generally narrow zones enclosing veins and breccias. At the Blackdome mine, British Columbia, quartz veins as much as 0.7 m thick and 2200 m long, within an area of about 2 by 5 km, are estimated to contain 8860 kg of gold. Veins comprising the Lawyers deposit and the Baker mine in the Toodoggone district, British Columbia, are commonly 2-7 m wide and as much as several hundred metres in length. The Silbak-Premier deposit in British Columbia has yielded thus far about 56 440 kg of Au from veins and breccia zones as wide as 40 m and as long as 1200 m (Main Zone; McDonald, 1990). Elsewhere, mineralized veins have been mined for a strike length of more than 5 km at Creede, Colorado (Heald et al., 1987), and occur for a distance of about 2 km at the Hishikari mine, Japan (Izawa et al., 1990). Alteration zones around the veins at Hishikari have been mapped in an area measuring as much as 2 km wide by more than 3 km long (Izawa et al., 1990).

GEOLOGICAL FEATURES

Epithermal gold deposits are in many cases fault controlled, and occur in igneous (generally volcanic), sedimentary, or, less commonly, metamorphic rocks. They may be of similar age to their host rocks where these are volcanic, or much younger. A magmatic heat source is commonly associated. The deposits comprise veins and/or related

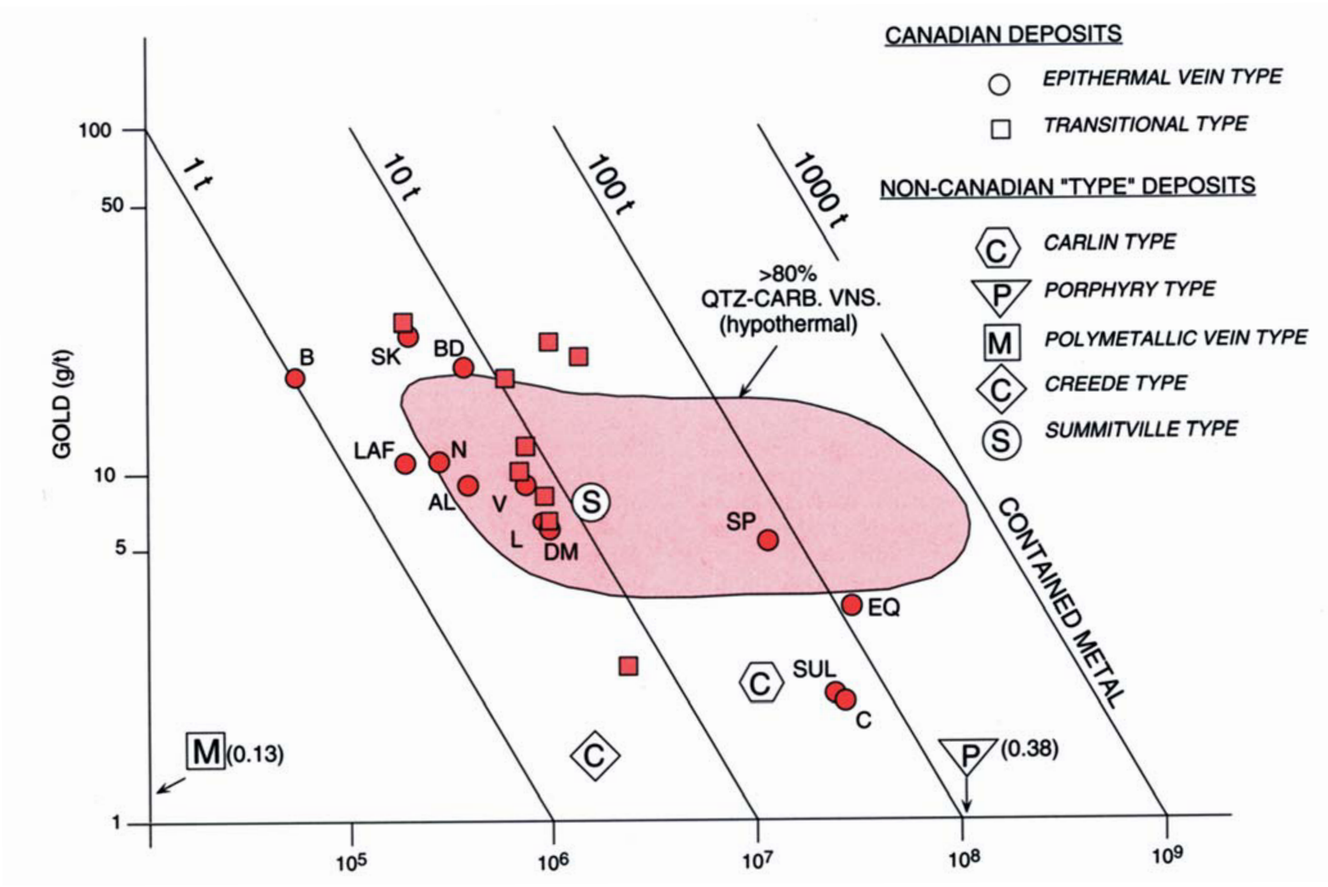

Figure 15.1-1. Plot of gold grade versus total tonnes (reserves + production) for Canadian deposits in Tables 15.1-1 and 15.1-2 (solid circles); SK, Mt. Skukum; B, Baker; BD, Blackdome; LAF, Laforma; N, Mt. Nansen; AL, Al; V, Venus; L, Lawyers; DM, Dusty Mac; SP, Silbak Premier; EQ, Equity Silver; SUL, Sulphurets; and C, Cinola. Also plotted (small squares) are hydrothermal vein deposits of a possible "transitional" or deep epithermal nature, and median grades and tonnages for several comparable "types" of deposits (open symbols; see Cox and Singer, 1986); M, polymetallic veins associated with felsic intrusions; C (diamond), Creede-type; C (octagon), Carlin-type; P, porphyry Cu-Au; S, Summitville-, or quartz-(kaolinite)-alunite-subtype; position of L (Lawyers) corresponds closely with that of Cox and Singer's (1986) Comstock-type (no symbol). Qtz-Carb. Vns. = quartz-carbonate vein gold deposits (subtype 15.2, this volume).

Table 15.1-2. Summary of geological setting, definitive characterisitics[1] and several examples of typical Au-bearing epithermal systems.

	QUARTZ-KAOLINITE-ALUNITE subtype Hosted in volcanic rocks	ADULARIA-SERICITE subtype Hosted in volcanic and plutonic rocks	 Hosted in sedimentary and mixed host rocks
Geological setting	volcanic terrane, often in caldera-filling volcaniclastic rocks; hot spring deposits and acid lakes may be associated.	Spatially related to intrusive centre; veins in major faults, locally ring fracture type faults; hot springs may be present.	In calcareous to clastic sedimentary rocks; may be intruded at depth by magma; can form at variety of depths.
Ore mineralogy	native gold, electrum, tellurides; *magmatic-hydrothermal*: py (+bn), en, tennantite, cv, sp, gn; Cu typically > Zn, Pb; Au-stage may be distinct, base metal poor; *steam-heated*: base-metal poor; gangue: quartz ("vuggy" silica), barite	electrum (lower Au/Ag with depth), gold; sulphides include: py, sp, gn, cpy, ss); gangue: quartz, adularia, sericite, calcite, chlorite; variable base metal content, high sulphide veins closer to intrusions.	gold (micrometre): within or on sulphides (e.g., pyrite unoxidized ore), native (in oxidized ore), electrum, Hg-Sb-As sulphides, pyrite, minor base metals; gangue: quartz, calcite.
Alteration mineralogy	advanced argillic + alunite, kaolinite, pyrophyllite (deeper); ± sericite (illite); adularia, carbonate absent; chlorite and Mn-minerals rare; no selenides; barite with Au; *steam-heated*: vertical zoning.	sericitic replaces argillic facies (adularia ± sericite ± kaolinite); Fe-chlorite, Mn-minerals, selenides present; carbonate (calcite and/or rhodochrosite) may be abundant, lamellar if boiling occurred; quartz-kaolinite-alunite-subtype minerals possible in steam-heated zone.	silicification, decalcification, sericitization, sulphidation; alteration zones may be controlled by stratigraphic permeability rather than by faults and fractures; quartz (may be chalcedonic)-sericite (illite)-montmorillonite.
Host rocks	silicic to intermediate (andesite)	intermediate to silicic intrusive/extrusive rocks.	felsic intrusions; most sedimentary rocks except massive carbonates (hosts to mantos and skarns).
$^{18}O/^{16}O$ - shift in wall rocks	may be less pronounced, or superposed on earlier high-^{18}O alteration.	moderate to large; pronounced in and immediately adjacent to veins.	very limited ^{18}O-shift of altered rocks, if present at all.
C-H-S isotopes	magmatic fluids indicated ($\delta^{13}C_{CO2} \cong -5\pm2$; $\delta D_{H2O} \cong -35\pm10$; $\delta^{18}O_{H2O} \cong +7\pm2$; $\delta^{34}S_{\Sigma S} \cong 0$); *magmatic-hydrothermal* alunite: $\delta^{34}S$ > sulphide minerals; $\delta D \cong -35\pm10$; *steam-heated* alunite: $\delta^{34}S \cong$ sulphides, $\delta^{18}O$ data indicate hydrothermal origin.	magmatic water (H_2O) may be obscured by mixing; surface waters dominate; C, S typically indicate a magmatic source, but mixtures with wall rock derived C, S possible	hydrogen isotope data (sericite, clays, fluid inclusions) in some cases indicate presence of evolved surface waters; organic carbon ($\delta^{13}C \cong -26\pm2$) may be derived from wall rocks.
Ore fluids (examples from-fluid inclusion studies)	160-240 °C; ≤ 1 wt.% NaCl (late fluids); possibly to 30 wt.% NaCl in early fluids; boiling common; (Nansatsu district, Japan; Hedenquist et al., 1994).	sulphide-poor: 180-310°C, ≤ 1 wt.% NaCl, about 1.0 molal CO_2 (Mt. Skukum: McDonald, 1987). sulphide-rich: ave. 250 °C, < 1 to 4 wt.% NaCl (Silbak-Premier: McDonald, 1990)	bimodal: 150-160 (most); 270-280°C, ≤ 1.5 wt.% NaCl; nonboiling: (Cinola: Shen et al., 1982); 230-250°C, ≤ 1 wt.% NaCl; nonboiling (Dusty Mac: Zhang et al., 1989)
Age of mineralization and host rocks	host rocks and mineralization of similar age.	mineralization variably younger (> 1 Ma) than host rocks.	mineralization variably younger (> 1 Ma) than host rocks.
Deposit size	small areal extent (e.g., ca. 1 km^2) and size (e.g, 2500-3500 kg Au)	may occur over large area (e.g., several tens of km^2); may be large (e.g, 100 000 kg Au).	may have large areal extent (e.g. >> 1 km^2), large size (e.g., 58 000 kg Au), low grades (e.g., 2.5 g/t).
Examples — Canadian	Mt. Skukum, Y.T. (alunite "cap") Al deposit, Toodoggone River, B.C.	Blackdome, B.C.; Mt. Skukum, Y.T. Silbak-Premier, B.C.	Cinola, B.C.
Examples — Foreign	Summitville, Colorado Kasuga, Japan	Hishikari, Japan Creede, Colorado	Carlin, Nevada
Modern analogues:	Matsukawa, Japan[2]	Broadlands, New Zealand[3]	Salton Sea geothermal field, California[4]

1) based, in part, on Heald et al., 1987; Taylor, 1987; Berger and Henley, 1989; Panteleyev, 1991; Rye et al., 1992; Sillitoe, 1993, and data reported for Canadian deposits and other examples cited in the text;
2) Nakamura et al., 1970; 3) Browne in Henley et al., 1986; 4) Williams and McKibben, 1989, but analogy not complete.
Abbreviations: py, pyrite; bn, bornite; en, enargite; sp, sphalerite; gn, galena; ss, sulphosalts; cv, covellite; cpy, chalcopyrite

mineralized breccia and wall rock (e.g., Mt. Skukum), or replacement bodies associated with zones of silicification (e.g., Cinola). Principal geological and other characteristics of each subtype of epithermal gold (±silver) deposit are listed in Table 15.1-2 (see Table 15.1-1 for data on individual examples). As may be seen from Table 15.1-2, both subtypes share many features.

The deposit subtype is distinguished primarily on the basis of associated alteration mineral assemblage, largely reflecting differences in the ore-forming fluids (i.e., oxidized, low pH: quartz-(kaolinite)-alunite; reduced, near-neutral: adularia-sericite). Alteration mineral assemblages and associated minor and trace elements are also influenced by the composition of the host rocks. Identification of the epithermal nature of a gold deposit principally entails recognition of evidence for a shallow origin; this may be based on, among other things: geological (stratigraphic) reconstruction of the depth of formation, nature and zoning of alteration and ore minerals, presence of hydrothermal breccia, form and structure of deposit, and mineralogical and textural characterisitics (noted later). Corroborative features such as high-temperature/low-pressure conditions indicated by primary fluid inclusions, or oxygen isotope depletion of wall rocks indicating high (meteoric) water:rock ratios (except in some quartz-(kaolinite)-alunite-subtype deposits with large amounts of magmatic

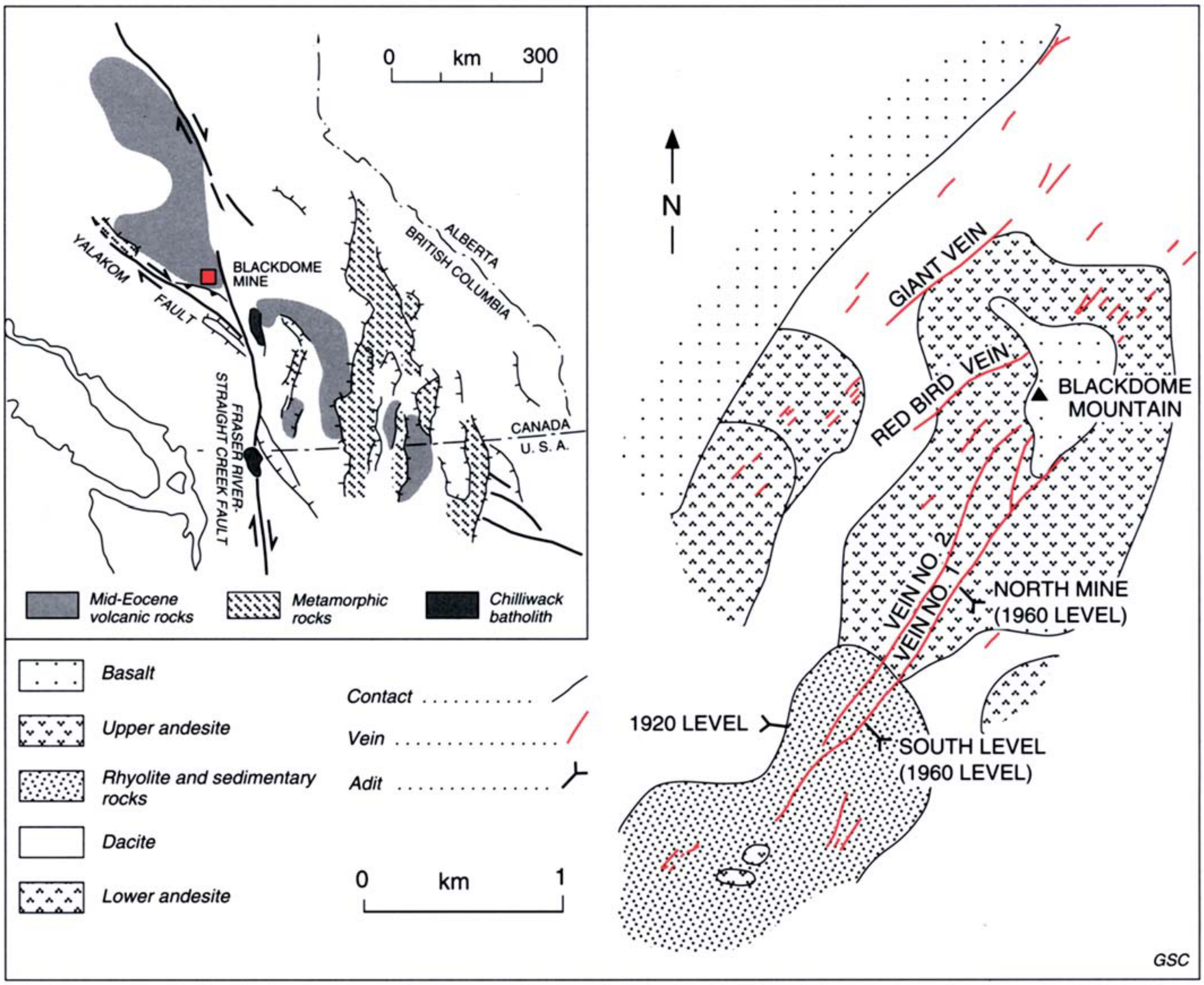

Figure 15.1-2. Geological map illustrating setting of the epithermal gold vein deposit at the Blackdome mine, British Columbia (data from: D. Rennie, unpub. rep., 1987). Inset map illustrates the regional tectonic setting of the Blackdome mine area (red square), between the Yalakom (55-45 Ma) and younger Fraser River-Straight Creek (40-35 Ma) strike-slip faults (Coleman and Parrish, 1990; R.R. Parrish, pers. comm., 1991).

volatiles) may also be helpful. Well-documented modern geothermal fields have many features in common with epithermal deposits, as discussed in following sections.

Geological setting

The tectonic settings of volcanic-associated epithermal gold deposits are numerous, and include island-arc volcanoes (e.g., Papua New Guinea; Sillitoe, 1989), continental-based arcs, and volcanic centres (e.g., Silverton caldera, Colorado). Extensional tectonism, whether on a local or regional scale, is often a common factor, as indicated by the steep normal faults which in some deposits (e.g., Blackdome, British Columbia) control the emplacement of dykes, veins, and breccia zones. The deposits of the Toodoggone River area are thought to have formed in an elongate, tectonically controlled graben in the medial portion of an island arc (Diakow et al., 1993). That this site was one of active deposition of younger rocks, rather than one of constructional volcanism and uplift, in a climate providing high erosion rates such as found today in Melanesia (e.g., Chivas et al., 1984), probably explains the preservation of these Early Jurassic epithermal deposits.

Volcanic structures, such as caldera ring fractures (e.g., Summitville, Colorado; Lipman, 1975) and radial fractures (e.g., Lake City, Colorado; Slack, 1980) may control magmatic and hydrothermal activity, and tension-producing resurgent doming may create vein-hosting extensional faults (e.g., Creede, Colorado). In British Columbia, however, regional tectonic stress fields related to Eocene strike-slip faulting appear to have been particularly important. For example, northeast-trending synvolcanic faults at Blackdome controlled the emplacement of dykes and gold-bearing quartz veins (Fig. 15.1-2). These faults have a similar orientation to normal faults found southeast of the Blackdome area and east of the Fraser River-Straight Creek fault, which are attributed to northwest extension along the Yalakom fault (e.g., Ewing, 1980; Parrish and Coleman, 1990).

The Mt. Skukum deposit, Yukon Teritory, is situated between two northwest-trending, dextral strike-slip faults, the Tintina and Denali-Shakwak. North-northeast- and northeast-trending veins are located in an eroded caldera within an andesitic stratovolcano (Pride, 1986). The mineralized veins are interpreted to have been controlled by Riedel shears, whose orientations are consistent with northeastward compression during the Eocene (Love, 1989). The more northerly trending vein orientation is consistent with extension, whereas Love (1989) suggested that the largest ore body developed in a dilational jog localized by the intersection of a strike-slip fault and a felsic dyke. Synchronous tectonic and hydrothermal activity is indicated in some deposits by the fact that many of the vein-bearing faults were active during and after vein-filling (e.g., Blackdome, Mt. Skukum, and Toodoggone deposits); tectonic vein breccias and displaced mineralized and altered rocks resulted.

Small volcanic- and volcaniclastic-hosted deposits in Canada are also found in other structural-tectonic settings. These include Dusty Mac deposit, British Columbia (e.g., Church, 1973; Zhang et al., 1989; Table 15.1-1), located in breccia and stockwork zones along reverse faults at the margin of the White Lake basin. Eocene rhyolitic dykes are associated with areas of adularia-sericite and gold-mineralized zones of silicification and argillic alteration along faults in the Tintina Trench, characterized on the surface by superimposed steam-heated or (probably) supergene quartz-(kaolinite)-alunite alteration mineral assemblages (cf. Duke and Godwin, 1986).

Sediment-hosted gold (±silver) deposits occur in a variety of settings in which sedimentary sequences have been intruded by magmas, and also in sedimentary rocks not obviously closely associated with intrusions. The deposits are located in some cases in the outer zones of hydrothermally altered rocks adjacent to intrusions (e.g., Cinola; Equity Silver, British Columbia). Carlin-type deposits are typically referred to as the classic (carbonate) sediment-hosted precious metal deposits, although they have a restricted distribution. Thirty-five of 39 such deposits tabulated by Bagby and Berger (1986) occur in Nevada. These deposits occur in "belts" in Paleozoic rocks which appear to be underlain by major structural discontinuities (e.g., thrust faults; deep fault zones in the basement, or along basement margins; cf. Cunningham, 1985) that have guided the emplacement of magma and controlled the distribution of hydrothermal fluids. For example, a granitic pluton about 120 m below gold ore at the Carlin-type Gold Acres deposit is thought to have been responsible for the overlying, fault-controlled mineralization (Wrucke and Armbrustmacher, 1975).

Age

Epithermal gold deposits, especially in volcanic terranes, are commonly Tertiary in age or younger; older deposits are more likely to have been removed from the geological record through erosion. However, gold deposits and their host rocks in the Toodoggone district, British Columbia are Jurassic in age (see Table 15.1-1). A Lower Paleozoic quartz-(kaolinite)-alunite-subtype gold deposit (Gidginbung) has been described by Lindhorst and Cook (1990) from the Lachlan fold belt, New South Wales, Australia, and Early Devonian hot spring sinter deposits have been recognized in Scotland (Nicholson, 1989). Other examples of pre-Tertiary epithermal gold deposits include those of Paleozoic age in the (former) Soviet Union (Y. Sofonov, pers. comm., 1990) and Queensland, Australia (Wood et al., 1990), and the Late Proterozoic Mahd adh Dhahab deposit, Arabian Shield (Huckerby et al., 1983).

The age of quartz-(kaolinite)-alunite-subtype deposits is typically within 0.5 Ma of their volcanic host rocks, whereas adularia-sericite-subtype deposits may also occur in considerably older volcanic and/or sedimentary (or other) host rocks (see Table 15.1-1). Essentially coincident ages of host rock alteration (and probably mineralization; 50.7 Ma) and volcanic host rocks (53.2 Ma) characterize the adularia-sericite-subtype deposits at Mt. Skukum, Yukon Territory. Quartz-(kaolinite)-alunite-subtype alteration at the Al deposit, Toodoggone River area coincided with the first of two periods of volcanism, whereas the principal adularia-sericite-subtype deposits may have formed several million years later (Clark and Williams-Jones, 1991). The relationship of the barren alunite-silica-pyrophyllite-kaolinite-bearing zone ("alunite cap") to the adularia-sericite gold deposit of the Cirque vein (and others) at Mt. Skukum is unclear. Love (1989) suggested that the acid-sulphate alteration formed on a different fault than that hosting the vein; the presence of pyrophyllite suggests a deeper (higher temperature) rather than shallower setting. Steam-heated quartz-(kaolinite)-alunite alteration also occurred above adularia-sericite-subtype alteration and mineralization of the same age at Sulphurets (Margolis, 1993). The relative positions of quartz-(kaolinite)-alunite and adularia-sericite alteration is similar in the Toodoggone and Mt. Skukum occurrences, but the exact age relationships are not clear; magmatic-hydrothermal origins, though less likely, cannot be excluded.

The sediment-hosted Cinola deposit is spatially associated with altered porphyritic rhyolite, which evidently invaded the same fault that focused hydrothermal fluids. Christie (1989) suggested that the intrusion is unrelated to the genesis of the deposit. The age of mineralization has not yet been determined directly, but it is likely Miocene, based on the 14 Ma K-Ar age for the altered rhyolite (Champigny and Sinclair, 1982).

Form and structure

In volcanic terranes, epithermal gold deposits typically occur in or adjacent to steeply-dipping faults, breccia zones, and fractures, and, therefore, comprise tabular mineralized zones within which there are higher-grade "pipes" or vertical zones (e.g., Cirque vein, Mt. Skukum; Fig. 15.1-3; Table 15.1-1). Mineralized faults may have also earlier served to localize intrusions.

Active faulting has in some cases occurred during and after mineralization, resulting in brecciation of previously emplaced veins (e.g., Mt. Skukum). Permeable zones can form along irregularities in fault planes: vertically-plunging ore zones in faults with strike-slip motion, and horizontal ore zones in dip-slip faults. Topographic (i.e., paleosurface) control of boiling by hydrostatic pressure can also result in horizontal or subhorizontal mineralized zones, limiting the vertical distribution of ore. The distribution of quartz-(kaolinite)-alunite alteration in steam-heated settings (possibly in the Toodoggone River camp, British Columbia) may also reflect a topographic control of the paleowatertable.

Silicified rocks are common in epithermal deposits. For example, irregularly silicified and mineralized wall rocks occur adjacent to faults and fractures in both volcanic (e.g., Blackdome) and sedimentary (e.g., Cinola) host rocks. Silicified and decarbonated rocks comprise the principal ore host of Carlin-type gold deposits (e.g., Bagby and Berger, 1986). At the Carlin mine, the ore zone comprises irregular, partially oxidized, pod-like lenses in the footwall of the Roberts Mountain thrust (Bakken and Einaudi, 1986). The silicification of wall rocks (and the distribution of ore) can be controlled by available primary permeability caused by, for example, bedding planes or rock fabric (e.g., Cinola) in addition to differences in host rock composition. Secondary permeability can also be produced by the hydrothermal fluids themselves. Sudden release of pressure on hydrothermal fluid (e.g., by faulting) can produce

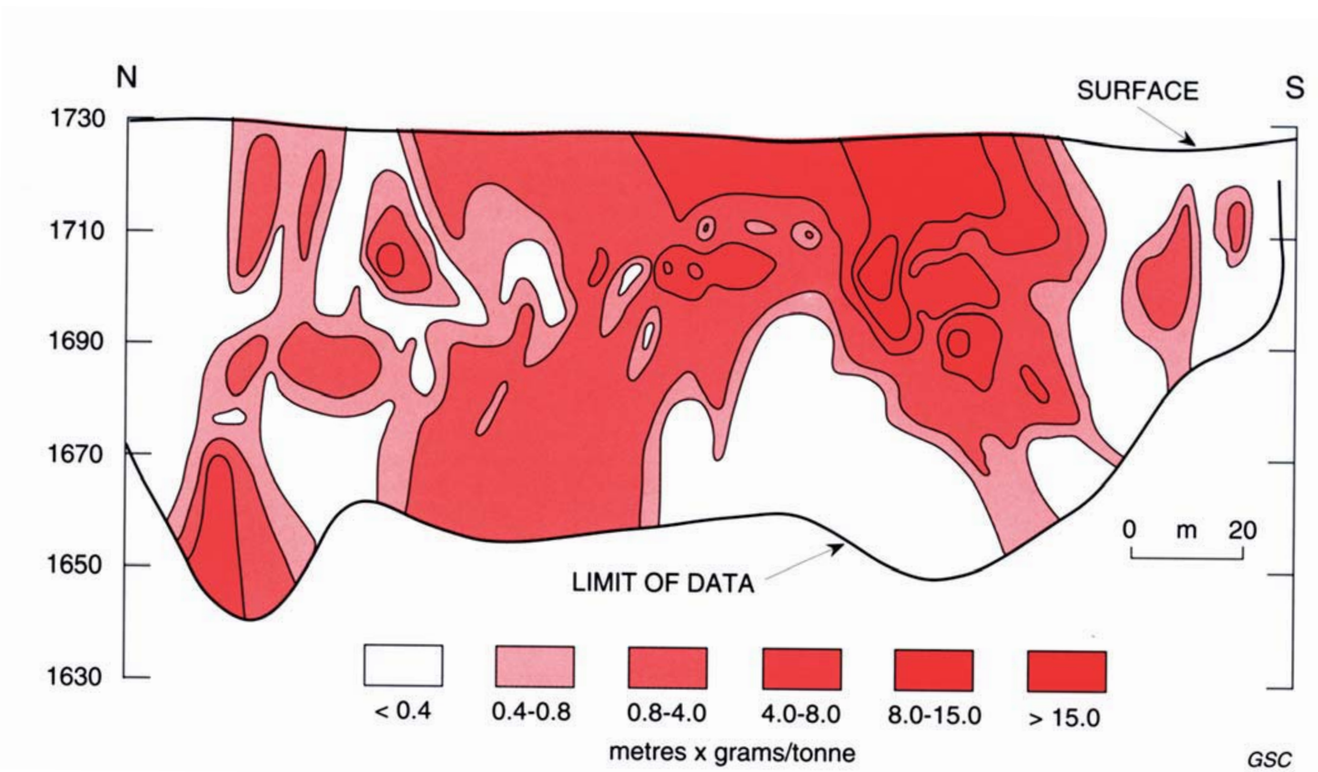

Figure 15.1-3. Longitudinal section of the Cirque vein, Mt. Skukum (modified after McDonald, 1987) illustrating distribution of gold (thickness x grade).

brecciation which forms slightly dismembered to completely milled zones in brittle rocks (e.g., Cinola, British Columbia). This can occur in geothermal systems within several hundred metres of the Earth's surface (e.g., Hedenquist and Henley, 1985). Hydrothermal fluids can also produce secondary permeability in carbonate rocks by dissolution.

Ore mineralogy, composition, texture, and zonation

Distinctive ore minerals and textures characterize each subtype of epithermal gold deposit. Mineralogical zonation around veins or zones of replacement, although different in mineralogical composition, records chemical and/or thermal gradients in both adularia-sericite- and quartz-(kaolinite)-alunite-subtypes of deposits. Both subtypes of deposits can contain very fine grained gold and gangue mineral assemblages in hot-spring and steam-heated environments.

Quartz-(kaolinite)-alunite volcanic-hosted deposits

Native gold and electrum are associated with the characteristic mineral assemblage pyrite+enargite±covellite±bornite±chalcocite. In addition to sulphosalts and base metal sulphides, tellurides and bismuthinite are present in some deposits. The total sulphide content is typically higher than in ores of many adularia-sericite-subtype deposits, although high sulphide contents may also characterize polymetallic adularia-sericite deposits (e.g., Silbak-Premier, British Columbia). Copper contents can vary enormously in quartz-(kaolinite)-alunite deposits (<0.1% to 5%: Sillitoe, 1993), but in quartz-(kaolinite)-alunite deposits in which base metals are present, copper typically predominates over zinc.

Adularia-sericite deposits

Native gold and electrum occur in typically sulphide-poor veins. Typical sulphide contents are usually a few per cent or less (e.g., Blackdome, British Columbia); pyrite is dominant. In deposits in which sulphide minerals are abundant, these sulphides commonly, in addition to pyrite, include chalcopyrite, tetrahedrite, galena, sphalerite, and arsenopyrite (e.g., Venus; Silbak-Premier: sulphide-rich stage).

Gold grains are mostly micrometre-size in Carlin-type deposits, although visible gold occurs in oxidized portions of some deposits. Gold is found in some cases coating sulphides and/or encapsulated in quartz in silicified rocks. Mercury, antimony, and arsenic sulphides accompany gold in these deposits, and are also found in deposits hosted by volcaniclastic rocks (e.g., McDermitt, Nevada). At Cinola, gold is most abundant in silicified sediments and hydrothermal breccia. Unique to deposits hosted by sedimentary rocks, or deposits which formed in hydrothermal systems encompassing sedimentary rocks, is the possibility for inclusion of sediment-derived hydrocarbons (e.g., Owen Lake, British Columbia; Thomson et al., 1992) during vein formation.

Hot spring deposits

Hot spring deposits may form as surface expressions of epithermal vein systems. These deposits (and steam-heated zones in general) are thought to have characteristically high precious metal/base metal ratios (Buchanan, 1981). Buchanan (1981) suggested that this results from deposition of gold in an upper, gas-rich, or boiling portion of the geothermal system. Base metals are deposited in deeper, more saline, liquid-dominated, portions of the system. Siliceous sinter deposits, which contain sulphate minerals, clays, and minor pyrite, typically form at the surface; broadly vertical zonation of alteration mineral assemblages is characteristic.

Gangue mineralogy and zonation

Quartz is the predominant gangue mineral in all epithermal gold deposits. Quartz-(kaolinite)-alunite deposits in the magmatic-hydrothermal environment characteristically contain quartz as a "vuggy silica" facies, formed by an increase in porosity associated with base leaching (particularly of feldspar) by very acidic fluids, and by concentration of residual silica (e.g., Summitville, Colorado; Stoffregen, 1987). This has occurred in quartz-(kaolinite)-alunite-subtype alteration zones at Mt. Skukum, Yukon Territory (alunite cap zone; Love, 1989) and at the Al deposit (Toodoggone River, British Columbia; Diakow et al., 1993). In quartz-(kaolinite)-alunite deposits, alunite is characteristic; barite (especially associated with gold), and sulphur (in some deposits) may be common. Manganese minerals and fluorite are rare.

In both adularia-sericite- and (steam-heated) quartz-(kaolinite)-alunite-subtype deposits, silica may be chalcedonic and form laminated veins (e.g., Cinola, British Columbia), occur as massive, sugary white quartz veins and breccia cements (e.g., Mt. Skukum), or form cockade or comb structures, as zones of inward-pointing crystals in laminated veins (e.g., Venus, Blackdome). Such textures are consistent with, but do not necessarily prove, a relatively shallow origin.

Gangue minerals in some adularia-sericite deposits include calcite, chlorite, adularia, barite, rhodochrosite, fluorite, and sericite. Anhydrite has been noted in minor amounts in hypogene veins at Mt. Skukum (McDonald, 1987). Lamellar or platy ("angel wing") calcite, in some cases pseudomorphically replaced by silica (e.g., Mt. Skukum, Yukon Territory), is of particular significance because it forms in boiling zones in adularia-sericite-subtype systems (e.g., Simmons and Christenson, 1994; see de Ronde and Blattner, 1988). Calcite is not characteristic of quartz-(kaolinite)-alunite-subtype deposits due to the high acidity of the hydrothermal fluids.

In sediment-hosted (adularia-sericite) deposits, especially those of Carlin type, gangue minerals constitute a characteristic assemblage and commonly include cinnabar, orpiment-realgar, and stibnite, in addition to jasperoid, quartz, dolomite, and calcite. Quartz veins (chalcedonic) and jasperoid are typically associated with ore, whereas calcite veins are in many cases more common further from ore, or paragenetically late.

Alteration mineralogy and zoning

Hydrothermal alteration mineral assemblages associated with both quartz-(kaolinite)-alunite- and adularia-sericite-subtype deposits are commonly regularly zoned about vein- or breccia-filled fluid conduits. In near-surface environments, or where permeable rocks have been replaced, zoning is in many cases less well defined. Characteristic alteration mineral assemblages in both deposit subtypes can give way to propylitically altered rocks containing quartz+chlorite+albite+carbonate±sericite±epidote±pyrite. The distribution and formation of the propylitic assemblage generally bear no obvious direct relationship to ore-related alteration mineral assemblages; propylitic alteration typically predates mineralization.

Quartz-(kaolinite)-alunite deposits are characterized by advanced argillic alteration mineral assemblages that include: quartz+kaolinite+alunite+dickite+pyrite in and adjacent to veins or zones of replacement in the magmatic-hydrothermal environment. Pyrophyllite is found in place of kaolinite in deeper (higher temperature and pressure) deposits. Argillic (smectite)±sericite mineral assemblages may occur in some outer zones (e.g., alunite "cap"; Mt. Skukum). Minerals such as topaz and tourmaline in high temperature zones indicate the presence of F and B in the hydrothermal fluids. The alteration minerals indicate a very low pH hydrothermal environment (occasionally below even that for alunite stability: Stoffregen, 1987), and one of high oxidation state (for hematite and sulphate stability). Consequently, carbonates are absent. Zones of silica replacement and "vuggy silica" are characteristic.

Acid-sulphate (quartz-(kaolinite)-alunite) alteration can also form by reaction of host rocks with steam-heated meteoric waters acidified by oxidation of H_2S (probably of magmatic origin: e.g., Rye et al., 1992), or by dissolution of CO_2. The distinction of the steam-heated environments, so-called because they are localized above deeper, boiling hydrothermal systems (Henley and Ellis, 1983), from shallow magmatic hydrothermal environments is less straightforward. Steam-heated quartz-(kaolinite)-alunite alteration zones may occur as "blankets" above adularia-sericite deposits, truncating older adularia-sericite alteration zones (e.g., Sulphurets, British Columbia; Margolis, 1993), and also at the top of quartz-(kaolinite)-alunite systems; such occurrences may or may not overlie mineral deposits (Henley, 1985). Alunite occurs in the steam-heated environment, and stable isotope studies (discussed below) may be required to distinguish between alunite of supergene, steam-heated, or magmatic-hydrothermal hypogene origin.

Supergene alteration of sulphide-bearing deposits can also produce quartz-(kaolinite)-alunite alteration minerals. Alunite of fine grained, poorly crystallized nature, evidence of sulphide oxidation, and presence of halloysite,

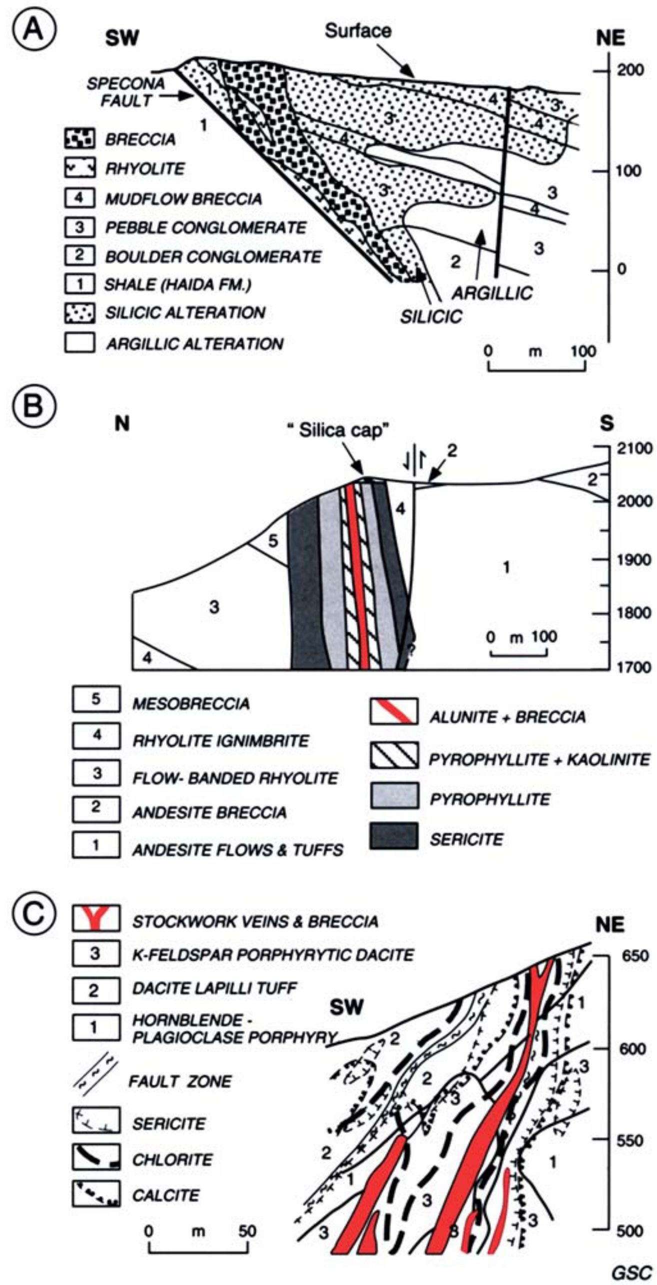

Figure 15.1-4. A) Geological cross-section through the Cinola sedimentary-hosted gold deposit (after Christie, 1989; adularia-sericite-subtype) illustrates localization of both magma (interpreted from faulted dyke) and hydrothermal fluids by the Specona fault, and the control exerted by primary lithological permeability on the distribution of zones of silicification and argillic alteration. **B)** Geological cross-section through a portion of the Mt. Skukum area (after Love, 1989; adularia-sericite-subtype, volcanic host) illustrating the distribution of alunite+silica, and advanced argillic alteration mineral assemblages near a principal normal fault. Supergene alteration has been superposed on quartz-(kaolinite)-alunite alteration zones. **C)** Geological cross-section through a portion of the Silbak-Premier deposit (after McDonald, 1990) illustrating the distribution of hydrothermal alteration minerals indicative of propylitic, sericitic, and potassic alteration assemblages in relation to a fault-controlled vein stockwork and breccia, and to porphyritic dacite.

iron oxides, jarosite, possible supergene enrichment, and subhorizontal mineral zonation are some of the features that characterize supergene quartz-(kaolinite)-alunite deposits. Additional, definitive evidence comes from the stable isotope composition of alunite (Rye et al., 1992).

Altered rocks in adularia-sericite deposits generally comprise two mineralogical zones: (1) an inner zone of silicification (characterized by replacement of wall rocks by quartz or chalcedonic silica); and (2) an outer zone of potassic-sericitic (phyllic) alteration (characterized by quartz+K-feldspar and/or sericite, or sericite and illite-smectite). Adularia is the typical K-feldspar in these deposits, but its prominence varies greatly; it may be absent altogether. Chlorite and carbonate are present in many deposits, especially in wall rocks of intermediate composition, and in some cases (e.g., Shasta deposit, Toodoggone River: Thiersch and Williams-Jones, 1990; Silbak-Premier: McDonald, 1990) chloritic alteration accompanies the potassic alteration and silicification. Argillic alteration (forming kaolinite and smectite clay minerals) occurs still farther from the vein. In some deposits (e.g., Cinola; Christie, 1989), argillic alteration predates silicification, giving evidence of the waxing and waning of hydrothermal systems. More commonly, argillic mineral assemblages are superposed on the above, or form higher level alteration zones (e.g., Toodoggone River area; Diakow et al., 1993), in which adularia is replaced by kaolinite. Kaolinite may occur closer to veins than smectite.

Bagby and Berger (1986) distinguished two types of sediment-hosted deposits based on the nature of silicification: jasperoidal- and Carlin-type deposits. Jasperoidal deposits occur in clastic sedimentary rocks, whereas those of Carlin type occur in carbonate or calcareous host rocks. These types of silicification are gradational and differ primarily in the manner in which silica occurs: quartz veins are common, and accompany replacement silicification in the jasperoidal type (e.g., Cinola, British Columbia), whereas replacement silicification is relatively more common in Carlin-type deposits. The effects of alteration are otherwise similar in the two deposit types, and include decarbonation and argillization. Alteration minerals include quartz, calcite, illite, cinnabar, orpiment, realgar, stibnite, pyrite, pyrrhotite, marcasite, and arsenopyrite. Subsequent weathering has markedly changed the appearance and mineralogy of much of the carbonaceous Carlin-type ore through bleaching and oxidation. Supergene minerals include calcite, iron oxides, sulphates, and supergene alunite (e.g., Arehart et al., 1992), as well as clay minerals.

The zonation of alteration minerals and their relationship to lithology are illustrated for portions of three Canadian deposits in Figures 15.1-4A-C. The examples chosen represent a sediment-hosted, adularia-sericite-subtype (Cinola, British Columbia), a sulphide-rich, volcanic-hosted adularia-sericite subtype (Silbak-Premier, British Columbia), and rhyolite/andesite-hosted quartz-(kaolinite)-alunite alteration of wall rocks topographically above the adularia-sericite subtype (Mt. Skukum deposit, Yukon Territory). In each case, the zones of alteration minerals are structurally controlled, and crosscut the host rocks. Zoning is broadly symmetrical about some veins (e.g., Mt. Skukum), but markedly asymmetrical in other cases (e.g., Cinola).

Stable isotopes and fluid inclusions

In addition to determining the source(s) of H, C, O, and S in ores and altered rocks (Table 15.1-2), stable isotope and fluid inclusion data may be utilized to map paleogeothermal systems and, in part, deduce their time-space hydrological evolution. Oxygen and hydrogen isotope and fluid inclusion investigations thus far indicate that gold-precipitating hydrothermal fluids in epithermal deposits comprised mixtures of low-salinity, meteoric waters and more saline waters. In some cases (magmatic-hydrothermal quartz-(kaolinite)-alunite deposits), the saline waters are magmatic fluids, in others (adularia-sericite deposits) these are largely evolved (reacted, boiled) surface waters with some magmatic components.

Hydrothermal alteration involving meteoric (or marine) waters results in a lowering of the $^{18}O/^{16}O$ ratios of the wall rocks and a concomitant increase of the $^{18}O/^{16}O$ ratio of the hydrothermal fluid (Fig. 15.1-4B). The extent of ^{18}O depletion of the host rocks in geothermal systems depends principally on the amount and isotopic composition of the recharged geothermal fluid, the isotopic composition of the wall rocks, and the temperature and lifetime (i.e., amount of heat supplied) of the system. At all but extremely small water:rock ratios, the D/H ratio of the altered rock is completely determined by the hydrogen isotope composition of the hydrothermal fluid. The hydrothermal fluids responsible for alteration in specific deposits, and in groups of deposits, plotted in Figure 15.1-5 predominantly represent altered or "evolved" meteoric waters whose compositions have been shifted to the right (i.e., to higher $\delta^{18}O$) of the present day meteoric water (PDMW) line during hydrothermal alteration of the host rocks. Involvement of seawater or low-latitude meteoric water is indicated for the Sulphurets area (Margolis, 1993).

Altered sedimentary wall rocks typically are less depleted in ^{18}O, but the hydrothermal fluids more enriched in ^{18}O, than in volcanic terranes. For example, the markedly higher $^{18}O/^{16}O$ ratios of hydrothermal fluids accompanying alteration and mineralization at Cinola, in comparison to those at Mt. Skukum and Blackdome (see Fig. 15.1-5), can be attributed largely to greater relative ^{18}O enrichment of deeply circulating hydrothermal fluids by reaction with sedimentary wall rocks with high $^{18}O/^{16}O$ ratios.

Mixtures of either marine, meteoric, or magmatic waters would plot along straight lines in Figure 15.1-5, whereas reacted, or evolved (i.e., isotopically altered) meteoric waters would plot along curved lines. Detailed paragenetic and isotopic studies are required to elucidate such processes. Evidence of the mixing of distinct fluids with distinct isotopic ratios and salinities has been reported for some vein deposits of the deep epithermal or "transitional" category (e.g., Finlandia vein, Peru; Kamilli and Ohmoto, 1977). Variations of δD or $\delta^{18}O$ of the fluids are usually accompanied by variations in wt.% $NaCl_{equiv.}$, suggesting the presence of a (deeper) saline fluid, and a (shallower) dilute fluid (summarized in Taylor, 1987). In some cases (e.g., Creede, Colorado), incorporation of the dilute fluids occurred abruptly, and late in the paragenesis (e.g., Foley et al., 1989). An unusual range in δD (-151 to -54) and $\delta^{18}O$ (recalculated: -7.6 to -2.6) for vein-depositing fluids in the Laforma vein was attributed by McInnes et al. (1990) to extensive boiling; fluid inclusion data and carbon, sulphur, oxygen, and hydrogen isotope data are also consistent, however with a magmatic-meteoric water mixing scenario. Meteoric waters formed the major component of the ore-forming fluids at the Blackdome (Vivian et al., 1987), Dusty Mac (Zhang et al., 1989), and Mt. Skukum (McDonald, 1987) deposits. Data reported in Diakow et al. (1993) indicates a broadly similar scenario in adularia-sericite deposits of the Toodoggone River area. Progressive mixing of magmatic water and seawater during potassic to sericitic to advanced argillic alteration at Sulphurets, British Columbia was inferred by Margolis (1993) from isotopic data and water-rock reaction modelling.

There is isotopic evidence from alunite (Rye et al., 1992) for a major component of magmatic water in some magmatic-hydrothermal quartz-(kaolinite)-alunite deposits. On the one hand, magmatic-hydrothermal alunite is characterized by $\delta^{34}S$ greater (by perhaps 8 permil or more) than that of associated sulphides due to disproportionation of magmatic SO_2 gas during cooling and reaction with hydrothermal water below about 400°C, according to (Holland, 1965): $4SO_2 + 4H_2O \rightarrow 3H_2SO_4 + H_2S$.

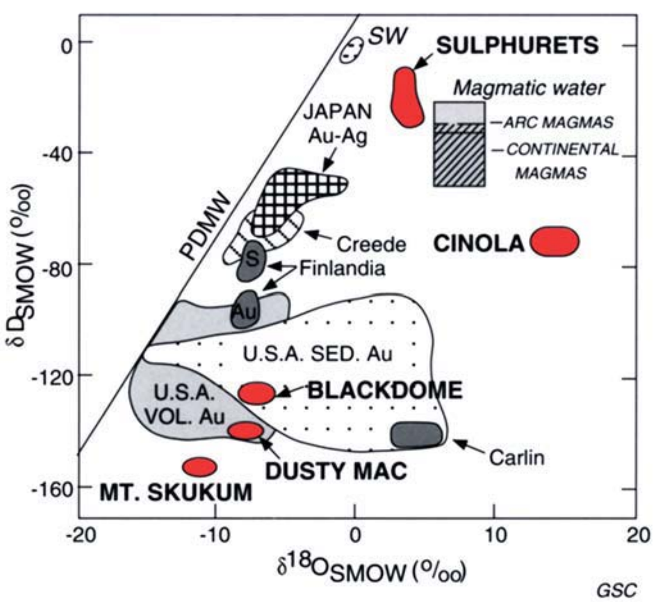

Figure 15.1-5. Plot of $\delta^{18}O$ versus δD for present day meteoric waters and for waters in equilibrium with gangue minerals in selected epithermal gold deposits; Canadian examples are shown in red. This diagram illustrates the origin and oxygen isotope enrichment of meteoric waters in many epithermal vein systems. Abbreviations are, for the Finlandia vein, Colqui district, Peru (S = sulphide stage; Au = precious metal stage); SW, sea water; PDMW, present day meteoric water; U.S.A. SED. Au= U.S.A. sedimentary rock-hosted Au; U.S.A. VOL. Au = U.S.A. Volcanic rock-hosted Au. Data for magmatic water are from Taylor (1987,1992). Sources of data for non-Canadian deposits: Taylor (1987); for Blackdome: Vivian et al. (1987); Dusty Mac: Zhang et al. (1989); Mt. Skukum: McDonald (1987) and B. Taylor (unpub. data,1991); and Cinola: B. Taylor and A. Christie (unpub. data,1991).

On the other hand, alunites of steam-heated and supergene origin have $\delta^{34}S$ values similar to those of accompanying sulphides, although oxygen isotope data indicate the hydrothermal deposition of the former (Rye et al., 1992).

Recognition of the source of sulphur depends on being able to establish the relative mass balance for the contributing sources. Host rock sulphur may comprise a significant component in some adularia-sericite deposits, whereas in other deposits, particularly quartz-(kaolinite)-alunite deposits, magmatic sulphur (as SO_2; $\delta^{34}S$ about 0-4 for felsic magmas; Taylor, 1987) dominates.

Carbon isotope data for calcite or CO_2 from fluid inclusions typically reveals its magmatic (ultimately mantle) origin, even in systems dominated by meteoric water (e.g., Laforma, Yukon Territory: McInnes et al., 1990; Mt. Skukum, Yukon Territory: McDonald, 1987). Admixture with terrestrial carbon sources may also occur (e.g., organic carbon in the Owen Lake deposit: Thomson et al., 1992).

Studies of fluid inclusions typically have shown the preponderance of fluids of low salinity (less than about 5 wt.% $NaCl_{equiv.}$) and filling temperatures of 150 to 300°C. Histograms of homogenization temperatures commonly have maxima in the neighbourhood of 260-280°C (e.g., Equity Silver; Shen and Sinclair, 1982; Blackdome, Vivian et al., 1987). This is not surprising, since a dilute vapour-dominated system at or near a boiling water table tends to evolve toward a rather uniform temperature of about 240°C due to the limitation imposed by a maximum in enthalpy of steam+liquid (e.g., White et al., 1971). Higher temperatures and salinities characterize some deep epithermal (transitional) environments close to genetically-related intrusions. Formation of fluid inclusions present at different times in a dynamic system complicates interpretation of the evolution of the system. Temporal changes within the Creede hydrothermal system, as identified by marked changes in the chemical and isotopic compositions of fluid inclusions associated with growth zones or fracture planes in crystals, demonstrates that the identity of ore-transporting fluids can be obscured by inappropriate sampling and analysis (Foley et al., 1989).

DEFINITIVE CHARACTERISTICS

Mineral assemblages, geological reconstruction demonstrating shallow emplacement, presence of sinters, fluid inclusion or textural evidence (e.g., lamellar calcite) for boiling, hydrothermal breccias and eruption deposits (e.g., Izawa et al., 1993), open-space crustiform veins, and marked ^{18}O-depletion of wall rocks comprise independent, definitive (but not always present) characteristics of epithermal deposits. Vertical zoning of alteration minerals, Au:Ag ratios in electrum, and spatial and temporal separation of gold and abundant base metals are also characteristic. Mineralogical characteristics which distinguish quartz-(kaolinite)-alunite (proximal) from adularia-sericite (distal) subtypes of gold-bearing systems are listed in Table 15.1-2. Quartz-(kaolinite)-alunite-subtype deposits are characterized uniquely by enargite+pyrite±covellite, and by advanced argillic alteration minerals, including hypogene alunite (Heald et al., 1987).

Most known epithermal gold deposits are Tertiary in age, and, therefore, age is a semi-"definitive characteristic", especially in volcanic terranes. However, preservation of epithermal vein gold deposits in pre-Tertiary geological terranes has occurred, probably due to special circumstances which prevented their erosion. In cases in which deformation and/or metamorphic recrystallization may have destroyed the mineralogical and geological characteristics noted above, $^{18}O/^{16}O$ ratios of silicate rocks can provide a unique record of alteration by meteoric waters. For example, five gold deposits in the Carolina Slate Belt are hosted by rocks containing pyrophyllite, andalusite, topaz, and traces of diaspore. These minerals suggest metamorphism of rocks subjected to the base leaching (and silica enrichment) associated with advanced argillic alteration in epithermal systems, and oxygen-isotope depletion of these and adjacent rocks (Klein and Criss, 1988) provides evidence for alteration by paleometeoric waters.

Metamorphosed magmatic-hydrothermally altered rocks can be discerned from those altered in supergene or steam-heated environments. McKenzie (1986) suggested the auriferous and pyrite-bearing quartz-andalusite-sericite schists at the Chetwynd disseminated gold deposits, Newfoundland, were the metamorphosed equivalents of an advanced argillic assemblage. Rocks of the Hope Brook zone at Chetwynd lack evidence of ^{18}O depletion characteristic of meteoric alteration fluids (B. Taylor and P. Stewart, unpub. data, 1990), but the data are consistent with a magmatically-dominated alteration system. The geochemical association of Hg-Sb-As-Tl (e.g., Harris, 1989) and the range in the $\delta^{34}S$ values of pyrite (Cameron and Hattori, 1985) at the large Hemlo (Ontario) disseminated gold deposit in the Precambrian Shield might suggest a metamorphosed epithermal deposit. However, mineralized rocks from the Hemlo deposit are not depleted in ^{18}O (Kuhns, 1988). A deep level of emplacement from dominantly magmatic fluids is suggested for Hemlo, and is supported by sulphate-sulphide sulphur isotope fractionations (Hattori and Cameron, 1986).

GENETIC MODELS

Recent documentation of epithermal gold deposits worldwide has helped to clarify their geological settings and characteristic mineral assemblages. Stable isotope and fluid inclusion studies have contributed to our knowledge of the origins and temperatures of the hydrothermal fluids. Studies of modern geothermal systems, volcanic gases, mineral solubility experiments and phase relations, and numerical water-rock reaction simulations have especially contributed to our knowledge of the chemical and physical nature of hydrothermal fluids, and also to our understanding of the processes which lead to the transport and deposition of gold, silver, and base metals. Large deposits appear to require a sustained (magmatic) heat source, and efficient, localized processes leading to supersaturation in one or more ore minerals (e.g., cooling and degassing by boiling and fluid mixing, and/or reaction with wall rocks). The site of deposition and the formation of an epithermal deposit are also influenced by many other factors, both local and regional (e.g., structural setting, paleohydrology, and climate; White and Hedenquist, 1990).

Lindgren (1922, 1933) originally suggested that ore-forming constituents were derived from degassing magmas. This supposition appears to be essentially correct for magmatic-hydrothermal quartz-(kaolinite)-alunite deposits (Stoffregen, 1987; Rye et al., 1992). However, for many deposits (e.g., the majority of adularia-sericite subtypes) stable isotope data permit only a very small fraction (i.e., <10%) of the hydrothermal water to be of magmatic origin, despite the close association of some deposits with cooling magmatic rocks. A complex origin, involving a more distant link to magmatic degassing, is indicated.

Schematic cross-sections illustrating the principal environments of adularia-sericite and quartz-(kaolinite)-alunite epithermal vein and hot spring deposits and their related geothermal systems, as discussed above, are shown in Figure 15.1-6. The figure was drawn to emphasize features found in at least some of the Canadian deposits noted previously.

Two fundamentally different hypotheses for the source of gold in epithermal vein gold deposits are: (1) the metals are supplied by the magma that is also the heat source, or (2) the metals are leached from the rocks which host the geothermal system. Proof of the involvement of meteoric waters has encouraged proponents of the second hypothesis. Stable isotope data indicate that sulphur and carbon are of magmatic origin in certain deposits (e.g., Summitville, Colorado: Rye et al., 1992) and magmatically-heated geothermal systems (e.g., Taylor, 1987), even when the dominant source of water was meteoric. The association of precious and base metals with magmatic Cl-, C-, and S-bearing gases has been demonstrated by Symonds et al. (1987) from analyses of (very high temperature) volcanic gases. Although both magmatic and nonmagmatic wall rocks can be sources for various chemical components (e.g., major elements and some metals) in hydrothermal fluids, and these can be released during alteration of the wall rocks, the introduction of metals with C- and S-rich magmatic volatiles into adjacent or overlying meteoric geothermal systems is also potentially significant. It is perhaps too simplistic to insist upon a (direct) sole source of all metals in epithermal deposits.

The alteration mineral assemblages described earlier indicate two broadly different chemical environments of alteration and mineralization: low to very low pH, oxidized fluids (quartz-(kaolinite)-alunite alteration) and near-neutral, more reduced fluids (adularia-sericite alteration). These two environments are contrasted in Figure 15.1-7, along with selected mineral stability fields and isopleths of gold solubility (after Giggenbach, 1992).

Because of sulphide abundances and the fact that enargite (rather than tetrahedrite) may dominate sulphide minerals in these deposits (e.g., Goldfield: Ashley, 1982), terms such as "high sulphur" (Bonham, 1988) and "high sulphidation" (Hedenquist, 1987) have been proposed to convey the fact that these features imply higher activities of sulphur in the hydrothermal fluids. Such terms can be misleading, despite their increasing usage, and do not convey the essential differences of the adularia-sericite and quartz-(kaolinite)-alunite geochemical environments. It is true that, from a thermodynamic point of view, higher activities of sulphur promote enargite in place of tennantite.

However, equally high (or even higher) activities of sulphur may have prevailed in Cu- or As-poor hydrothermal fluids (liquids) in adularia-sericite systems. For example, chalcopyrite (found in deposits of both subtypes) can be stable at higher activities of sulphur than those indicated by the presence of enargite, and over broad ranges of temperature (e.g., 200-300°C) and oxidation state (e.g., Henley et al., 1984, p. 109; Heald et al., 1987, p. 20). Some authors have used the term "high sulphidation" to also imply "high oxidation states of sulphur"; the terms are not synonymous, although magmatic hydrothermal quartz-(kaolinite)-alunite environments are highly oxidized owing to chemical buffering by magmatic SO_2 (e.g., Giggenbach, 1992).

The two principal geochemical environments of epithermal mineralization and alteration are determined largely by the source and relative abundance of two different fluids, and by water-rock reaction. On the one hand, magmatic-hydrothermal environments that are dominated by acidic, magmatic fluids (epithermal environment: saline liquids with dissolved CO_2, HCl, and S-species; volcanic environment: CO_2-, HCl-, and SO_2-rich vapour) produce quartz-(kaolinite)-alunite mineral assemblages characterized by oxidized forms of iron (e.g., hematite) and sulphur (e.g., alunite) and by base leaching of wall rocks. This environment may overlie porphyry systems (Sillitoe and Bonham, 1984). On the other hand, near-neutral, more

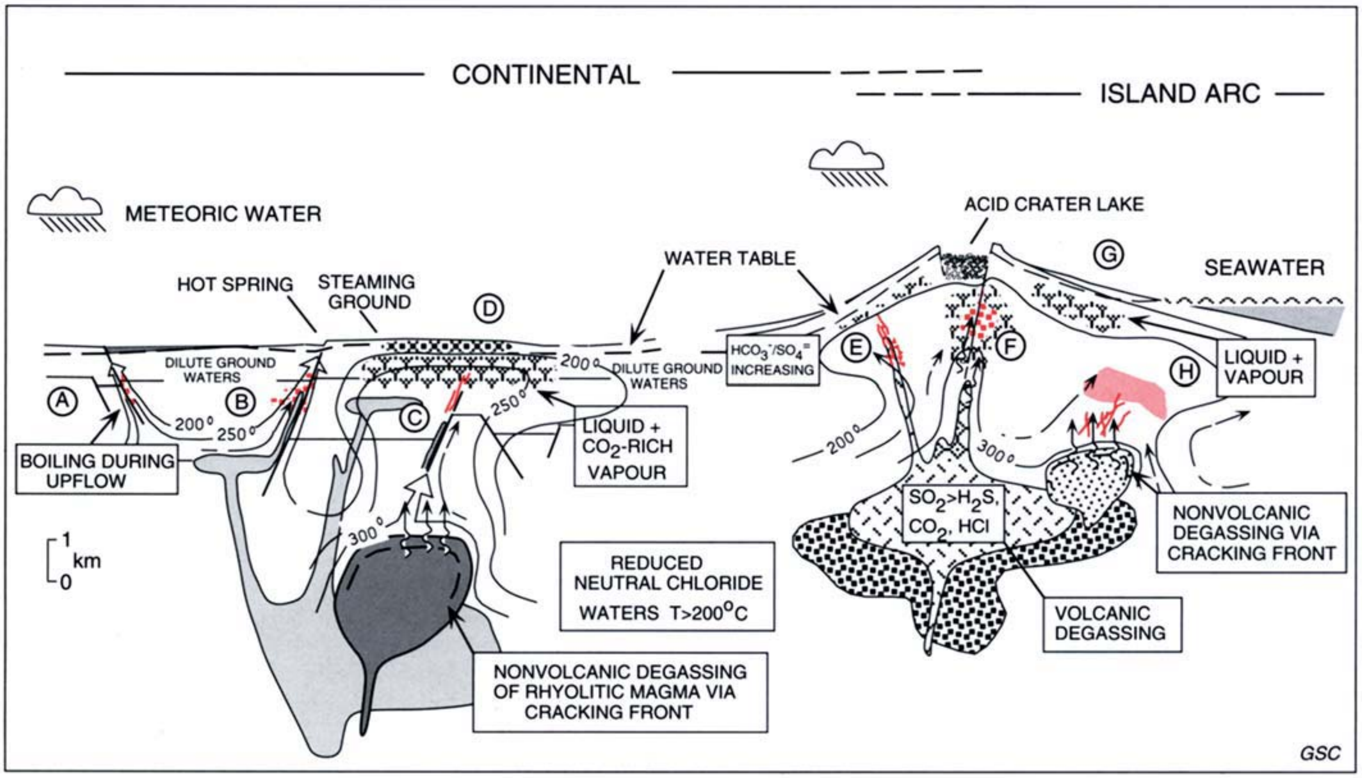

Figure 15.1-6. Schematic cross-section illustrating the general geological and hydrological settings of quartz-(kaolinite)-alunite and adularia-sericite deposits (includes concepts partially adapted from Henley and Ellis,1983; Rye et al.,1992). Characteristics shown evolve with time; all features illustrated are not implied to be synchronous. Interpreted settings are indicated for several Canadian deposits discussed in the text; see also Table 15.1-1. Local environments and examples of adularia-sericite deposits include: (A) basin margin faults: Dusty Mac; (B) disseminated ore in sedimentary rocks: Cinola; (C) veins in degassing, CO_2-rich, low sulphide content systems: Blackdome, Mt. Skukum; (E) porphyry-associated vein-stockwork, sulphide-rich and sulphide-poor stages: Silbak-Premier; and (H) disseminated replacement associated with porphyry-type and stockwork deposits, involving seawater: Sulphurets. Examples of quartz-(kaolinite)-alunite environments include: (D and G) steam-heated advanced argillic alteration (quartz-(kaolinite)-alunite) zone: Toodoggone River district; (F) magmatic-hydrothermal quartz-(kaolinite)-alunite replacement deposit: Summitville, Colorado, or Nansatsu district, Japan. Fluid flow parallels isotherms. Upflow zones shown schematically by arrowhead-shaped isotherm. Volcanic degassing refers to magmatic degassing driven by depressurization during emplacement ("first boiling"). Nonvolcanic degassing refers to vapour exsolution during crystallization ("second boiling"). The SO_2 disproportionates to H_2S and H_2SO_4 during ascent beneath environment (F). Note that free circulation occurs only in crust above about 400°C. All shown temperatures are in Celsius degrees.

reduced, meteoric-dominated waters containing Cl, H_2S, and CO_2, yield adularia-sericite mineral assemblages through hydrolysis reactions involving feldspar in the wall rocks. The chemical state of magmatic-hydrothermal quartz-(kaolinite)-alunite fluids may be said to be buffered by magmatic volatiles (especially HCl and SO_2), whereas the chemical state of adularia-sericite fluids is buffered largely by water-rock reaction (e.g., feldspar hydrolysis).

The upwardly welling, highly acidic, magmatic-hydrothermal plume may produce a quartz-(kaolinite)-alunite deposit (magmatic-hydrothermal environment). The hydrothermal-mineralization event is likely to be short-lived, limited by shallow degassing of the magma in response to depressurization during its ascent (so-called "first boiling") and by the eventual neutralization of the fluids due to reaction with wall rocks and/or dilution by meteoric fluids. In contrast, meteoric fluids, heated by cooling magmatic rocks, can provide potential fluids for mineralization and alteration over somewhat longer periods of time, and at sites further removed from the magmatic heat source. With time, the meteoric water dominated "environment" may encroach upon the earlier, hotter, hydrothermal-magmatic environment.

Slowly cooling epizonal plutons which undergo "subvolcanic" rather than "volcanic" degassing as they crystallize (i.e., "second boiling"), probably provide mineralizing constituents to overlying or adjacent meteoric hydrothermal systems via protracted leakage of magmatic volatiles across cracking fronts at the margins of the crystallizing magma. Variations on this theme derive also from differences in the sulphur content of rhyolitic (lower) to andesitic (higher) magmatic volatiles, from differences in crustal level at which magmatic degassing occurs, and from the relative proportions of magmatic and meteoric fluids involved through time. Additional discussion can be found, for example, in Henley (1985), Stoffregen (1987), White and Hedenquist (1990), Rye et al. (1992), Giggenbach (1992), and Sillitoe (1993).

Active geothermal systems provide instructive analogues to adularia-sericite-producing hydrothermal systems. Geochemical studies of dominantly volcanic-hosted geothermal systems in the Taupo Volcanic Zone, New Zealand (see Henley and Hedenquist, 1986) have demonstrated the existence of two principal types of fluids: (1) a deep chloride water, generally 200° to about 300°C, and (2) a shallower, less than 100° to 200°C steam-heated, low chlorinity, acidic water. The interface between waters with markedly different salinities has been described in the Salton Sea geothermal system by Williams and McKibben (1989). These deep chloride waters produce adularia-sericite-subtype alteration (e.g., Henley, 1985), and where they are rapidly depressurized, degassed of CO_2 and H_2S, and cooled, precious and base metals are deposited (Clark and Williams-Jones, 1990). The well scales studied by Clark and Williams-Jones (1990) revealed a vertical separation of precious metals (higher) and base metals (lower) analogous to that described by Ewers and Keays (1977) for the Broadlands geothermal field (New Zealand), and by Buchanan (1981) for a number of deposits.

Simple conductive cooling is, itself, sufficient to cause gold precipitation (see Fig. 15.1-7). Boiling also causes cooling, chemical fractionation, and an increase in pH. This leads to saturation and precipitation of chloride-complexed metals (e.g., Cu, Pb, Zn; Drummond and Ohmoto, 1985; Spycher and Reed, 1989). Also, degassing of initially CO_2-rich fluids in gas-rich systems depletes the liquid in H_2S which is carried off in a CO_2-rich vapour. The loss of H_2S eventually leads to precipitation of sulphur-complexed metals (e.g., gold; Drummond and Ohmoto, 1985; Henley, 1985; Hayashi and Ohmoto, 1991). Carbon dioxide and hydrogen sulphide are well correlated in some geothermal fluids (reviewed in Taylor, 1987). Boiling and chemical fractionation of the hydrothermal fluid provides an explanation for the separation of precious and base metals. This separation results in a vertical zonation where fluids are upwardly flowing (Clark and Williams-Jones, 1990), or in relative temporal stages, such as at Silbak-Premier and El Indio. As a corollary, larger vein deposits require the movement of larger amounts of fluid through localized zones of boiling, and thus the importance of structural analysis in exploration is obvious. Neutralization and cooling of ore fluids may also occur (1) by mixing with dilute groundwaters, and (2) by water-rock reaction (e.g., sulphidation of ferrous iron-bearing minerals), especially during formation of disseminated and replacement-type ore bodies.

The steam-heated acid waters, formed by the oxidation and condensation of H_2S (boiled off deeper geothermal reservoirs) in groundwater, produces quartz-(kaolinite)-alunite-subtype alteration of the volcanic rocks (Henley and Hedenquist, 1986). The Champagne pool, in the CO_2-rich Waitapu geothermal field (quartz-(kaolinite)-alunite), New Zealand, is a hydrothermal eruption feature below which gold and silver are being deposited in response to boiling and loss of H_2S over the approximate temperature interval 250-175°C (Hedenquist, 1986). Ore-grade, gold-bearing amorphous sulphides precipitate in the pool at 75°C, and base metal sulphides occur below the zone of boiling. Acidic waters produce advanced argillic alteration, and, with variation in P_{CO_2}, evolve to cause the replacement of adularia and albite by sericite. Thus, by chemical evolution, a geothermal field, initially boiling and producing quartz-(kaolinite)-alunite-subtype alteration, may eventually produce minerals characteristic of adularia-sericite-subtype alteration.

The precious metal content of steam-heated alteration zones may also be related to the rate of fluid ascent versus the extent of boiling and H_2S loss: faster moving fluids and/or those less depleted in H_2S may produce higher grades of precious metals in steam-heated alteration zones. This might apply to the ascension of boiling magmatic hydrothermal plumes as well as to boiling meteoric and marine geothermal fluids.

RELATED DEPOSIT TYPES

Lindgren (1933) included in his scheme of classification a qualitative assessment of the depth of formation which is, in a relative sense, largely still valid, despite the sometimes broader application today of his term "epithermal deposit". Deep epithermal (or shallow mesothermal) veins ("transitional" deposits of Panteleyev, 1986) provide an example of the extended depth of formation currently included in the broad sense of epithermal. Intrusion-related vein deposits in the Sulphurets, Mt. Washington, and Zeballos camps, all in British Columbia, are possible examples (Anon., 1992 – B.C. MINFILE; Margolis, 1993). Other hydrothermal deposits are also broadly related to epithermal vein deposits by

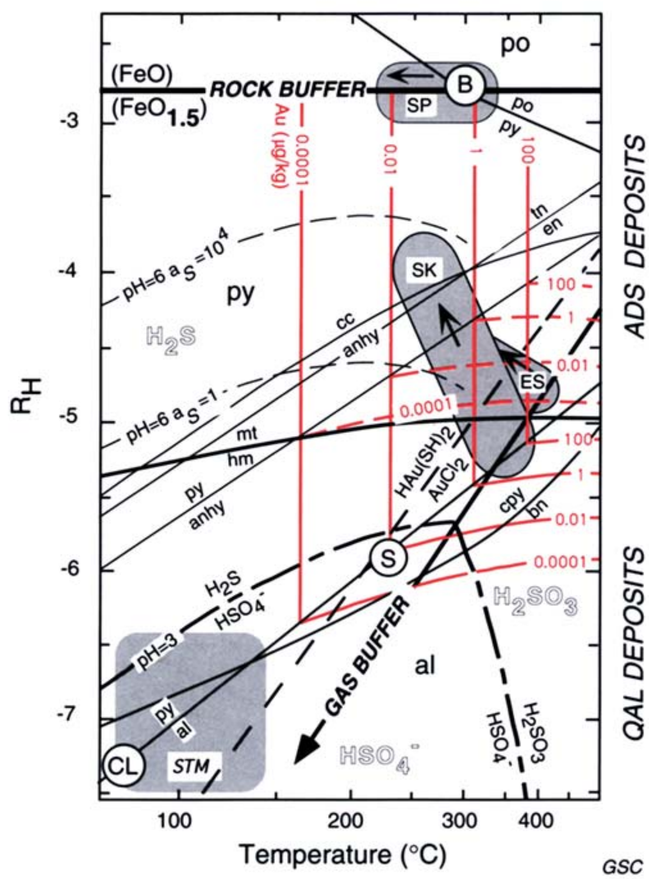

Figure 15.1-7. Diagram of redox potential ($R_H = \log f_{H_2}/f_{H_2O}$) versus temperature (modifed after Giggenbach, 1992; Hedenquist et al., 1994). Calculated isopleths of gold in µg/kg solubility (as the disolved species $HAu(SH)_2$; (Giggenbach, 1992) are shown in red. An equimolar isopleth for $HAu(SH)_2$ and $AuCl_2$ (after Hedenquist et al., 1994) is shown for pH = 3 and 1.0 wt. % Cl (or, pH = 5 and 10 wt.% Cl). The thiogold complex $HAu(SH)_2$ probably dominates as the gold-transporting agent in much of the epithermal environment at pH<5 (Giggenbach, 1992). Redox conditions for mineral deposition in the Broadlands-Ohaaki geothermal system (B), Summitville deposit (S), and in Crater lakes (CL) (e.g., Ruapehu, New Zealand) are from Giggenbach (1992). Fields showing approximate conditions of formation, and their variation with time shown by arrows, for Mt. Skukum (SK), Equity Silver (ES), and Silbak-Premier (SP; also Blackdome and others) are based on data in references cited in Table 15.1-1. Also shown are approximate conditions for steam-heated deposits (STM) of quartz-(kaolinite)-alunite subtype. The diagram shows stability limits and reactions for several minerals discussed in the text. Diagram represents a large variation in system composition, and not all mineral reactions are implied to occur in all deposits. The "gas buffer" curve represents redox control by a magmatic SO_2-H_2S gas mixture; the Fe^{+2}/Fe^{+3} couple provides redox control in "rock dominated" systems (rock buffer). Quartz-(kaolinite)-alunite deposits form under oxidizing, acidic conditions of the lower one-third of the diagram. Conditions of formation of adularia-sericite deposits are represented by the upper half of diagram, with most forming near the "rock buffer" curve. Isopleths of gold solubility (in µg/kg) are shown in red for two sets of buffered conditions, one set buffered by the coexistence of pyrite and alunite, the other by pyrite and anhydrite. Dashed isopleths apply to the pyrite-anhydrite buffered conditions. Abbreviations are: $a_S = a_{H_2S}/a_{SO_4^=}$; po, pyrrhotite; py, pyrite; anhy, anhydrite; tn, tennantite; en, enargite; cpy, chalcopyrite; bn, bornite; mt, magnetite; hm, hematite; cc, calcite; al, alunite.

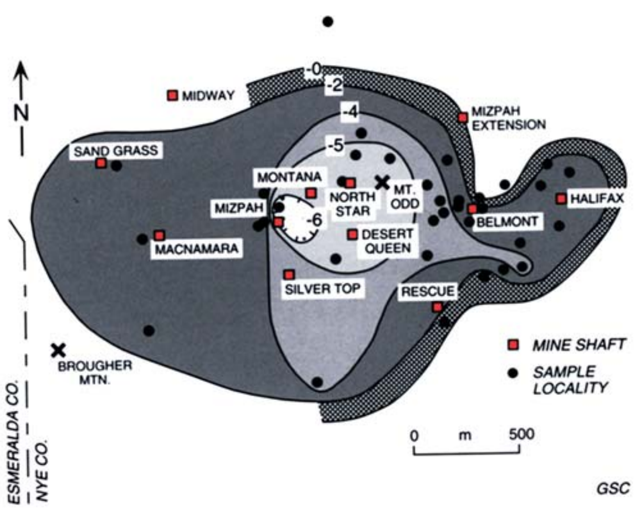

Figure 15.1-8. A $\delta^{18}O$ isopleth map for whole-rock samples (filled circles) in the vicinity of epithermal gold deposits at Tonopah, Nevada (after H.P. Taylor, 1973) illustrates oxygen isotope depletion of wall rocks by reaction with a meteoric water hydrothermal system. Greatest depletions (i.e., most negative $\delta^{18}O$ values) are closely associated with higher density of deposits as indicated by mine shafts (square symbols).

virtue of similar magmatic-hydrothermal and meteoric-hydrothermal processes. These deposits include gold-bearing skarns (high-temperature, silica-replacement deposits; e.g., Hedley, British Columbia) and manto deposits (sulphide-rich replacement; e.g., Ketza River, British Columbia) in carbonate rocks (see "Skarn gold", subtype 20.3).

Figure 15-2 (see Introduction above) represents a schematic cross-section which, although not meant to imply a continuum, graphically represents the relative geological environments of hot spring and epithermal vein deposits, skarns, mantos, Carlin-type deposits, and porphyry systems. Indeed, the geothermal systems which formed epithermal veins may have been situated well above zones in which porphyry-type deposits formed, and separated from them by a "barren gap". The geothermal systems would have acted as "traps" for the magmatic hydrothermal plumes. In addition, Figure 15-2 compares the environments of these deposits with that of "hypothermal" quartz-carbonate gold veins (see "Quartz-carbonate vein gold", subtype 15.2).

The occurrence of epithermal and hot spring environments in close spatial (but variable temporal) proximity is well documented in the Taupo Volcanic Zone, New Zealand (Henley et al., 1986). A genetic link with high-level intrusions is suggested by several studies. Vein quartz-(kaolinite)-alunite deposits at Butte, Montana are superposed upon earlier, disseminated, or porphyry-type mineralized rocks (Brimhall and Ghiorso, 1983). This suggests that juxtaposition of epithermal vein and porphyry deposits may develop largely as a consequence of a change in the relative position of the meteoric geothermal system and magmatic heat source. Epithermal gold-bearing veins are superposed on slightly older Cu-Mo-Au porphyry deposits in the Coromandel Peninsula, New Zealand (Merchant in Henley et al., 1986), and superposition of an adularia-sericite-subtype deposit on a porphyry copper-type deposit has been documented in the Philippines (Acupan: Cooke and Bloom, 1990). The extent of superposition of related epithermal and porphyry environments is tectonically and climatically controlled, facilitated by rapid uplift, high erosion rates, and volcanic sector collapse (Sillitoe, 1993). Such an association has provided a genetic framework useful in the exploration for epithermal gold deposits in the United States (Berger and Eimon, 1983) and in British Columbia (Panteleyev, 1986).

The term "epithermal" is commonly reserved for non-marine deposits. However, volcanogenic massive sulphide (VMS) deposits are also epithermal deposits in the broadest sense, having formed from submarine hot spring and geothermal systems, although they are sulphide rich and are mined principally for base metals. Gold-bearing VMS deposits do occur (e.g., Horne mine, Noranda; Eskay Creek 21B, British Columbia: Britton et al., 1989), although subaerial oxidation is essential to render some VMS deposits economically mineable for gold.

EXPLORATION GUIDES

A young age of intermediate to felsic volcanism (Toodoggone River camp excepted) is particularly significant in selecting a prospective area. Specific exploration guides for epithermal vein gold deposits depend on the search scale. At a regional scale (within a volcanic province) documentation of structural setting, and identification of areas which have experienced high heat flow and geothermal activity (e.g., in or adjacent to volcanic structures or rift zones), is of foremost importance. Although Tertiary and Recent terranes are preferable, older extensional terranes that have not been eroded deeply should not be overlooked. Geochemical analysis of stream sediments for precious and base metals (especially Pb and Zn), Hg, As, Tl, and Sb may be useful.

At the district scale, mapping (including structural analysis) and geochemical and stable isotopic analyses are important to define the size of the hydrothermal system, and the prospective locations of potential deposits. These studies may entail documentation of (1) mineralogical evidence of wall rock alteration (type and zoning; recognition of deposit subtype); (2) open-space filling vein textures; (3) oxygen isotope depletion and zoning in wall rocks; (4) evidence for boiling (e.g., presence of platy calcite; variable vapour/liquid ratios in primary fluid inclusions); (5) evidence regarding the origin of alunite; and (6) the relative distribution of gold, silver, and base metals, plus the volatile elements, Hg, Sb, As, and Tl, by mapping and obtaining analytical data.

Oxygen isotope mapping (e.g., Fig. 15.1-8 and 15.1-9) may also prove useful for recognizing hydrothermal alteration associated with hidden vein systems. Because the oxygen isotope composition of surface-derived, marine or meteoric waters ($\delta^{18}O < 0$; Fig. 15.1-5) differs markedly from that of typical rocks ($\delta^{18}O > 6$), and because surface-derived waters dominate in epithermal systems, mappable oxygen isotope alteration of rocks occurs during reaction with hydrothermal fluids. The magnitude of the change in the rock's initial isotopic composition is proportional to temperature and fluid flux, as previously noted, and oxygen isotope mapping thus provides a potential tool for delineating zones of upflow and potential mineralization in the paleohydrothermal system. For example, Figure 15.1-8 shows that mines in a classic district of adularia-sericite deposits are concentrated within the area of greatest ^{18}O depletion of volcanic host rocks, an area of presumable hydrothermal upflow. Areas of upflow can be associated with boiling and cooling which lead to precipitation of ore minerals.

Oxygen isotope zonation is readily detected in the andesitic wall rocks of the veins at Hishikari, Japan. A general correlation between patterns of ^{18}O depletion and alteration mineral assemblages around the veins can also be noted in Figure 15.1-9. It can be seen from the cross-section in this figure, that oxygen isotope evidence for hydrothermal circulation extends several hundreds of metres into the wall rocks, above the buried veins. In some cases, oxygen isotope alteration may be more readily detected than alteration mineral assemblages.

Prospective areas for hidden deposits may also be targeted by various geophysical techniques. These may include gravity surveys to map subsurface structure, and electrical resistivity and electromagnetic surveys to map hydrothermally altered rocks.

At the deposit or mine scale, the mapping of hydrothermal conduits and their structural expression, the identification of faults and their sense and magnitude of displacement, and determination of the distribution of gold (and silver) become most important. All of the above have as their goals the location of permeable zones. Documentation of mineralogical and structural guides to ore distribution and zones of boiling can also guide mine development.

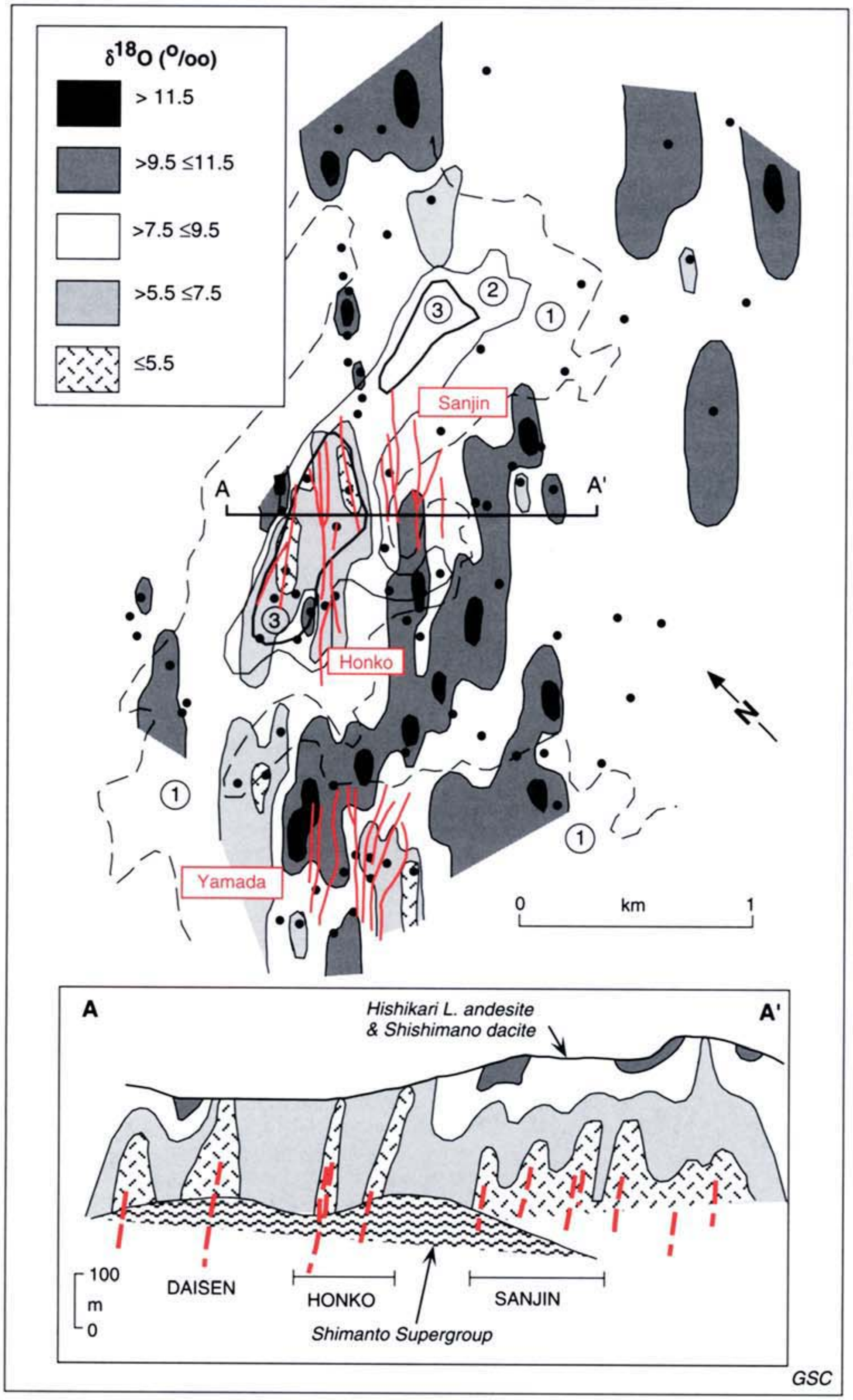

Figure 15.1-9. The $\delta^{18}O$ isopleth map and cross-section of the Hishikari area, Japan, modified after Naito et al. (1993). Positions of Daisen quartz vein, Honko vein system, and Sanjin vein system (shown in red) are projected to surface and into plane of section A-A'. Oxygen isotope data of Naito et al. (1993) were recontoured to emphasize structural control of oxygen isotope zonation. Fresh andesite and dacite are presumed to have $\delta^{18}O$ of 8.5 (cf., Naito et al.,1993). Locations of whole-rock oxygen isotope samples are shown by filled circles, but the locations of subsurface samples, which provide the basis for isotopic zonation in the cross-section, are omitted for simplicity. Alteration mineral zones (after Izawa et al.,1990) are: (1) chlorite- smectite and/or sericite-smectite; (2) quartz- smectite and/or kaolin minerals; and (3) cristobalite-smectite+kaolinite or halloysite. Chlorite-sericite dominate at depth.

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15.2 QUARTZ-CARBONATE VEIN GOLD

François Robert

INTRODUCTION

This subtype of gold deposits consists of simple to complex quartz-carbonate vein systems associated with brittle-ductile shear zones and folds in deformed and metamorphosed volcanic, sedimentary, and granitoid rocks. In these deposits, gold occurs in veins or as disseminations in immediately adjacent altered wall rocks, and is generally the only or the most significant economic commodity. The veins occur in structural environments characterized by low- to medium-grade metamorphic rocks and brittle-ductile rock behavior, corresponding to intermediate depths within the crust, and by compressive tectonic settings. Deposits of this type have commonly been referred to as mesothermal gold-quartz vein deposits, but they in fact encompass both mesothermal and hypothermal classes as initially defined by Lindgren (1933).

Quartz-carbonate vein gold deposits are widely spread throughout Canada and they occur principally in the following geological areas (Fig. 15.2-1): the greenstone belts of the Superior, Churchill, and Slave provinces, the oceanic terranes of the Canadian Cordillera, and the turbiditic Meguma terrane and the ophiolitic Baie Verte district in the Appalachians. The largest concentration of these deposits occurs in the greenstone belts of the south-central Superior Province.

Typical Canadian examples of such deposits, located on Figure 15.2-1, include: Goldenville, Nova Scotia; Sigma-Lamaque, O'Brien, and Casa-Berardi, Quebec; Kerr Addison, Macassa, Dome, Hollinger-McIntyre, Campbell Red Lake, and MacLeod-Cockshutt, Ontario; San Antonio,

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[1] *Editorial note:* Within this volume, in a companion account of gold deposits hosted by iron-formation (subtype 15.3), Lupin is presented as the type example of stratiform iron-formation hosted gold deposits and has been interpreted to be a syngenetic deposit.

Manitoba; Star Lake, Saskatchewan; Giant Yellowknife, Camlaren, and Lupin[1], Northwest Territories; Bralorne-Pioneer and Cariboo Gold Quartz-Island Mountain, British Columbia. Other examples throughout the world include the following deposits or districts: Mother Lode and Grass Valley, California; Alaska-Juneau, Alaska; Homestake, South Dakota; Mt. Charlotte, Victory, Norseman, and Bendigo-Ballarat, Australia; Ashanti and Prestea, Ghana; and Passagem, São Bento and Crixas, Brazil.

IMPORTANCE

Quartz-carbonate vein deposits account for approximately 80% of the production from lode gold deposits in Canada (Fig. 15.2-2). The Canadian Shield, and the Superior Province in particular, contains the most significant deposits and accounts for more than 85% of the gold production from quartz-carbonate veins in Canada. Total production from the main geological areas of occurrence in Canada is given in Table 15.2-1.

SIZE AND GRADE OF DEPOSITS

Quartz-carbonate vein gold deposits display a wide range of sizes (Fig. 15.2-2), which can vary as a function of the price of gold, as it is possible in almost every case to selectively mine the higher grade portions of the deposits at times of lower gold prices, and lower grade material as well at times of higher prices. Deposits of Superior Province are the largest, typically containing between 6 and 60 t of gold to a maximum of 1000 t, those of Churchill Province between 5 and 10 t, and those of the Meguma terrane, less

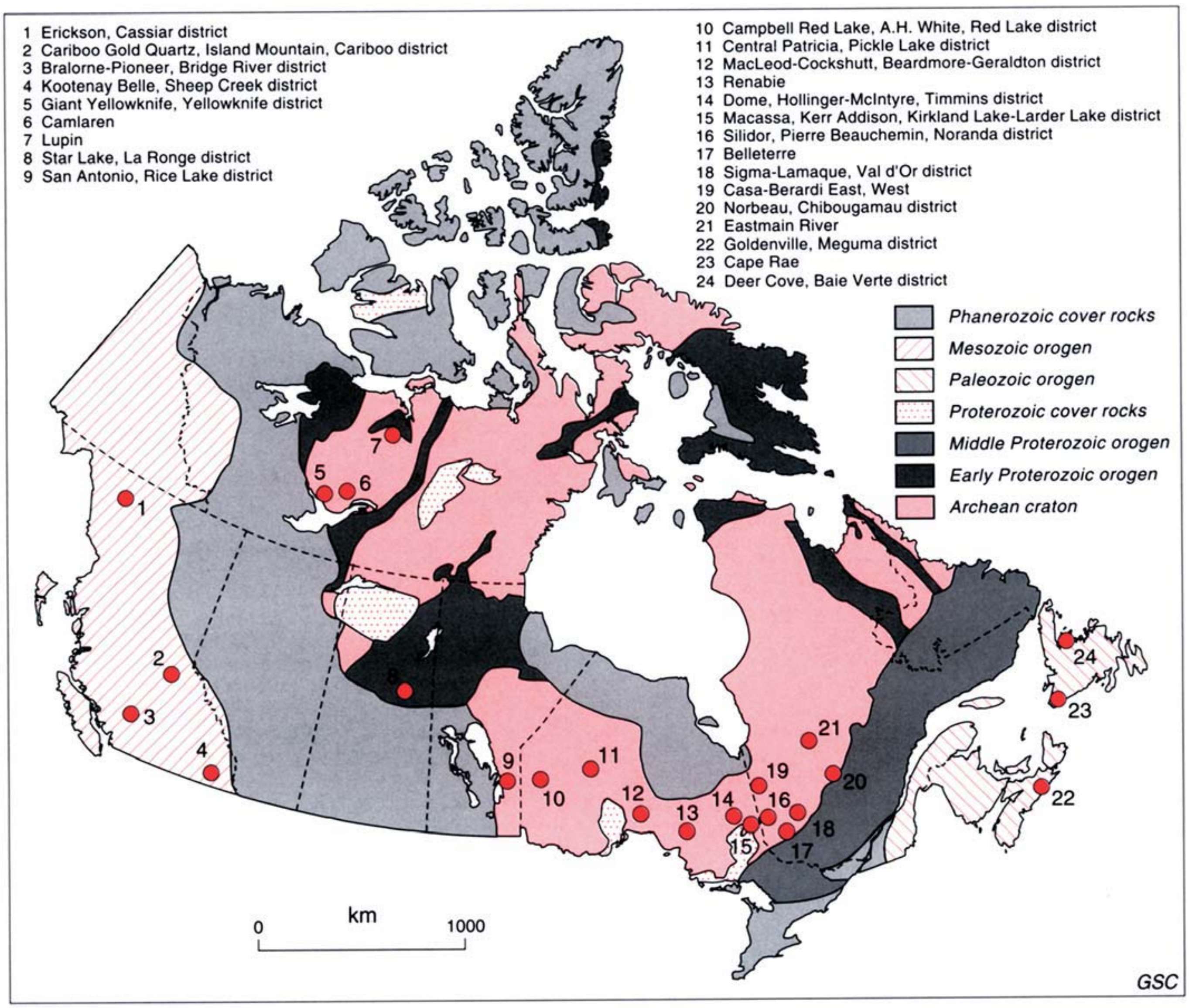

Figure 15.2-1. Distribution of selected Canadian quartz-carbonate vein gold deposits and districts.

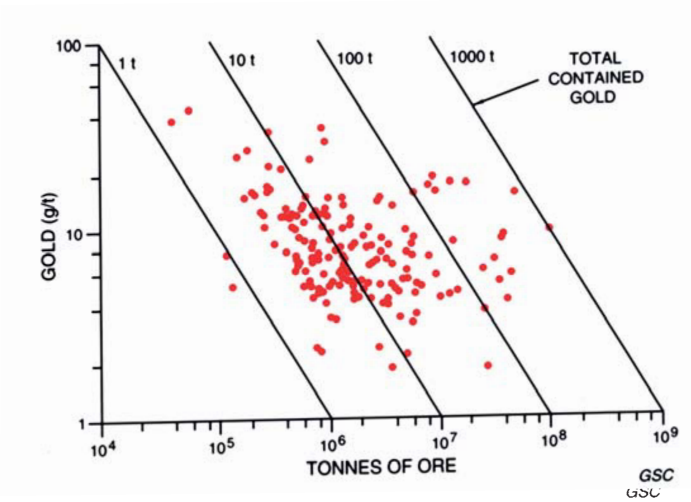

Figure 15.2-2. Tonnage versus grade diagram for Canadian quartz-carbonate vein gold deposits.

Table 15.2-1. Approximate gold content and typical grade and tonnage figures for individual quartz-carbonate vein deposits in the three main geological gold-producing areas in Canada.

	Appalachian Province	Canadian Shield	Canadian Cordillera
Total production (t)	66	6000	360
Deposit grade (g/t)	10	8	14
Deposit tonnage (t)	5 x 10^5	6 x 10^6	2 x 10^6

than 3 t (Table 15.2-1). Typical tonnage and grade of quartz-carbonate vein deposits are a few million tonnes of ore at a grade of 6 to 10 g/t gold (Fig. 15.2-2).

GEOLOGICAL FEATURES

Geological setting

At the regional scale, quartz-carbonate vein gold deposits occur in two contrasting geological environments: deformed clastic sedimentary terranes and deformed volcano-plutonic terranes containing diverse volcanic assemblages of island-arc and oceanic affinities. Despite lithological and structural differences (see below), these two types of environments share the following characteristics: greenschist to locally lower amphibolite metamorphic facies, brittle-ductile nature of the deformation, and geological structures recording compressional to transpressional tectonic settings.

Quartz-carbonate vein gold deposits in these environments tend to occur in clusters, or districts, and they are by far more abundant in volcano-plutonic terranes than in clastic sedimentary terranes. Both types of environments are present in a number of districts, in which they are separated by major fault zones. However, in such cases auriferous quartz-carbonate veins preferentially occur in the volcano-plutonic domains. Key characteristics and examples of these two geological environments are presented below.

Clastic sedimentary terranes

Clastic sedimentary terranes mineralized with quartz-carbonate veins are not very common in Canada but, where present, they typically occupy extensive areas. These terranes include the Meguma terrane, Nova Scotia (Fig. 15.2-3), the "Yellowknife basin" in the Slave Province, and sedimentary rocks of the Sheep Creek district and of the Barkerville terrane in the Cariboo district, both in British Columbia.

Most clastic sedimentary terranes are characterized by important thicknesses of well-bedded turbidites consisting of greywacke, mudstone, shale, and minor conglomerate. In the Meguma terrane (Fig. 15.2-3), the turbidite sequence consists of vein-bearing quartz-rich greywacke and interbedded slate of the Goldenville Formation and overlying thinly laminated slate of the Halifax Formation (Graves and Zentilli, 1982). Some sequences, such as the Contwoyto Formation in the Slave Province, also contain significant proportions of interbedded iron-formation and mafic volcanic rocks. The presence of quartzite and/or limestone in the Cariboo (Sutherland-Brown, 1957) and Sheep Creek districts (Matthews, 1953) are indicative of continental margin environments. Clastic sedimentary sequences contain only small proportions of intrusive rocks, most of which form large, postfolding dioritic to granitic bodies such as the Devonian granodiorites and monzogranites in the Meguma terrane (Fig. 15.2-3).

Gold-bearing clastic sedimentary sequences are invariably folded, and commonly in a complex manner. Folds range from open to isoclinal, and may be accompanied by a penetrative axial plane cleavage. In many cases, younger faults cut the folds at moderate to high angles. The Meguma terrane is characterized by a series of shallowly plunging, northeast-to east-northeast-trending upright folds which are cut by northwest-striking faults and intruded by Devonian granites (Fig. 15.2-3). Most sequences have been metamorphosed to the greenschist facies, and in some regions, such as in the Contwoyto Lake area, to the lower and middle amphibolite facies.

Volcano-plutonic terranes

Volcano-plutonic terranes are the most important hosts to vein gold mineralization in Canada. They are represented by the abundant Precambrian greenstone belts of the Canadian Shield and by the Phanerozoic island arc-oceanic assemblages of the Canadian Cordillera and the Appalachians. Representative districts include: Baie Verte, Newfoundland; Val d'Or, Cadillac, and Casa-Berardi, Quebec; Larder Lake, Kirkland Lake, Timmins, Beardmore-Geraldton district, and Red Lake, Ontario; Rice Lake, Manitoba; La Ronge, Saskatchewan; and Coquihalla, Bridge River, and Cassiar, British Columbia (Fig. 15.2-1).

Mineralized volcano-plutonic terranes form elongate belts bounded by, or transected by, crustal-scale fault zones. These belts typically comprise contrasting geological domains, which may include clastic sedimentary sequences, separated from the volcano-plutonic domains by the major fault zones. This is the case at Val d'Or (Fig. 15.2-4) and Beardmore-Geraldton (Fig. 15.2-5), where volcano-plutonic terranes to the north are separated from turbidite sequences to the south by the Larder Lake-Cadillac and Barton Bay fault zones, respectively. In other districts, such as Bridge River, major faults may separate contrasting volcanic assemblages: the Fergusson thrust fault separates the oceanic Bridge River Group from the Cadwallader Group of island arc affinity (Fig. 15.2-6; Leitch, 1990).

Volcano-plutonic terranes are lithologically more diverse than clastic sedimentary sequences. Volcanic supracrustal rocks dominate and typically include basaltic tholeiitic domains of oceanic affinity and mafic to felsic, tholeiitic to calc-alkaline domains of island arc affinity. Ultramafic rocks are volumetrically important in some Archean terranes where they form komatiitic volcanic domains. In Phanerozoic terranes, ultramafic rocks occur mostly as serpentinite bodies along fault zones, as in the Bridge River district (Fig. 15.2-6), and may represent remnant ophiolite sequences. Narrow belts of clastic sedimentary rocks are also present in many volcano-plutonic terranes and include both flysch-like and molasse-like facies. The flysch-like facies consist of greywacke-mudstone

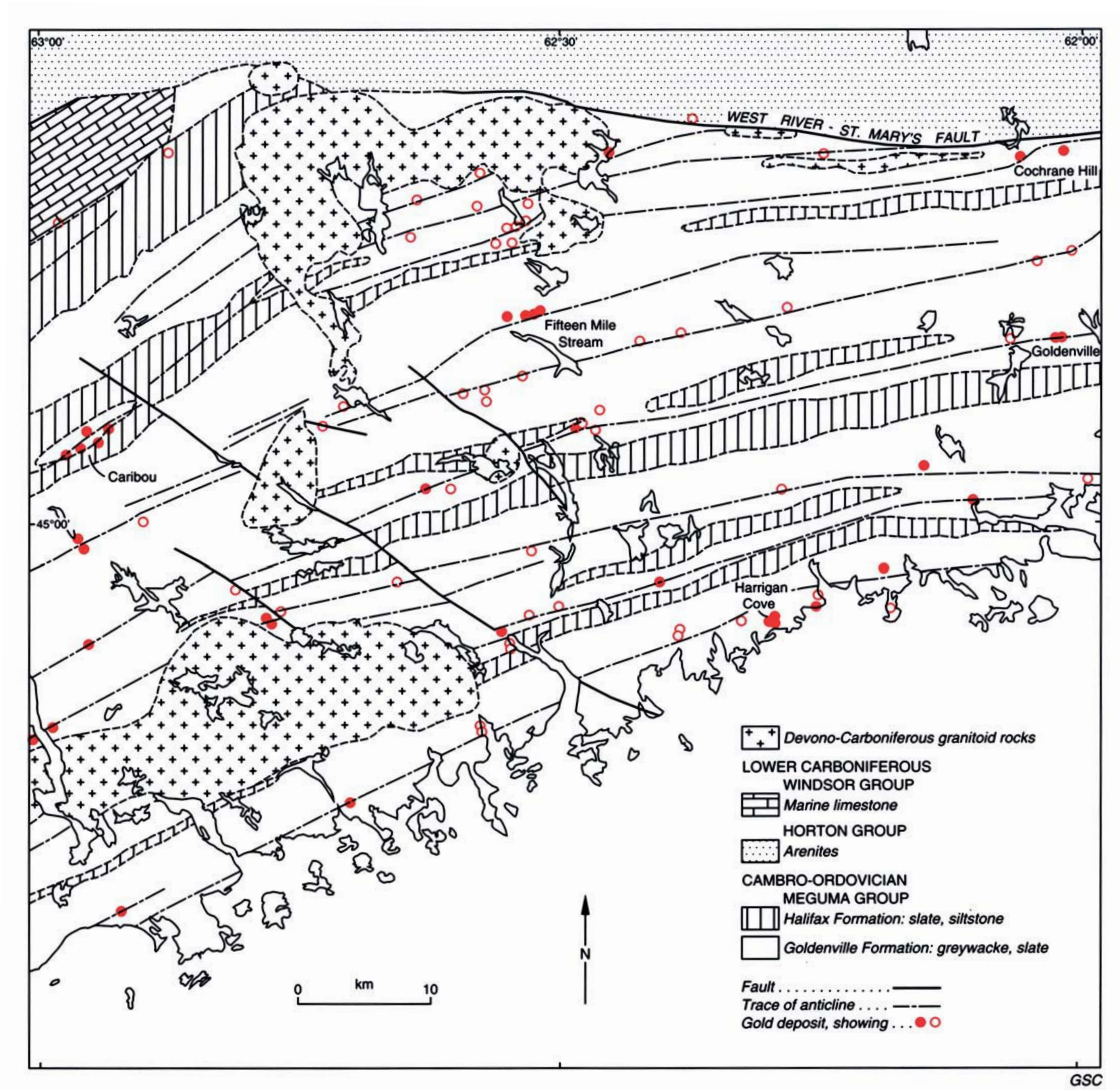

Figure 15.2-3. Simplified geological map of the eastern portion of the Meguma terrane, Nova Scotia, showing the distribution of quartz-carbonate vein gold deposits. (modified from McMullen et al., 1987)

with locally abundant conglomerate and iron-formation, as represented by the Cadillac Group at Val d'Or (Fig. 15.2-4) and the Northern, Central, and Southern Metasedimentary Belts at Beardmore-Geraldton (Fig. 15.2-5). Fluvial-alluvial sequences of polymictic conglomerate, arenite, and sandstone, referred to as Timiskaming-type in Superior Province, are representative of the molasse-like facies and are present along major fault zones and uncomformably overlie volcanic rocks in many Precambrian districts such as Kirkland Lake, Rice Lake, and La Ronge. In the Bridge River district, ribbon chert and argillites overlie basalts of the oceanic Bridge River Complex (Fig. 15.2-6).

In contrast to clastic sedimentary sequences, volcano-plutonic terranes contain abundant associated intrusive rocks, including batholiths, stocks, sills, and dykes, emplaced at several stages during their volcanic and tectonic evolution. Early, synvolcanic intrusions include gabbro sills and dykes and subvolcanic diorite-tonalite plutons such as the Bourlamaque pluton at Val d'Or (Fig. 15.2-4) and the Bralorne intrusions at Bridge River (Fig. 15.2-6). Syn- to late tectonic intrusions evolve from commonly porphyritic diorite-tonalite stocks and dykes, to monzonitic to syenitic plutons, to late granitic batholiths.

Superimposed tectonic fabrics and folds in many volcano-plutonic terranes indicate complex structural evolutions linked with the history of associated major fault zones. In many areas, a dominant episode of compressional deformation, involving thrusting, folding, and development of upright penetrative fabrics subparallel to major faults, is followed by transcurrent deformation largely localized along the major faults (Card, 1990; Leitch, 1990). In addition to first-order major faults, these terranes are characterized by abundant higher-order subsidiary shear zones and faults, subparallel to the regional trend, any of which may host auriferous quartz-carbonate veins. Metamorphic grade is greenschist in most volcano-plutonic terranes but reaches lower amphibolite in some districts such as Red Lake, Ontario.

Distribution of quartz-carbonate vein districts and deposits

A large number of quartz-carbonate vein gold districts, especially those in volcano-plutonic terranes, are spatially associated with crustal-scale fault zones, which are generally regarded as the major conduits for auriferous fluids. This association is particularly well illustrated by gold

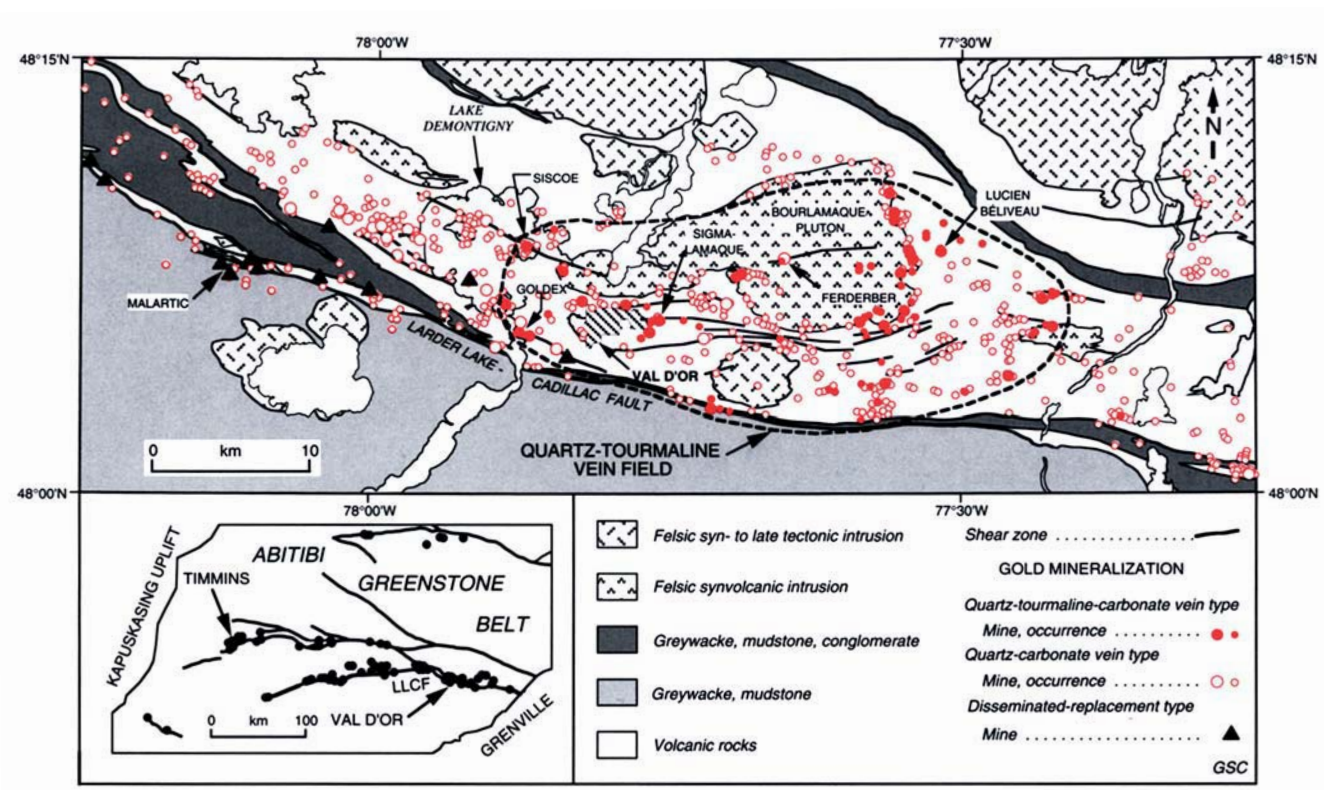

Figure 15.2-4. Simplified geological map of the Val d'Or district, southeastern Abitibi Subprovince, showing the distribution of the major vein gold deposits. In contrast to the widely distributed quartz-carbonate veins, quartz-tourmaline-carbonate veins occur in a well defined field. The inset shows the distribution of gold deposits and major fault zones within the Abitibi Subprovince; LLCF = Larder Lake-Cadillac fault (modified from Robert, 1994).

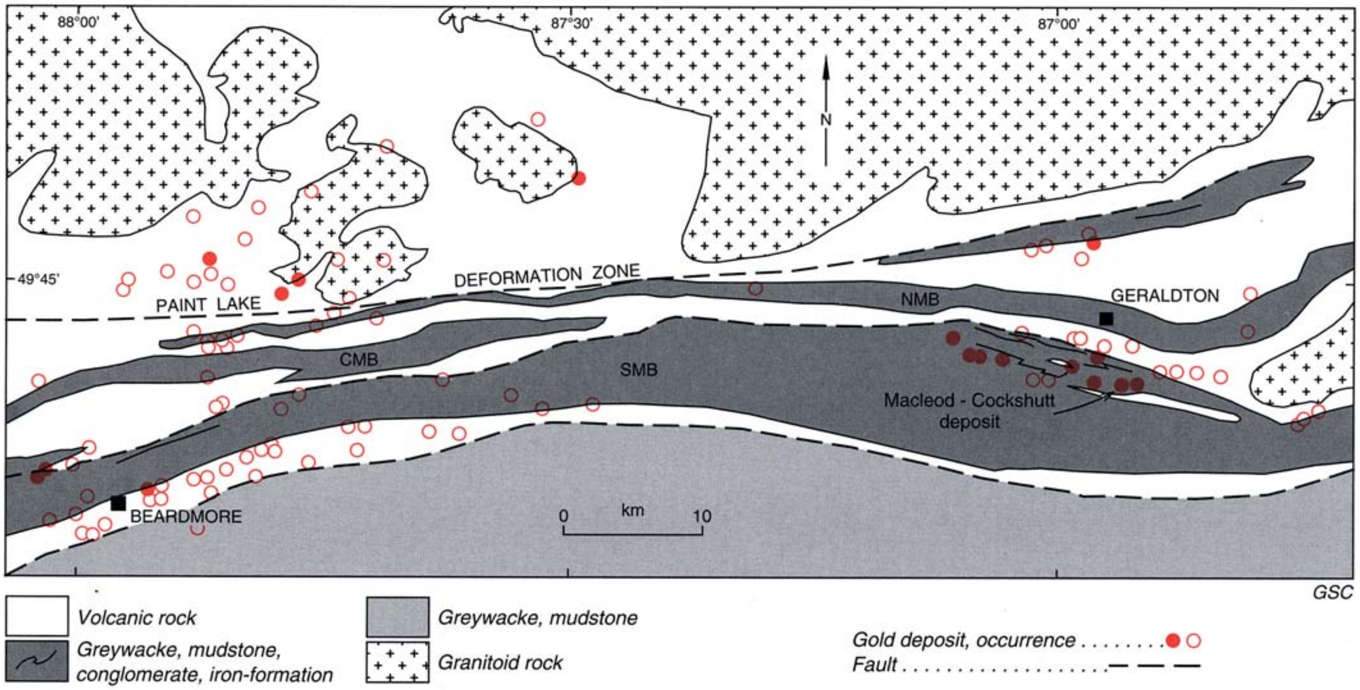

Figure 15.2-5. Simplified geological map of the Beardmore-Geraldton district, Ontario, showing the distribution of quartz-carbonate vein gold deposits; SMB, CMB, and NMB: Southern, Central, and Northern Metasedimentary Belts, respectively. (modified from Ontario Department of Mines, 1966)

deposits of the Abitibi greenstone belt (inset, Fig. 15.2-4). Within districts, however, auriferous veins are in fact more closely associated with smaller subsidiary structures adjacent to major faults, resulting in a dispersion of deposits away from such faults, as in the Val d'Or district (Fig. 15.2-4).

Within volcano-plutonic terranes, quartz-carbonate veins may occur in any rock type present within a district, and deposits typically consist of simple to complex networks of veins and related shear zones. They are most common in parts of the districts that are dominated by mafic volcanic rocks, as in the Red Lake, Yellowknife, and Cassiar districts. Vein deposits also occur in areas dominated by iron-formation-bearing clastic sedimentary belts such as in the Beardmore-Geraldton district (Fig. 15.2-5), and in large felsic plutons as illustrated by the Bourlamaque pluton at Val d'Or (Fig. 15.2-4). These different lithological associations are considered further in a subsequent section.

In clastic sedimentary terranes not adjacent to volcano-plutonic terranes, the distribution of gold districts does not show any recurring pattern and appears to reflect features specific to the host sequence. In the Meguma terrane, for example, gold districts are located at the crests of gently- and doubly-plunging anticlines and occur mostly within the Goldenville Formation (Fig. 15.2-3), whereas the distribution of deposits in the Contwoyto Formation, Northwest Territories, is controlled by that of folded iron-formation (Lhotka and Nesbitt, 1989). Mineralized veins may occur in fold hinges as in the Camlaren deposit in the Slave Province or in the Goldenville deposit (Fig. 15.2-7), or in postfolding veins parallel to fold axial planes as at the MacLeod-Cockshutt deposit (Fig. 15.2-8) or in oblique faults as in the Sheep Creek and Cariboo districts.

Age of host rocks and mineralization

Volcanic and sedimentary host rocks to quartz-carbonate vein gold deposits in Canada range in age from Archean to Jurassic. However, most veins occur in rocks of four main age groups: Late Archean, Early Proterozoic, Cambrian-Ordovician, and Triassic-Jurassic. Of these four groups, rocks of Late Archean age have yielded most of the Canadian gold production from deposits of this type (Table 15.2-2).

In a large number of volcano-plutonic terranes, field and geochronology studies show that the gold-bearing veins formed relatively late in the local structural evolution, after folding of supracrustal rocks and emplacement of the syn- to late tectonic intrusions. At Val d'Or, the Sigma-Lamaque vein system (Fig. 15.2-9) cuts a 2685 ± 2 Ma tonalite stock and a swarm of 2694 ± 2 Ma feldspar porphyry dykes that have both intruded 2705 ± 2 Ma volcanic rocks (Wong et al., 1991). Deposits in the Kirkland Lake and Timmins districts, hosted in 2725-2700 Ma volcanic rocks, postdate Timiskaming sedimentation, bracketed between 2680 and 2676 Ma, and the intrusion of 2673 +6/-2 Ma albitite dykes at Hollinger-McIntyre (Corfu, 1993). In the Red Lake district, gold mineralization is bracketed between 2720 and 2700 Ma, corresponding to the last stages of tectonism and plutonism, and is much younger than the volcanism, which lasted from 3000 to 2730 Ma (Corfu and Andrews, 1987). Similar young relative ages are indicated for the Bralorne-Pioneer deposit (Fig. 15.2-6): quartz-carbonate veins are hosted by 270 ± 5 Ma diorite-tonalite and coeval volcanic rocks, but they cut albitite dykes dated at 91.4 ± 1.4 Ma (Leitch, 1990). Thus, in most documented cases, quartz-carbonate veins are significantly younger than the host

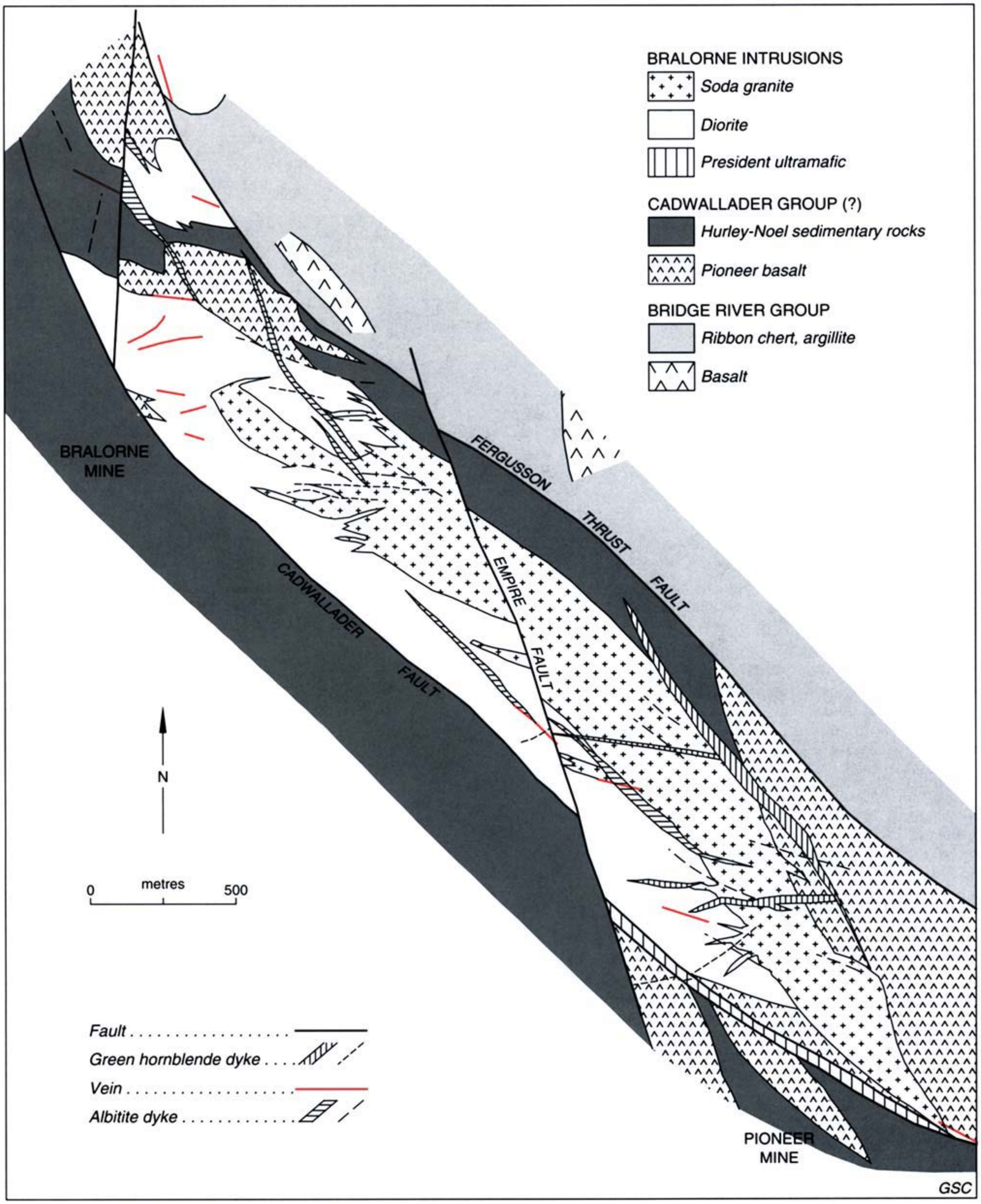

Figure 15.2-6. Simplified geological map of the Bralorne-Pioneer deposit, Bridge River deposit, British Columbia (modified from Leitch, 1990).

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volcanic sequences and emplaced more or less synchronously with late magmatic activity within, and adjacent to the greenstone belts during the late Archean.

In clastic sedimentary terranes, two distinct relative ages of vein formation are recognized: (1) prefolding, such as in the sedimentary strata of the Meguma terrane of Nova Scotia (Fig. 15.2-7; Graves and Zentilli, 1982); and (2) postfolding, associated with fractures and faults oblique to fold axial surfaces, such as in the Cariboo and Sheep Creek districts in British Columbia (Matthews, 1953; Sutherland-Brown, 1957).

The absolute ages of quartz-carbonate vein deposits are not well constrained. In southern Abitibi greenstone belt, direct dating of hydrothermal rutile, scheelite, and muscovite by U-Pb, Sm-Nd, and ^{40}Ar-^{39}Ar techniques, respectively, give ages 50-80 Ma younger than any known plutonic rock in the area (Corfu, 1993). At Val d'Or, rutile and scheelite ages of ~2600 Ma from quartz-tourmaline-carbonate veins at the Sigma deposit conflict with the 2682 Ma age of a hydrothermal zircon from the same sets of veins (Claoué-Long et al., 1990). The significance of such "young" ages is still unclear.

Table 15.2-2. Age distribution of host rocks to quartz-carbonate vein deposits and respective gold endowment.

Age	Examples	Contained gold (t)
Archean	Greenstone belts of the Superior and Slave provinces	6000
Proterozoic	Churchill and Grenville provinces	150
Cambrian to Ordovician	Cariboo, B.C.; Meguma terrane, N.S.; Baie Verte, Nfld.	100
Triassic to Jurassic	Cassiar and Bridge River districts, Canadian Cordillera	150

In the Canadian Cordillera, the age of the Bralorne-Pioneer deposit is bracketed between ~90 and ~85 Ma by premineral albitite dykes and intra- to postmineral hornblende-bearing dykes (Leitch, 1990). The K/Ar ages of vein-related white micas suggest mineralization ages of ~130 Ma in the Cassiar district (Sketchley et al., 1986) and ~140 Ma in the Cariboo district (Andrew et al., 1983). Similar Lower Cretaceous mineralization has also been documented along the Mother Lode gold belt in California (Bohlke and Kistler, 1986).

In some districts, there is growing evidence for the existence of multiple generations of auriferous quartz-carbonate veins. In the Rice Lake district, Brommecker et al. (1989) have documented two generations of gold-bearing quartz-carbonate veins related to two distinct deformation increments. At Val d'Or, late quartz-tourmaline-carbonate veins crosscut dykes and are typically not deformed, whereas earlier quartz-carbonate veins are overprinted by deformation and commonly cut by dykes (Robert, 1994).

Host rock associations

In general, quartz-carbonate veins occur in any rock type present in a given district. However, there are a number of recurring deposit-scale lithological associations which are in part reflected in the geometric and/or hydrothermal characteristics of the deposits. These different lithological

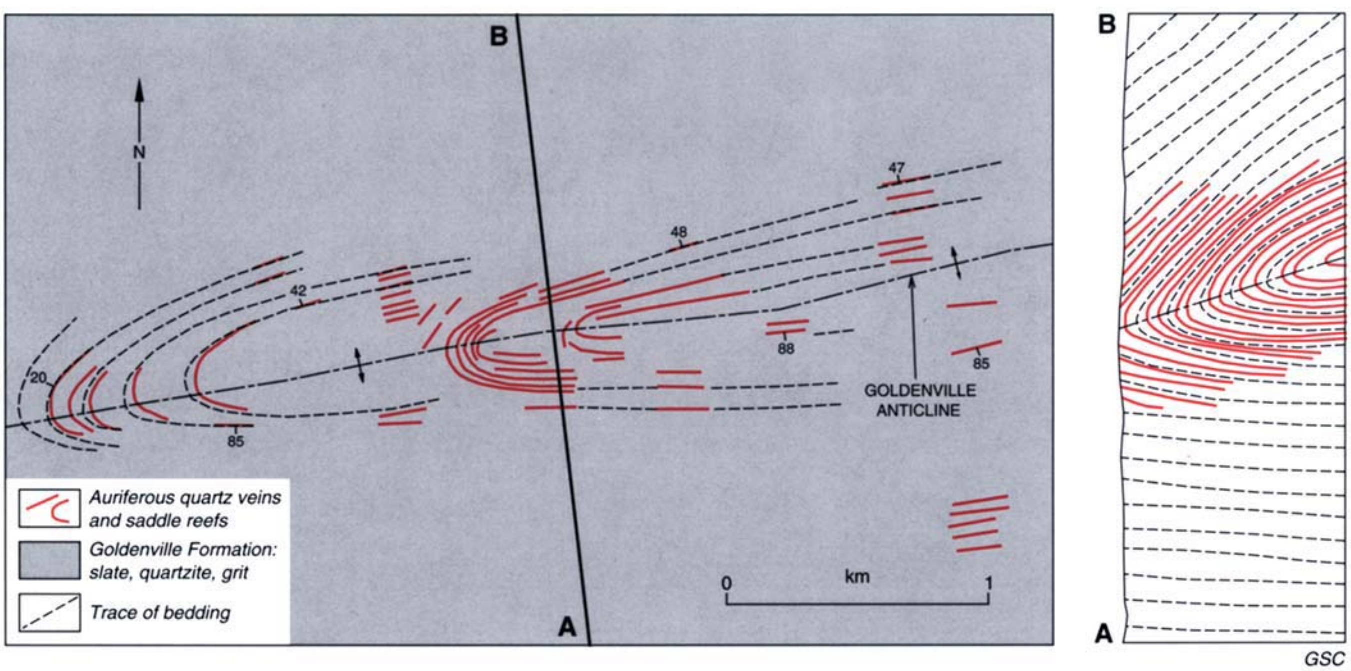

Figure 15.2-7. Generalized geological plan and section of the Goldenville gold district, Meguma terrane, Nova Scotia (modified from Boyle, 1979).

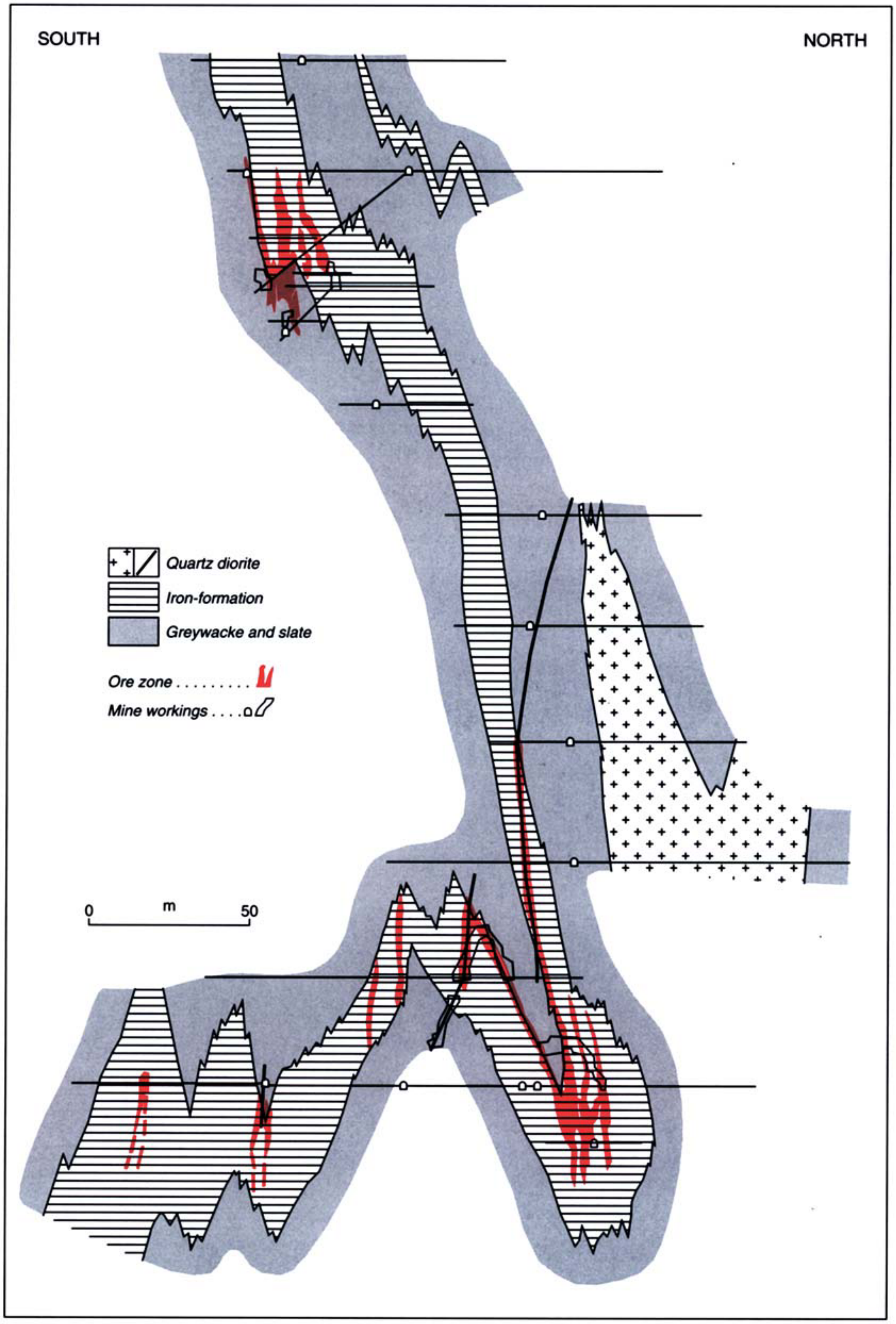

Figure 15.2-8. Cross-section through the MacLeod-Cockshutt deposit, Beardmore-Geraldton district (adapted from Horwood and Pye, 1955).

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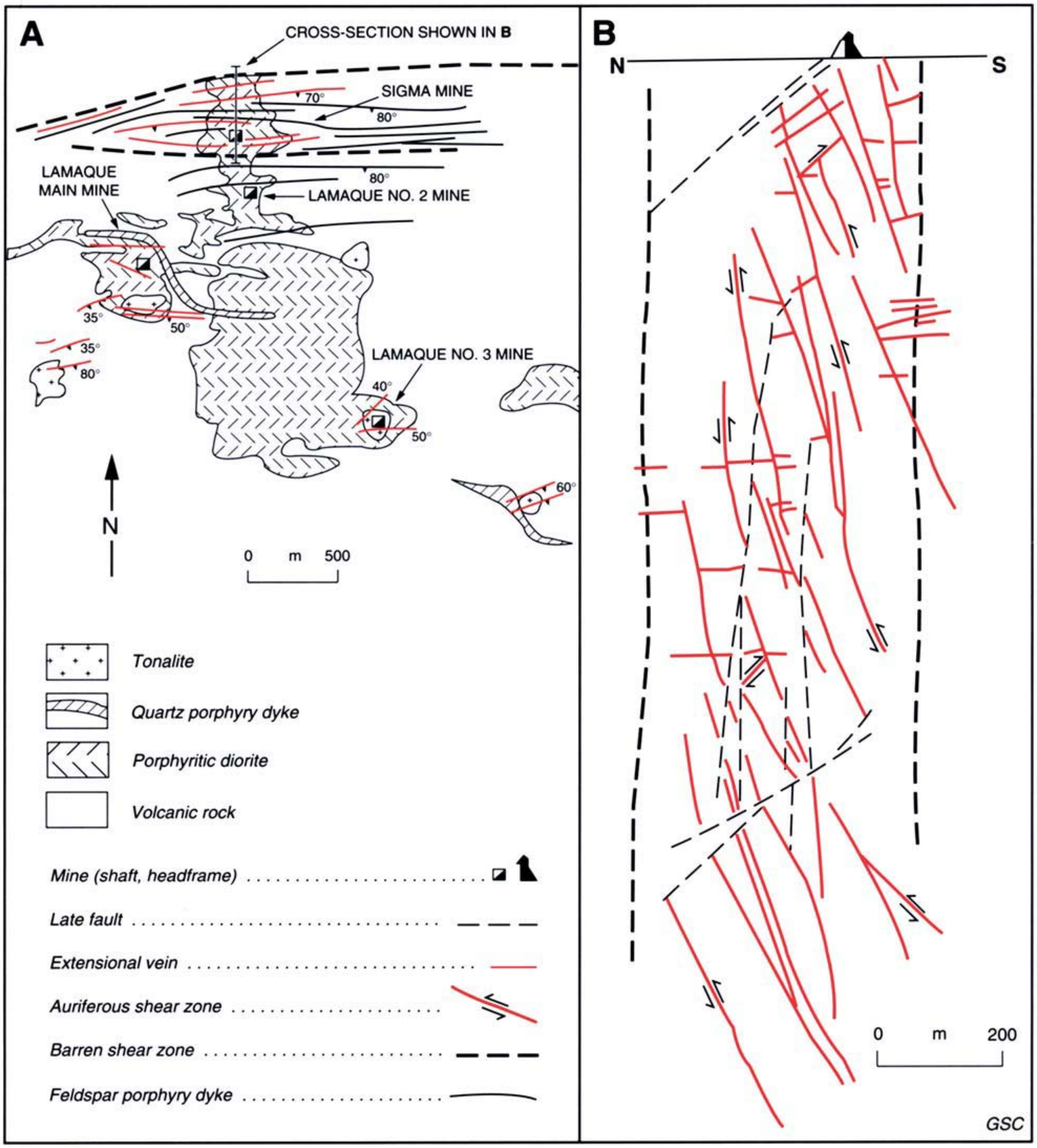

Figure 15.2-9. A) Simplified geological map of the area surrounding the Sigma and Lamaque deposits. **B)** Simplified vertical cross-section through the Sigma mine, showing the configuration of the shear zone and vein network (adapted from Robert and Brown, 1986a).

associations are best regarded as different facies, or styles, of quartz-carbonate vein deposits. They reflect variations in structural and chemical controls exerted by the host lithology on the development of the vein networks.

Volcanic-hosted quartz-carbonate vein deposits are the most common. They occur most commonly in mafic volcanic rocks and associated ultramafic rocks and are represented by the Belleterre, Kerr Addison, Campbell Red Lake, Giant Yellowknife, and Erickson deposits. Characteristics common to this category of deposits include relatively wide, highly schistose host shear zones and wide haloes of carbonate alteration (fuschsite-bearing if hosted in ultramafic rocks), reflecting both the ductile and the Fe-Mg-rich nature of the host rocks. Several deposits of this group are centered on intrusive complexes comprising stocks, irregular bodies, and dykes of diorite, tonalite, and syenite, which are commonly porphyritic. This is the case at the Sigma-Lamaque (Fig. 15.2-9A), Macassa, Dome, Hollinger-McIntyre, and Bralorne-Pioneer (Fig. 15.2-6) deposits, which display relatively complex vein and shear zone patterns. Other deposits, represented by the San Antonio and Norbeau mines, occur in laterally extensive differentiated tholeiitic gabbro sills. They consist of relatively complex vein networks which are largely confined to the most differentiated, quartz-bearing or granophyric units within the sills. Veins may be confined to such units because of their more competent nature and because their Fe-rich nature is favourable for gold precipitation. Volcanic-hosted deposits include many of the largest Canadian quartz-carbonate vein deposits. Some deposits of this subtype also have the greatest vertical extent, reaching 2 km or more in several mines, including Sigma (Fig. 15.2-9B).

Another group of deposits is *tonalite-hosted* and occurs in large diorite-tonalite and monzonite plutons within volcano-plutonic terranes. Examples include the Ferderber and other deposits in the Bourlamaque pluton at Val d'Or (Fig. 15.2-4), the Silidor and Pierre Beauchemin deposits in the Flavrian pluton at Noranda, and the Star Lake deposit and pluton in the La Ronge belt. The host intrusion may also lie immediately outside greenstone belts, as at Renabie. Deposits of this type are characterized by relatively simple geometries and the quartz-carbonate veins and host shear zones are spatially associated with mafic dykes present in these intrusions.

Iron-formation-hosted quartz carbonate veins also form an important group of deposits in both clastic sedimentary sequences and volcano-plutonic terrane, represented by the Central Patricia, MacLeod-Cockshutt (Fig. 15.2-8), and Lupin deposits. Orebodies in such deposits are within zones that contain abundant quartz-carbonate veins and that are generally restricted to the iron-formation layers. The veins in all cases postdate folding of the sedimentary layers and, in a number of cases, they are parallel to the axial planes of the folds (Fig. 15.2-8).

Finally, other deposits are *turbidite-hosted*. In these, veins either occur in fold hinges as at Goldenville (Fig. 15.2-7) and at Camlaren (Boyle, 1979), or in fractures and faults cutting the folds at a moderate to high angle, as in the Cariboo and Sheep Creek districts. These deposits lack obvious spatial relationships to intrusive rocks and are characterized by poorly developed alteration haloes. In some districts, specific sedimentary units are preferentially mineralized, such as the Upper Nugget and Upper Navada quartzites in the Sheep Creek district (Matthews, 1953), or the Rainbow Formation in the Island Mountain deposit (Sutherland-Brown, 1957).

In several districts within volcano-plutonic terranes, there is one particular setting of quartz-carbonate veins which dominates, despite the presence of other rock types. For example, nearly all vein deposits in the La Ronge district occur within granitoid intrusions, whereas those in the Beardmore-Geraldton district are associated with iron-formation (Fig. 15.2-5).

Form and structure

Quartz-carbonate vein gold deposits consist of networks of veins and related host structures. An important characteristic of a large number of vein deposits, especially in volcano-plutonic terranes, is their significant vertical extent, which exceeds 1 km in several deposits, and 2 km in a few deposits listed above. The networks display simple to complex geometries involving single to multiple sets of veins and host structures (Hodgson, 1989). They comprise veins in one or more of the following structural settings: (1) in faults and shear zones; (2) in extensional fractures and stockwork zones, including breccias; and (3) in association with folds. As illustrated by the Sigma-Lamaque deposit at Val d'Or, a large number of networks combine veins in shear zones and in spatially associated extensional fractures (Fig. 15.2-9B). Veins and their different settings are described below. Vein networks in volcanic-hosted deposits commonly display complex geometries, especially those centred in intrusive complexes such as Bralorne-Pioneer (Fig. 15.2-6) and Sigma-Lamaque (Fig. 15.2-9B), whereas those in tonalite-hosted deposits generally consist of a single set of mineralized structures.

Veins in faults and shear zones

Faults and shear zones probably represent the most common host structures to quartz-carbonate veins, and they are a component of almost every gold deposit. Veins hosted by these types of structures occur principally in volcanic-dominated terranes, where they are found in practically every rock type. The nature of the host shear zones ranges from ductile to most commonly brittle-ductile, correlating in part with the metamorphic grade of the host rocks (Colvine, 1989). These shear zones have moderate to steep dips, and can be traced for several hundred metres to a few kilometres along strike and down dip. They are typically high-angle reverse to reverse-oblique shear zones, and less commonly strike-slip.

The mineralized shear zones may occur individually, as parallel sets, or may form anastomosing, conjugate, or more complex arrays (Poulsen and Robert, 1989). These shear zones are generally discordant to the stratigraphic layering but, in a number of cases, they parallel bedding planes or intrusive contacts (such as along dykes), reflecting the influence of strength anisotropy on their development.

Quartz-carbonate veins in shear zones and faults, commonly referred to as shear veins, typically form tabular to lenticular bodies within the central parts of brittle-ductile shear zones, either parallel, or slightly oblique, to the host structure (Hodgson, 1989; Poulsen and Robert, 1989). The veins range in thickness from a few tens of centimetres to a few metres and may reach a few hundred metres in their longest dimension. Mineralized shear veins or portions of veins commonly occur at splays and intersections of shear zones, at bends in the general trend of the host structure, as well as at the intersection of the shear zone with a specific rock type.

Shear veins in shear zones are typically laminated (Fig. 15.2-10A). Laminations are defined by thin septa and slivers of altered and foliated wall rocks, incorporated into the vein by multiple-opening episodes. In several deposits, individual quartz-carbonate laminae are also bounded by striated slip surfaces, in some cases with hydrothermal slickenlines indicating vein development in active shear zones. With increasing proportion and thickness of wall rock slivers, laminated veins may also grade into sheeted veinlet zones.

In a number of deposits, shear veins display some degree of folding and boudinage due to postvein displacement along the host shear zone or to subsequent folding of the entire shear zone (Poulsen and Robert, 1989).

Veins in extensional fractures and stockwork zones

Veins in extensional fractures, or extensional veins, stockwork zones, and hydrothermal breccias occur principally in volcano-plutonic terranes and are present in a significant number of deposits. They are not as common as shear veins and represent a major source of ore in only a small proportion of deposits.

Extensional veins may form arrays of planar to sigmoidal veins within shear zones or at frontal and lateral terminations of shear veins (Robert, 1994), or form sets of regular tabular bodies (Fig. 15.2-10B) extending outside shear zones in less deformed rocks, such as the subhorizontal extensional veins of the Sigma-Lamaque deposit (Fig. 15.2-9B). They also occur as sets of en echelon veins in relatively competent host lithologies such as small intrusions of intermediate to felsic composition. In most cases, extensional veins are spatially associated with shear veins and they have relatively shallow dips, which are consistent with the reverse to reverse-oblique movements along the associated shear zone.

Extensional veins within shear zones and stockwork zones are typically a few centimetres thick and a few metres long, whereas those outside shear zones are commonly several tens of centimetres thick and a few hundred metres in their longest dimensions. At the Sigma-Lamaque deposit, subhorizontal extensional veins, less than one metre thick, commonly occupy areas as great as 5000 m^2 in extent (Robert and Brown, 1986a). The internal structure of extensional veins contrasts with that of shear veins and is commonly characterized by mineral fibres at high angles to vein walls (Fig. 15.2.-10B), as well as by crack-seal and open-space filling textures.

Stockwork zones are important in a number of deposits; at San Antonio in the Rice Lake district, for example, they constituted a large proportion of the ore mined. Stockworks consist of several sets of extensional veins (Fig. 15.2-10C), which can grade into hydrothermal breccias in areas of intense veining. They are preferentially developed in competent lithologies, such as the granophyric facies of the differentiated gabbro sill hosting the San Antonio deposit. Other types of hydrothermal breccias also occur along shear veins: they include "jigsaw-puzzle" breccias, characterized by angular fragments of altered wall rock in a fine grained matrix of quartz and/or tourmaline, and by fault breccias, composed of crushed and rotated vein and wall rock fragments in a dominantly hydrothermal matrix.

Veins associated with folds

Veins associated with folds probably represent the least common structural setting of quartz-carbonate veins. Veins in such settings occur almost exclusively in folded clastic sedimentary rocks, in either volcano-plutonic or clastic sedimentary terranes.

Quartz-carbonate veins are associated with folds ranging from those of regional scale, as in the Meguma terrane (Fig. 15.2-3), to deposit-scale asymmetric folds, as in the MacLeod-Cockshutt deposit (Fig. 15.2-8). Veins display diverse geometric and age relationships to the folds. They may be folded along with their host rocks, as in the case of bedding-parallel veins in the Meguma terrane (Fig. 15.2-10D), which occur in anticlinal hinge areas where they are typically stacked and saddle-shaped (Fig. 15.2-7). Veins may also be syn- to late folding and be either parallel to axial plane cleavage in hinge zones, as at MacLeod-Cockshutt (Fig. 15.2-8), or in extensional veins perpendicular to fold axes (AC joints), as is the case in the Cariboo district (Sutherland-Brown, 1957). In other cases, laminated quartz veins occur in fractures and faults cutting obliquely across fold axial surfaces as at the Lupin deposit (Lhotka and Nesbitt, 1989) and in the Sheep Creek district (Matthews, 1953).

Ore and gangue mineralogy

Ore mineralogy

In most quartz-carbonate vein deposits, as at Sigma-Lamaque, gold mineralization occurs in both the veins and the adjacent altered wall rocks, in varying proportions. The bulk of the gold occurs within the veins in turbidite-hosted deposits but within altered wall rocks in iron-formation-hosted deposits. In most cases, gold is intimately associated with sulphide minerals, both in the veins and altered wall rocks. The dominant sulphide mineral is pyrite, or arsenopyrite in sediment-hosted deposits, commonly accompanied by variable, but minor amounts of sphalerite, chalcopyrite, pyrrhotite, and galena. Trace amounts of molybdenite are also present in a number of deposits. The sulphide contents of the veins rarely exceed 5 volume per cent; within laminated veins, sulphide minerals are commonly distributed along thin, altered wall rock slivers, which thus indirectly control the distribution of gold within the veins.

The main ore mineral in most deposits is native gold, which typically contains some silver. Gold-to-silver ratios of the ore range from 5:1 to more than 9:1, and cluster around a ratio of ~9:1, distinct from that of most epithermal veins (see Introduction, "Lode gold"). Gold typically occurs as coatings on, or as inclusions and fracture-fillings within, sulphide grains, as well as isolated grains and fracture fillings in quartz. Other significant ore minerals in quartz-carbonate veins are tellurides, mostly petzite and

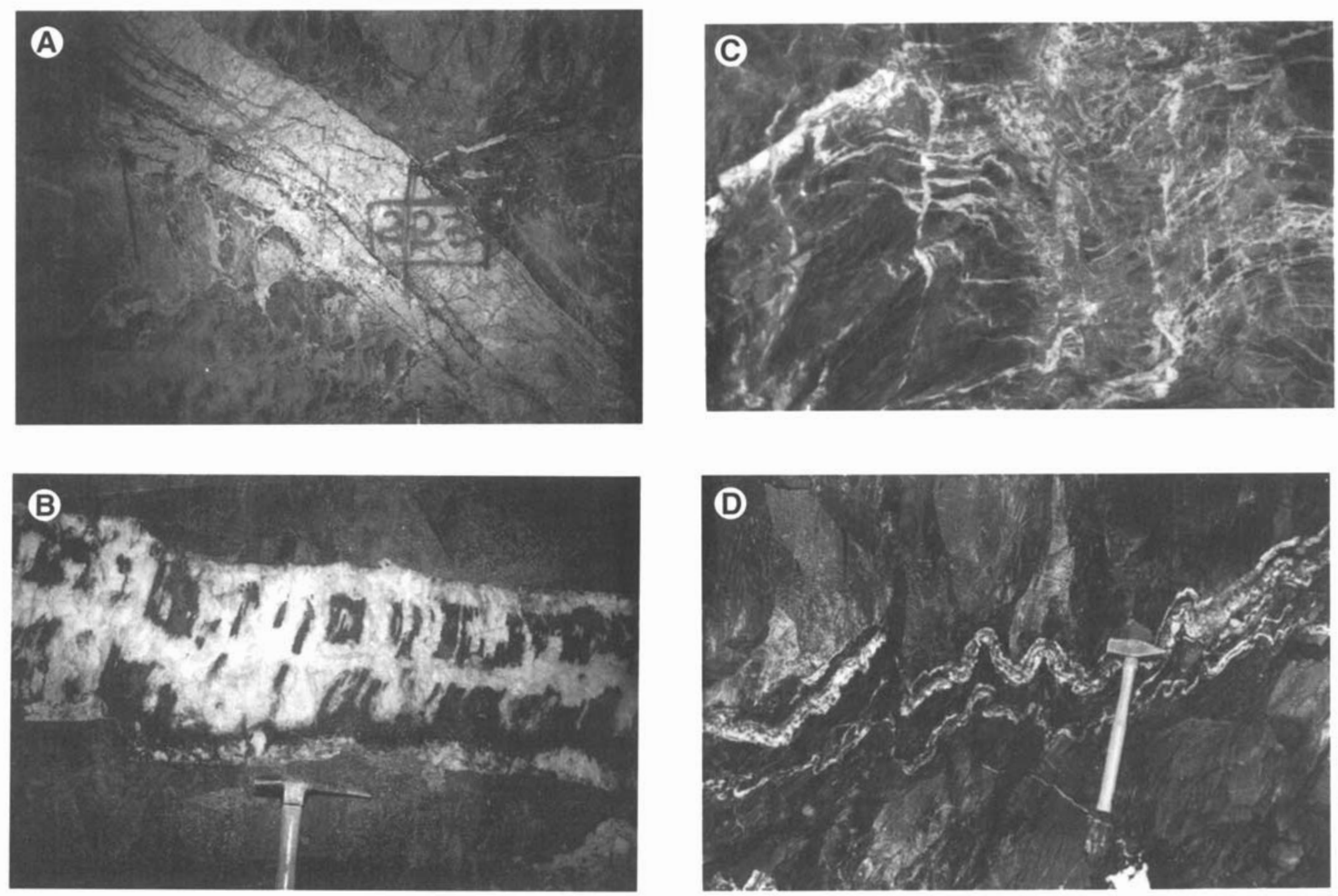

Figure 15.2-10. Photographs of typical quartz-carbonate vein features.

A) Shear zone-hosted laminated shear vein; Lucien Béliveau deposit, Val d'Or district. The fine dark laminae within the vein, marked by tourmaline, are slip surfaces. Field of view ~5 m. Photo by F. Robert. GSC 1994-398

B) Subhorizontal quartz (white)-tourmaline (black) extensional vein; Sigma mine, Val d'Or, Quebec. Subvertical tourmaline fibres are cut by a quartz-rich ribbon in the center of the vein, indicating repeated opening episodes. Hammer for scale. Photo by F. Robert. GSC 1994-399

C) Stockwork from the San Antonio mine, Bissett, Manitoba, consisting of shallowly dipping sigmoidal veins and subvertical veins. Due to increasing vein abundance towards its core, the stockwork grades into a hydrothermal breccia. Field of view ~2 m. Photo by K.H. Poulsen. GSC 1995-024

D) Folded veins in slate at their contact with overlying greywacke on the crest of an anticline, Tangier district, Meguma terrane. Hammer for scale. Photo by A.L. Sangster. GSC 204390-S calaverite, which are particularly abundant in deposits associated with felsic stocks such as Macassa (Thompson et al., 1950) and Sigma-Lamaque (Robert and Brown, 1986b).

Gangue mineralogy

The most common gangue minerals in the vein deposits considered here are quartz and carbonate. Quartz typically accounts for more than 85% of the vein fillings. Carbonates, including calcite, dolomite, or ankerite in various combinations, typically comprise less than 10-15% of the vein fillings. Veins at the Campbell Red Lake deposit, which are dominated by dolomite and ferro-dolomite, represent a notable exception (Andrews et al., 1986). Other generally minor constituents of the veins include albite, chlorite, and white mica. Tourmaline and scheelite are also present in minor amounts in many quartz-carbonate veins. Tourmaline is particularly abundant in veins in the Val d'Or district, where it may represent up to 15-20 volume per cent of the vein fillings (Robert and Brown, 1986b).

Host rock composition exerts some influence on the accessory gangue mineralogy of the veins. Arsenopyrite rather than pyrite is the dominant vein and altered wall rock sulphide mineral in deposits hosted by sedimentary rocks, such as Lupin and those of the Meguma terrane. The composition of carbonate minerals in the veins also reflects that of the host lithology: the Fe and Mg contents of Ca-carbonates increase proportionally with the Fe and Mg contents of the host rocks. Fuschite normally occurs in veins which are in the vicinity of altered ultramafic rocks.

Quartz-carbonate vein deposits typically lack vertical mineralogical zoning, despite their significant vertical extent. A notable exception is the Sigma-Lamaque deposit, in which the tourmaline-pyrite assemblage gives way in some veins to a pyrrhotite-chlorite-biotite assemblage at depths in excess of 1.6 km (Robert and Brown, 1986b). In general, pyrite is the dominant sulphide mineral in deposits hosted by greenschist grade rocks, whereas pyrrhotite dominates in deposits hosted by amphibolite grade rocks (Colvine, 1989).

Hydrothermal alteration

Wall rock hydrothermal alteration around auriferous quartz-carbonate veins varies in scale, intensity, and mineralogy as a function of host rock composition. Several fundamental types of alteration can be distinguished and these generally combine to form zoned alteration haloes at the vein or the deposit scales. In most documented cases, alteration assemblages have been superimposed on previously metamorphosed rocks, as is the case at Bralorne-Pioneer (Leitch, 1990) and at Sigma-Lamaque (Robert and Brown, 1986b). Two documented exceptions include the Campbell Red Lake and adjoining A.H. White (Dickenson) deposits, where wall rock alteration either predated or was synchronous with amphibolite grade metamorphism (Andrews et al., 1986), and the Eastmain River deposit in northern Quebec, where wall rock alteration is interpreted to have taken place during amphibolite grade metamorphism (Couture and Guha, 1990).

Alteration types

The main types of alteration around quartz-carbonate veins include carbonatization, sulphidation, alkali metasomatism, chloritization, and silicification (Boyle, 1979). Carbonatization is the most common and most extensive type of alteration. Zones of carbonate alteration around individual veins and structures commonly coalesce to envelope the entire orebody. This type of alteration involves progressive replacement of Ca-, Fe-, and Mg-silicates by carbonate minerals and is characterized by additions of CO_2, accompanied by release of Al and Si, fixed in other alteration minerals or in veins. The amounts of introduced carbonates depend, in part, on the amount of Ca, Fe, and Mg present in the host lithology.

Sulphidation of wall rocks is common around veins and, in most cases, is restricted to their immediate proximity. Pyrite is the most common sulphide, followed by pyrrhotite, mostly present in amphibolite grade rocks. Arsenopyrite is also common around veins hosted by clastic sedimentary rocks. Sulphides generally comprise less than 10% of the altered rocks, except in oxide facies iron-formation, in which they make up as much as 75% of the altered rocks, as at McLeod-Cockshutt (Horwood and Pye, 1955).

Sodium and potassium metasomatism is observed in proximity to most quartz-carbonate veins. Potassium metasomatism is the most common and typically consists of sericitization of chlorite and plagioclase; fuchsite, rather than sericite, is generally present in altered ultramafic rocks, and K-feldspar and biotite are alteration products in a few deposits. Sodium metasomatism results largely in the formation of albite, and in some cases of paragonite. Chloritization of amphibole, biotite, and pyroxene (at constant Fe and Mg), commonly accompanies incipient carbonatization. In some deposits, intense chloritization may be accompanied by addition of Fe and Mg to the rock. A distinction should be made between hydrothermal chlorite considered here and chlorite produced by metamorphism of the host rocks. Silicification, sensu stricto, i.e. the addition of silica, has been documented mostly in clastic sedimentary rocks (Boyle, 1979). A more common form of silicification in mafic and ultramafic host rocks, due to silica release from carbonatization reactions, is a local increase in the abundance of quartz, either as quartz-flooding of the rock matrix or as abundant quartz veinlets.

Gold is commonly enriched in intensely altered rocks adjacent to quartz-carbonate veins. In many cases, as at Sigma, these altered zones reach economic grades (Robert and Brown, 1986b). In fact, a significant proportion of the extracted gold in several deposits is derived from altered rocks adjacent to veins.

Alteration zoning patterns

The above different types of alteration commonly combine to form zoned alteration envelopes around veins or deposits (Roberts, 1987). The resulting zoning patterns, summarized in Table 15.2-3, result largely from progressive carbonatization of wall rocks and accompanying alkali metasomatism.

Table 15.2-3. Idealized alteration zoning patterns (from least to most altered assemblages) around quartz-carbonate veins and deposits in igneous host rocks of different compositions. Note that not all zones are necessarily present around a given vein. Adapted from Roberts (1987).

rock composition	alteration zone	serpentine	talc	amphibole	epidote	chlorite	albite	quartz	sericite	calcite	dolomite	pyrite
ultramafic	unaltered[1]	X	X	X		X						
	chloritic[1]		X			X	X	X			X	
	chloritic[2]					X	X	X			X	
	carbonate[1]						X	X	X		X[2]	X
	carbonate[2]						X	X			X[2]	X
mafic	unaltered			X	X	X	X	X				
	chloritic					X	X	X		X		
	carbonate[1]						X	X	X		X[3]	X
	carbonate[2]						X	X			X[3]	X
Intermediate	unaltered			X	X	X	X	X	X			
	chloritic					X	X	X	X	X		
	carbonate[1]						X	X	X		X[3]	X
	carbonate[2]						X	X			X[3]	X

[1] Mineral assemblages of unaltered rocks are taken here as the most commonly observed greenschist assemblages.
[2] Siderite and magnesite may also be present.
[3] Ferroan dolomite and ankerite are the dominant carbonate minerals in most cases.

In igneous wall rocks of ultramafic to intermediate composition, outer alteration zones are characterized by replacement of metamorphic amphibole, epidote, and/or serpentine by calcite±dolomite and chlorite; those minerals are accompanied by talc±tremolite in ultramafic rocks and albite in mafic to intermediate rocks (Table 15.2-3). With increasing intensity of alteration and proximity to veins, chlorite-calcite assemblages are replaced by dolomite-white mica assemblages with or without pyrite. Inner alteration assemblages consist of ankerite-albite-pyrite assemblages; magnesite and siderite are also present in Mg- and Fe-rich igneous host rocks. In general, the iron content of carbonate minerals increases towards the mineralized zones.

Veins in clastic sedimentary rocks typically lack well defined alteration envelopes. Where present, they tend to be narrow and are characterized by replacement of chlorite and biotite by carbonates, white mica, and albite, and by formation of arsenopyrite. Where veins intersect iron-formation, the alteration is typically controlled by bedding and laminations: for example, layers of magnetite are selectively altered and replaced by sulphides, generally pyrite, over distances as great as several decimetres on either side of a vein.

DEFINITIVE CHARACTERISTICS

Quartz-carbonate vein gold deposits consist of simple to complex vein and shear zone networks with significant vertical extents, hosted by rocks in deformed volcano-plutonic terranes, and less commonly in deformed clastic sedimentary terranes. The deposits occur in districts spatially associated with large-scale fault zones. The veins occupy shear zones, faults, stockwork zones, and extensional fractures, or are associated with folds: they are generally discordant, at least in part, to lithological units. The veins are composed mainly of quartz, with less abundant carbonate and pyrite. Commonly associated minerals include tourmaline, scheelite, fuchsite, and arsenopyrite. Hydrothermal alteration of wall rocks is dominated by carbonatization, and accompanied by alkali metasomatism and sulphidation of the rocks immediately adjacent to the veins.

GENETIC MODELS

In contrast to many other deposit types, there is no real consensus on the origin of quartz-carbonate veins in deformed terranes and, as a result, a number of genetic models have been proposed for their formation (Roberts, 1987; Kerrich, 1989). Studies of fluid inclusions and hydrothermal alteration in several deposits point to a relatively uniform fluid composition and temperature, irrespective of their occurrence in volcano-plutonic or clastic sedimentary terranes (Kerrich and Wyman, 1990). The auriferous fluids are typically CO_2-bearing (5-15 mol % CO_2±CH_4), low-salinity fluids, at 300-350°C, which underwent phase separation in a number of deposits. Differences between districts in the Sr, Pb, C, and O isotope compositions of the auriferous fluids contrast with the relatively uniform bulk fluid composition and indicate multiple source regions for these fluid components, including sources external to, and underneath, the host supracrustal sequences (Kerrich, 1989). However, such isotopic tracers do not allow unequivocal discrimination of the nature and origin of the fluids.

Among all the genetic models proposed for quartz-carbonate veins, the orthomagmatic model has historically been the most commonly advocated (e.g., Emmons, 1937). According to this model, gold and the hydrothermal fluids are derived from ascending felsic magmas generated during tectonism and metamorphism. A variation on this model involves derivation of the gold from the host supracrustal sequences by their interaction with the magma and associated hydrothermal fluids.

In the last two decades, a number of fluid-source models, based largely on fluid inclusion and isotopic tracer studies, have also been proposed and reviewed by Roberts (1987), Kerrich (1989), and others. In the metamorphic model, gold is considered to be leached from the underlying supracrustal rocks by a metamorphic fluid released during prograde metamorphism and focused into shear zones and related dilational zones. A variation on this model has been suggested by Graves and Zentilli (1982) for the origin of the folded veins of the Meguma terrane by which pore fluids, released by greenschist metamorphism during incipient folding and cleavage development, induced hydraulic fracturing and transported locally-derived gold and other vein constituents into these fractures. Nesbitt and Muehlenbachs (1989) developed a model involving deep circulation of meteoric waters in the vicinity of major fault zones for quartz-carbonate vein deposits of the Canadian Cordillera. In the mantle degassing/granulitization model, upward streaming of mantle-derived CO_2 is thought to induce dehydration and granulitization of the lower crust, possibly accompanied by magma generation; the resulting H_2O-CO_2 fluids, leaching gold from the lower crust, rise to higher crustal levels along major shear zones, where gold and other components are deposited.

In light of the recent recognition that many quartz-carbonate vein gold districts occur at transpressive accretionary plate margins, many authors relate the formation of these deposits to accretionary processes (e.g. Kerrich and Wyman, 1990). In this model, fluids are generated by thermal re-equilibration and metamorphism of subducted material following cessation of subduction. Such deep fluids, which may dissolve gold and other vein components anywhere along their path, are thought to be channelled upwards along crustal-scale faults.

RELATED DEPOSIT TYPES

A number of gold deposits that are primarily of quartz-carbonate vein type, contain orebodies typical of the disseminated-replacement subtype of gold deposits (see subtype 15.4), which suggests a possible genetic link between the two subtypes. In the Cariboo district, for example, both quartz-carbonate veins and pyrite replacement (manto) orebodies in limestone were mined (Sutherland-Brown, 1957); the Campbell Red Lake-Dickenson deposit, apart from more abundant quartz-carbonate vein orebodies, also includes sulphidic orebodies of the East South "C" type (Andrews et al., 1986). In the Cariboo district, quartz-carbonate veins clearly overprint pre-existing pyrite replacement orebodies (Robert and Taylor, 1990) and the two styles of ore are not related to the same hydrothermal event. However, in most hybrid gold deposits, the temporal and possible genetic relationships between different styles of orebodies are not clearly established.

A similar problem exists for iron-formation-hosted gold deposits of the stratiform type (see subtype 15.3): the relationships are not clearly established between finely disseminated gold in cherty sulphide-banded iron-formation and quartz-carbonate veins, with which at least some gold is spatially associated. In contrast, iron-formation-hosted gold deposits of the nonstratiform type simply represent a subset of the quartz-carbonate vein deposits considered here.

EXPLORATION GUIDELINES

Because quartz-carbonate vein gold deposits are typically sulphide-poor deposits, geophysical methods commonly fail to reveal their presence. As a result, exploration must be based heavily on geological criteria, as reviewed by Hodgson et al. (1982).

At the regional scale, portions of volcano-plutonic terranes containing significant volumes of mafic volcanic rocks and a major fault zone, especially along terrane boundaries, should be considered favourable. At the district- and mining property-scale, exploration should focus on shear zones and faults subsidiary to, and distributed around, major fault zones. Emphasis should be placed on segments of shear zones intersecting or following favourable host rocks such as small felsic intrusions and dykes, iron-formations, and iron-rich igneous rocks. Favourable segments of shear zones could also be selected on the basis of splays or deflections of the overall trend of the shear zone and, in mafic to ultramafic lithologies, on the basis of mapping the distribution of the different carbonate minerals along carbonatized shear zones and units, using simple mineral staining techniques.

Geophysical methods can be used directly, for example to identify shear zones and faults, or indirectly for selection of favorable target areas. For example, the abrupt loss of magnetic signature along a magnetic unit, such as iron-formation, serpentinized ultramafic rock, or iron-rich gabbro, may indicate the presence of a zone of carbonatization or sulphidation related to gold mineralization.

In glaciated areas such as the Canadian Shield, heavy mineral concentrates in basal till, as well as surficial till geochemistry, can be used to outline mineralized areas along major shear zones (DiLabio, 1982).

ACKNOWLEDGMENTS

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15.3 IRON-FORMATION-HOSTED STRATABOUND GOLD

J.A. Kerswill

INTRODUCTION

Gold deposits hosted by iron-formation are characterized by: (1) a close association between native gold and iron sulphide minerals; (2) the presence of gold-bearing quartz veins and/or shear zones; (3) structural complexity of the host terranes; and (4) paucity of lead and zinc in the ores. Two principal varieties of iron-formation-hosted gold deposits can be defined, based on the dominant style of gold distribution (Kerswill, 1986, 1993): stratiform and non-stratiform (or vein type). Some deposits have characteristics of both varieties and thus have a hybrid character.

In the vein-type deposits, gold hosted by iron-formation is restricted to late structures (quartz veins and/or shear zones) and/or iron sulphide-rich zones adjacent to such structures. Ore is confined to discrete, commonly small shoots separated by barren (gold- and sulphide-poor) iron-formation, typically of oxide facies. These nonstratiform ores are essentially a variety of the mesothermal quartz-carbonate vein deposits that are described elsewhere (see subtype 15.2).

Deposits of the stratiform-type can be subdivided into those occurring within sediment-dominated settings and those within mixed volcanic-sedimentary settings. In the former, gold is uniformly disseminated in thin, but laterally extensive units of cherty pyrrhotite-rich iron-formation that are conformably interlayered with sulphide- and oxide-poor iron-formation and pelitic sedimentary rocks in portions of turbidite basins relatively distant from felsic volcanic centers. In the deposits within mixed settings, gold is uniformly disseminated in thin, but laterally extensive units of cherty sulphide-iron-formation that are associated with carbonate-iron-formation and black carbonaceous shale relatively close to volcanic centres.

Gold is the principal commodity in all deposits and occurs in the free native form. Silver is recovered with the gold from all deposits, but the gold:silver ratio is variable (see below).

Examples of vein-type deposits include: the North ore zone of the Hard Rock and MacLeod-Cockshutt properties in the Geraldton camp, Ontario (Horwood and Pye, 1951; Macdonald and Fyon, 1986); the Central Patricia mine and portions of the Pickle Crow mine near Pickle Lake, Ontario (Thomson, 1938); the Cullaton Lake B-zone in the Northwest Territories (Page, 1981; Sethu Raman et al., 1986; Miller, 1992); a number of deposits in Western Australia, including the Hill 50, Nevoria, and Water Tank Hill mines (Phillips et al., 1984); several deposits in Zimbabwe, including the Lennox mine (Foster, 1989); and probably the São Bento mine in Brazil (Mosley and Hofmeyr, 1986). Recently discovered iron-formation-hosted gold deposits in the George Lake (Olson, 1989; Chandler and Holmberg, 1990; Padgham, 1990) and Meliadine (Miller et al., 1993) areas of the Northwest Territories also appear to be vein type.

Important examples of the sediment-hosted stratiform-type deposits include: the Lupin mine, Northwest Territories (Gardiner, 1986; Kerswill, 1986; Lhotka, 1988; Bullis, 1990), the Jardine deposit, Montana, U.S.A. (Hallager, 1984; Cuthill et al., 1990), and probably the Homestake mine, South Dakota, U.S.A. (Nelson, 1986; Caddey et al., 1991). Iron-formation-hosted gold mineralization in the Russell Lake area (Bunner, 1988), Northwest Territories, also appears to be of this type.

Examples of stratiform deposits in mixed volcanic-sedimentary settings include the Morro Velho (Ladeira, 1980; Vieira et al., 1991b) and Cuiabá (Vial, 1988; Vieira et al., 1991a) mines in Brazil, and the Agnico-Eagle mine in Quebec (Barnett et al., 1982; Wyman et al., 1986; Dubé et al., 1991).

Several Canadian deposits have characteristics of both the vein and stratiform subtypes. These include the Wedge Lake deposit in the La Ronge Domain, Saskatchewan (Netolitsky, 1986) and the Musselwhite (Hall and Rigg, 1986) and Dona Lake deposits in Ontario (Cohoon, 1986). However, these appear to be dominantly vein type.

IMPORTANCE

Combined total world-wide production and reserves for all iron-formation-hosted gold deposits exceed 3000 t. Much of the production has come from a few world-class deposits.

Nine significant Canadian deposits (Table 15.3-1) within this class account for about 220 t of contained gold (production plus reserves) or about 5% of the lode gold category. Deposits of the vein-type have not been large producers in Canada. Central Patricia produced more than 19 t gold and the North ore zone at Geraldton produced more than 15 t gold. However, at the global scale (Fig. 15.3-1), Hill 50 and São Bento can be considered major deposits.

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[1] *Editorial note:* Within this volume, in a companion account of quartz-carbonate vein gold deposits (subtype 15.2), Lupin is presented as an example of a quartz-carbonate vein gold deposit and has been interpreted as epigenetic.

Contents

Table 15.3-1. Grades and tonnages of selected Canadian iron-formation-hosted gold deposits.

Deposit	Type	Tonnage (t)	Grade (g/t)	Contained gold (t)	Au:Ag
Central Patricia	Vein	1 568 780	12.34	19.30	10.7
Cullaton B-zone	Vein	321 870	17.14	5.50	14.1
North ore zone, Geraldton	Vein	3 175 200	5.14	16.20	29.9
Pickle Crow	Vein	199 580	17.14	3.40	8.6
Agnico-Eagle (Joutel)	Stratiform	4 031 780	6.51	25.50	5.0
Lupin	Stratiform	9 080 000	10.75	97.58	6.2
Dona Lake	Hybrid	1 179 360	9.26	10.90	??
Musselwhite	Hybrid	4 200 000	9.60	40.32	9.1
Wedge Lake	Hybrid	544 320	6.17	3.40	??
?? = unknown					

The Lupin mine, a stratiform deposit, is one of Canada's largest gold producers and has an average annual production of about 6 t. The Homestake mine is one of the largest gold producers in the world, and its total gold production since 1876 has been in excess of 1100 t gold. Indeed, production at the Homestake mine in 1993 was 13 t, (447 600 ounces), its highest annual output since 1971. Morro Velho is the largest lode deposit in South America and has produced more than 310 t gold since 1834.

SIZE AND GRADE OF DEPOSITS

Tonnage and grade figures for nine Canadian deposits are presented in Table 15.3-1 and selected deposits are plotted in Figure 15.3-1. It is noteworthy that Lupin and Agnico-Eagle, the only stratiform deposits and the only deposits currently in production, contribute more than half the total contained gold in Canadian banded iron-formation-hosted deposits.

GEOLOGICAL FEATURES

All iron-formation-hosted deposits are characterized by a strong association between native gold and iron sulphide minerals, the presence of gold-bearing quartz veins, the occurrence of deposits in structurally complex terranes, and lack of lead and zinc enrichment in the ores.

Vein-type deposits

Gold in vein-type deposits is restricted to late structures or to sulphide-iron-formation adjacent to the veins and/or shear zones. The ores occur in either sediment- or volcanic-dominated portions of greenstone belt terranes. All deposits are structurally controlled, occurring particularly in fold hinges (Fig. 15.3-2A), and most are hosted by rocks of relatively low metamorphic grade. Oxide-iron-formation is the dominant type of iron-formation associated with gold. Pyrite and/or pyrrhotite clearly replace other pre-existing iron-rich minerals (Fig. 15.3-3A). Arsenic-bearing minerals are common, but not always present; where they are present, a strong positive correlation generally exists between gold and arsenic. Ores are relatively silver-poor with gold:silver ratios characteristically greater than 8.0 (Table 15.3-1). Intrusions of feldspar porphyry are spatially associated with a number of the deposits and may contain shear- or vein-related mineralization similar in style to that hosted by the nearby banded iron-formation (Fig. 15.3-2A).

Stratiform-type deposits

Setting

In sediment-hosted stratiform deposits such as Lupin, Jardine, and Homestake, gold is restricted to Algoma sulphide-iron-formation occurring within portions of greenstone terranes dominated by clastic sedimentary rocks (mostly turbidites) or, locally, to quartz veins that crosscut such banded iron-formation. Pelitic sedimentary rocks are commonly interbedded with the gold-bearing sulphide-iron-formation. Clearly identifiable products of volcanism do not occur within the orebodies, but volcanic rocks are typically interbedded with basinal clastic sedimentary rocks at the regional scale.

The sedimentary rocks that host these deposits are typically deformed, with at least local domains characterized by tight to isoclinal folding. Several generations of folds have been recognized, but major regional scale faults ("breaks") similar to those associated with many vein-type deposits have yet to be identified near the deposits.

Granitoid bodies of variable size and age have intruded the supracrustal rocks near deposits of this type. A locally pegmatitic tourmaline-bearing peraluminous two-mica granite occurs within the late Archean Contwoyto batholith to the north of Lupin. Quartz-feldspar porphyry intrusions have not been recognized at Lupin or Jardine, although Tertiary dykes, sills, and local breccias are abundant at Homestake.

Metamorphic grade at these deposits ranges from middle greenschist to lower amphibolite facies. Homestake is well within greenschist facies (staurolite-bearing clastic metasedimentary rocks, i.e., knotted schists, diagnostic of amphibolite facies metamorphism, occur several kilometres northeast of the mine). Jardine is upper greenschist grade, and Lupin occurs at the greenschist to amphibolite grade transition.

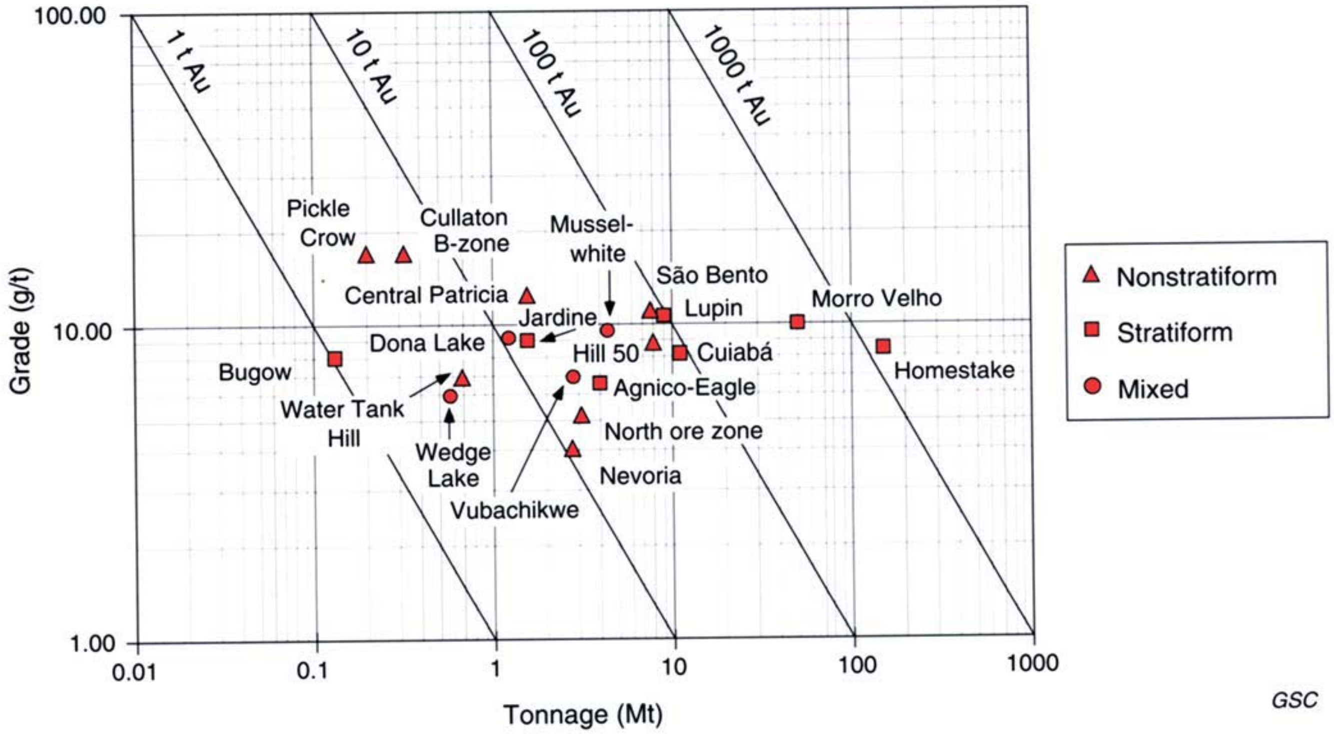


Figure 15.3-1. Grade-tonnage diagram for selected iron-formation-hosted gold deposits.

In deposits in mixed volcanic-sedimentary settings, gold occurs in pyritic sulphide-iron-formation that is associated with felsic pyroclastic rocks in the upper portions of volcanic cycles (Agnico-Eagle and Cuibá) or in pyrrhotite-rich sulphide-iron-formation interbedded with lapa seca (banded to massive quartz-carbonate rock) and rhyolitic tuff in a pelite-dominated environment (Morro Velho). Carbonate-iron-formation, other carbonate-bearing lithologies, and carbonaceous shales occur within the mine sequences. Metamorphic grade is lower greenschist at all three deposits.

Age of host rocks and mineralization

The supracrustal rocks that host the iron-formation at Lupin, Jardine, Morro Velho, Cuibá, and Agnico-Eagle are late Archean (2.6-2.8 Ga.), but Homestake occurs in rocks of Proterozoic age (1.9-2.1 Ga.; DeWitt et al., 1986; Redden et al., 1987).

Structure

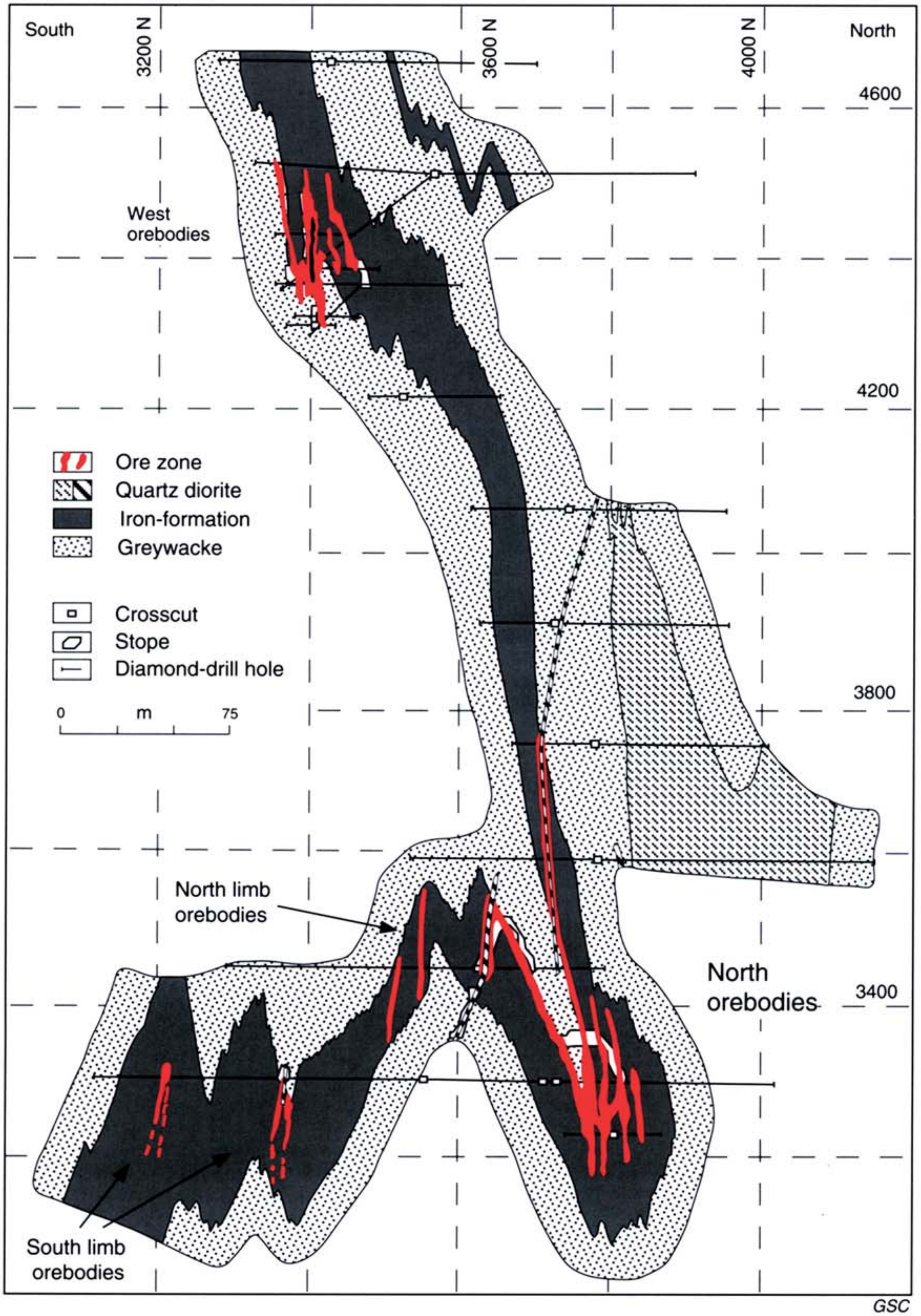
The rocks that host the stratiform deposits, as well as the orebodies themselves, are deformed, principally by folding. In the Homestake mine area two principal sets of folds have been recognized regionally (Dewitt et al, 1986). Early northeast-trending isoclinal folds were refolded by northwest-trending isoclinal folds. At the mine itself, Caddey et al. (1991) identified two major deformational events which include six periods of folding. Early F_{1b} open to isoclinal folds that trend northwesterly and plunge southeasterly overprint late F_{1a} sheath folds of similar trend and plunge. At Lupin, the ore is confined to a tightly folded Z-shaped portion (Fig. 15.3-2B) of a larger doubly-plunging structure that was produced by two generations of folding (Relf, 1989). Three periods of deformation have been identified in the Jardine area; an early period of isoclinal folding was followed by northwest-trending and northeast-trending folding events. Caddey et al. (1991) have identified an anastomosing set of late shear zones (middle D_{1b}) in the Homestake mine which were synchronous with retrogressive metamorphism and emplacement of gold-bearing quartz veins. Auriferous quartz veins in other stratiform deposits are also related to later stages of deformation.

Orebodies

Deposits are stratiform by definition, but in all cases, particularly at Homestake, the original geometry of orebodies has been obscured by folding. However, lateral or down-plunge extents of orebodies are tens to hundreds of times greater than their thicknesses.

In both sediment-hosted deposits and those occurring within mixed volcanic-sedimentary settings, gold is concentrated in several discrete units of sulphide-iron-formation that are conformably interlayered with barren silicate-and/or carbonate-iron-formation (Fig. 15.3-3B). Gold is, for the most part, relatively uniformly disseminated throughout the sulphide-iron-formation of individual orebodies, although the late quartz veins contain modest amounts of coarse (visible) gold. Arsenic is a significant component in all sediment-hosted deposits (Fig. 15.3-3C) except those in the Russell Lake area (Bunner, 1988), but is less common in deposits in mixed settings. Indeed, it is possible to identify two principal types of ore in sediment-hosted stratiform deposits on the basis of arsenic content.

A


South
North
3200 N
3600 N
4000 N
4600
4200
3800
3400
West orebodies
Ore zone
Quartz diorite
Iron-formation
Greywacke
Crosscut
Stope
Diamond-drill hole
0
m
75
North limb orebodies
North orebodies
South limb orebodies
GSC

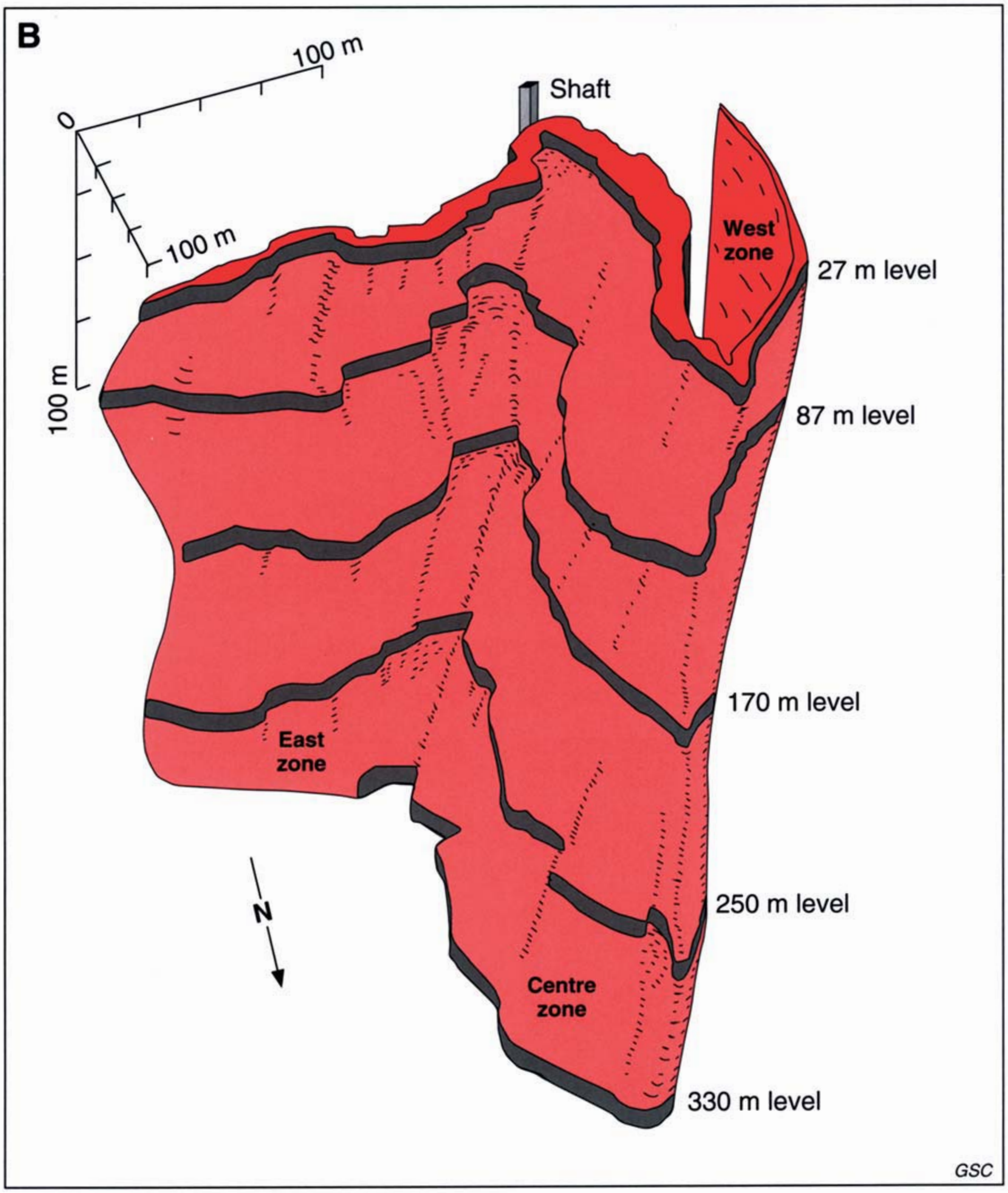
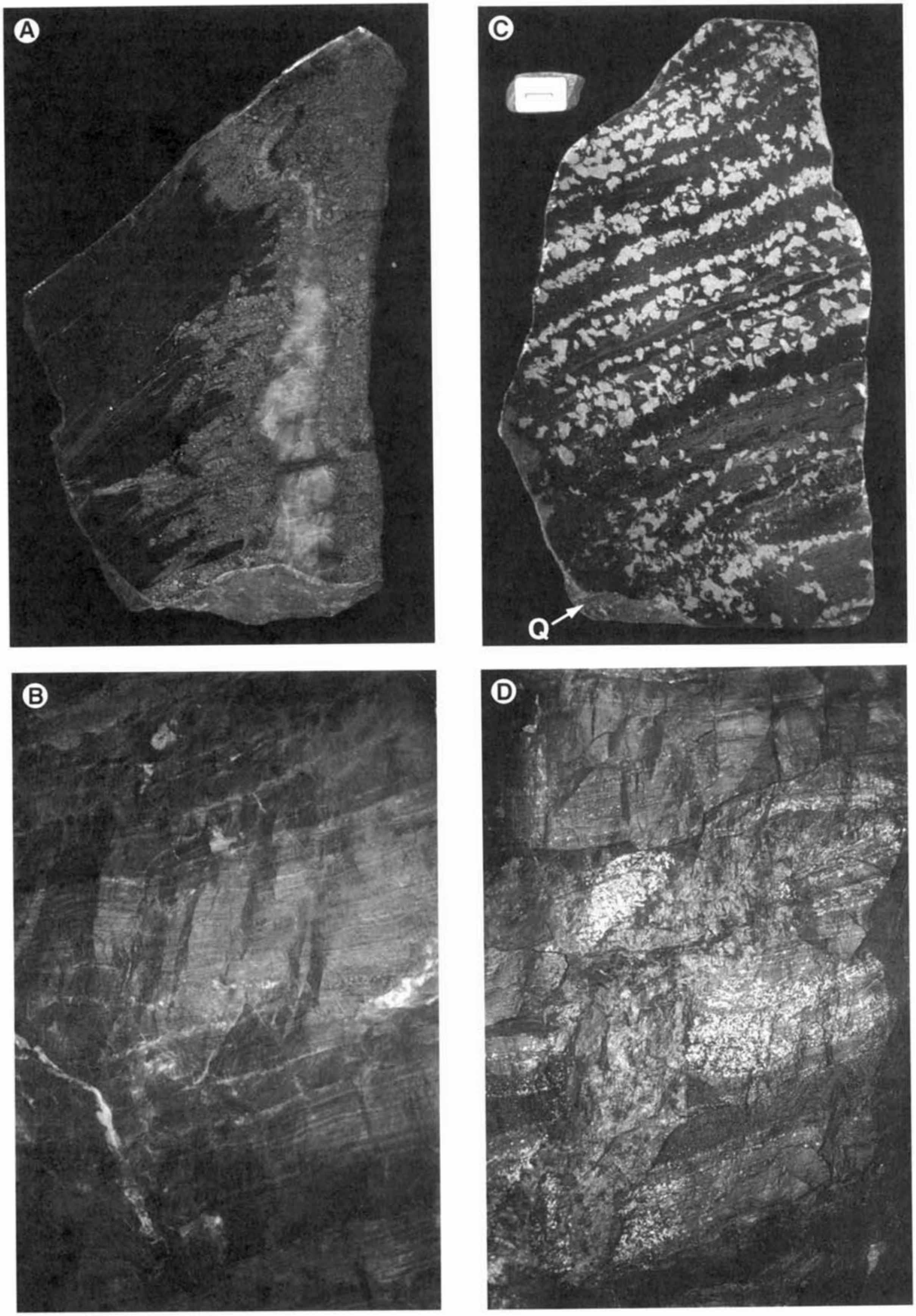


Figure 15.3-2. A) Vertical north-south section along 17400E, MacLeod-Cockshutt mine showing the distribution of several ore zones, including the North ore zone (after Horwood and Pye, 1951). The nonstratiform ore is confined to structurally controlled sulphide-rich shoots that are separated by much barren oxide-iron-formation. **B)** Lupin orebody, Northwest Territories; isometric view of upper levels as defined by assay data using a cutoff grade of 6.86 g/t or 0.2 troy oz./ton (after the 1982 Annual Report of Echo Bay Mines Ltd.). The continuity of gold distribution is one of the most remarkable features of the Lupin deposit and is a critical constraint in modelling genesis. The strike extent of the stratiform orebody exceeds 800 m. Ore reserves defined at the end of 1990 extended to a depth of greater than 1000 m. Average width of the orebody varies from about 2.5 m in the West zone to greater than 20 m in fold-thickened portions of the Centre zone. The average width of ore in the Centre zone is about 10 m.


A
B
C
D
Q

Arsenic-rich sulphide-iron-formation occurs in areas immediately adjacent to late quartz veins or shear zones at Lupin (Fig. 15.3-3D) and Homestake (Caddey et al., 1991), and appears to be similarly controlled at Jardine (Seager, 1944). Arsenic-poor sulphide-iron-formation is more widely distributed and is the principal ore type in all deposits.

At the Homestake mine, production has come from nine elongate zones or "ledges" confined to the Homestake Formation, and each zone contains a large number of discrete orebodies. Sulphide-iron-formation that forms these orebodies constitutes approximately 3% of the total volume of the Homestake Formation. The Lupin mine occurs within the Lupin ore unit and, in at least the upper portions of the deposit, can be viewed as a single orebody with mineralization essentially continuous throughout the deposit (Fig. 15.3-2B). The limits of the Lupin orebody coincide with a marked decrease in the proportion of auriferous sulphide-iron-formation relative to barren silicate-iron-formation and clastic sedimentary rocks in the ore unit.

Although stratiform orebodies are tightly to isoclinally folded and quartz veins are locally abundant, the distributions of gold and sulphur are not obviously controlled by either the folds or the veins. At Lupin, the arsenic-rich sulphide-iron-formation adjacent to late quartz veins does not consistently contain more gold or sulphur than arsenic-poor sulphide-iron-formation further from the veins. Furthermore, in much of the deposit, mesobands of consistently auriferous pyrrhotite-rich iron-formation can be traced around fold hinges and along fold limbs without significant changes in thickness or sulphur or gold contents for tens of metres. Such mesobands are clearly not restricted to the vicinity of quartz veins or to areas of closely spaced quartz veins. The spacing between quartz veins in the Lupin orebody varies from less than one metre to greater that 10 m and averages about 4 m.

Figure 15.3-3. A) Replacement of oxide iron-formation by sulphide minerals, principally pyrite, adjacent to late quartz vein, Solomons Pillars property, Geraldton area (Colvine et al., 1988, photograph by J. Macdonald). GSC 203652-I **B)** Sulphide-rich iron-formation at Lupin: underground photograph illustrating stratiform character of arsenic-poor variety of sulphide-iron-formation. Note alternating units of pyrrhotite-rich sulphide-iron-formation (gold-bearing) (light grey-white, banded), garnetiferous silicate-banded iron-formation (barren) (dark grey, banded), and pelitic sedimentary rock (barren) (dark grey, massive). Individual units of sulphide-iron-formation can be followed for tens of metres without significant change in thickness, sulphide content, or gold content. Dimensions of the photographed area approximately 2 m by 3 m. GSC 1993-170H **C)** Arsenic- and pyrrhotite-rich variety of sulphide-iron-formation at Lupin, occurring immediately adjacent to a late quartz vein (Q). Note megacrysts of arsenopyrite-löllingite-pyrrhotite that appear to overgrow banded pyrrhotite. Scale bar adjacent to the polished slab is one centimetre. GSC 1995-025 **D)** Arsenic-poor and arsenic-rich varieties of sulphide-banded iron-formation at Lupin (underground photograph). Note restriction of arsenic-rich ore to zones immediately adjacent to a late quartz vein and the decrease in both the abundance and size of the arsenic-bearing megacrysts with distance from the vein. The dimensions of the photographed area approximately 2 m by 3 m. GSC 1993-170I

Caddey et al. (1991) reported a strong spatial association between gold-rich sulphide-iron-formation (arsenic-poor as well as arsenic-rich varieties) and late structures (shear zones and quartz veins) at Homestake. Recent work at Lupin by Bullis et al. (1992) has resulted in the discovery of narrow gold- and sulphide-rich haloes immediately adjacent to several late quartz veins in lower grade portions of the Lupin orebody at depth. However, fieldwork by the writer indicates that most, but clearly not all, of the ore on the deeper levels at Lupin is of the stratiform-type and similar to that on the upper levels of the mine.

Alteration

Alteration related to deposition of the stratiform ores is not clearly defined, largely because it is difficult to consistently determine whether individual minerals are products of isochemical metamorphism of auriferous chemical sedimentary rocks, or of metasomatism associated with formation of the late quartz veins. Both processes have undoubtedly affected the rocks at all deposits. Chlorite-rich alteration envelopes occur immediately adjacent to the late quartz veins at Homestake, Lupin, and Jardine, but chlorite unrelated to vein formation is also abundant in sulphide-banded iron-formation relatively distant from veins. Carbonate minerals are present at some stratiform deposits. The widespread Mg-rich siderite (sideroplesite) at Homestake is generally not thought to be a product of pervasive carbonatization associated with formation of the quartz veins. At Agnico-Eagle, however, carbonate-rich tuffs and agglomerates, as well as abundant ferroan dolomite veins, have been interpreted as products of late carbonatization coeval with gold concentration (Wyman et al., 1986). The origin of the Lapa Seca at Morro Velho is controversial.

Mineralogy

In sediment-hosted stratiform deposits, pyrrhotite is ubiquitous in cherty sulphide-iron-formation and is closely associated with gold. Pyrite is present in some cases, but appears to be either vein-related or a late alteration product after pyrrhotite. As noted previously, arsenic-bearing sulphide minerals occur in most of these deposits, but are spatially related to late quartz veins and/or shear zones and appear to be later than pyrrhotite. Pyrrhotite content of sulphide-iron-formation averages between 10 and 15 modal per cent at Lupin and around 8 modal per cent at Homestake (Caddey et al., 1991). The modal abundance of arsenic-bearing minerals varies from greater than 50 per cent immediately adjacent to quartz veins to less than one per cent several tens of centimetres away from veins. There is no consistent correlation between gold and arsenic at Lupin or Homestake, because much of the ore is arsenic-poor. Löllingite occurs with arsenopyrite at Lupin and a number of other occurrences in the Contwoyto Lake area, but is rare or unreported at Homestake and Jardine. Non-sulphide minerals associated with gold-rich iron-formation include quartz, chlorite, siderite, grunerite, garnet, hornblende, and hedenbergite. At Lupin, hornblende and chlorite are more abundant in gold-rich iron-formation than in

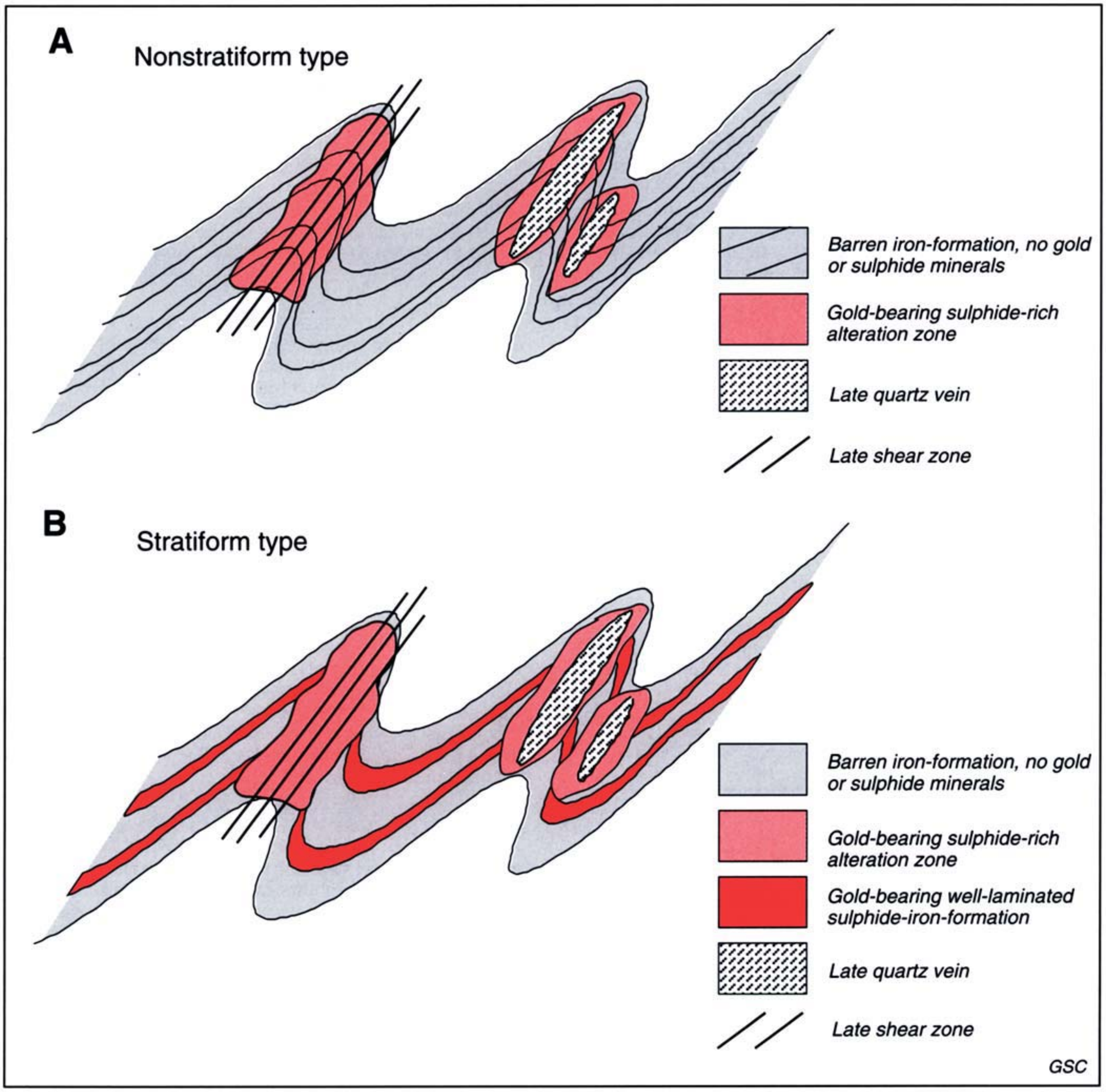


Figure 15.3-4. The two principal types of iron-formation-hosted gold deposits. **A)** Gold restricted to late structures or to sulphide-iron-foundation immediately adjacent to such structures. Examples are many and include the North ore zone, Geraldton, Ontario, Central Patricia and portions of Pickle Crow, Pickle Lake, Ontario, numerous deposits in Western Australia, including Hill 50, Nevoria, and Water Tank Hill, numerous deposits in Zimbabwe, including the Lennox mine, and probably São Bento in Brazil and the Cullaton B-zone, Northwest Territories. **B)** Gold occurs in thin, but laterally continuous units of well laminated sulphide-iron-formation as well as in sulphide-rich alteration zones adjacent to late structures. Examples are few but include Lupin, Northwest Territories; Jardine, Montana; and probably Homestake, South Dakota; all within sediment-dominated settings, as well as Morro Velho and Cuiabá, Brazil, and probably Agnico-Eagle, Quebec, all within mixed sedimentary-volcanic terranes.

gold-poor iron-formation, whereas garnet and grunerite are more abundant in gold-poor iron-formation. However, hornblende is also an essential mineral in barren silicate-iron-formation, not only in the Lupin and Jardine orebodies, but also throughout the Lupin and Jardine areas. Carbonaceous material is locally abundant at Lupin, Homestake, and Jardine.

In stratiform deposits occurring within mixed volcanic-sedimentary settings, as at Agnico-Eagle and Cuiabá, gold is associated with pyrite (characteristically greater than 20 modal per cent), and both pyrrhotite and arsenopyrite are rare. Pyritic iron-formation at these deposits is interlayered with carbonate-banded iron-formation. At Morro Velho gold occurs with pyrrhotite, pyrite, and arsenopyrite.

Gold is present as the native metal and is silver-rich compared to that in nonstratiform ores hosted by iron-formation. Gold-silver ratios for Lupin and Agnico-Eagle, as well as for Homestake, Jardine, Morro Velho, and Cuiabá, fall within the relatively restricted range of 4.0 to 6.5.

Ore textures

The sulphide-rich iron-formation in sediment-hosted stratiform deposits is typically well laminated. All components of the iron-formation, including the iron sulphide minerals, occur in clearly defined layers (Fig. 15.3-3B). Sulphidation textures, which are common in vein-type deposits in iron-formation (Fig. 15.3-3A) and which demonstrate replacement of iron oxide, carbonate, or silicate minerals by iron sulphide minerals, are lacking in the stratiform pyrrhotite-rich ores. By contrast, arsenic-bearing sulphide minerals in arsenic-rich sulphide-iron-formation adjacent to quartz veins or shear zones appear to have overgrown or replaced pyrrhotite (Fig. 15.3-3C,D). At Lupin, gold most commonly is in direct contact with pyrrhotite, but also occurs interstitially to silicate minerals in sulphide-iron-formation. In the arsenic-rich ore adjacent to quartz veins at Lupin, significant gold occurs along arsenopyrite-löllingite grain boundaries in complex megacrysts of pyrrhotite, arsenopyrite, and löllingite. Minor gold occurs along fractures in the sulphides.

The stratiform ores in mixed volcanic-sedimentary settings range from well laminated to relatively massive. Gold in the Cuiabá ore is in well laminated, cherty sulphide-iron-formation and is intimately associated with both a microcrystalline variety of pyrite and a more coarsely crystalline euhedral variety of pyrite. At Agnico-Eagle, much of the gold also occurs in well laminated, cherty sulphide-rich iron-formation. At least some of this gold is associated with a distinctive fine grained euhedral form of pyrite, and occurs along intragranular fractures, as 3-5 µm particles embedded within pyrite, and as small veinlets as much as 10 µm in length (Wyman et al., 1986). The sulphide-rich ore at Morro Velho, though banded, is typically relatively massive.

There is considerable textural evidence in some stratiform deposits that gold-rich sulphide-iron-formation was present before metamorphism and deformation. For example, thin bands of arsenic-poor sulphide-iron-formation at Lupin are commonly more tightly folded than the interlayered units of silicate-iron-formation and clastic sedimentary rocks, suggesting that the sulphide-iron-formation was present before folding. Also at Lupin, the ubiquitous occurrence in arsenic-poor sulphide-iron-formation of pyrrhotite in lens-shaped mosaics in which individual pyrrhotite grains meet at triple junctions, the presence of chalcopyrite at such triple junction positions, a greater sulphide grain size in more deformed portions of the deposit, and an increase of not only discordant pyrrhotite veinlets, but also of nonmagnetic pyrrhotite in the more highly metamorphosed portions of the deposit, are compatible with the presence of sulphide-banded iron-formation before deformation and metamorphism. At both Lupin and Homestake coarse clots to pods of massive pyrrhotite are common in sulphide-banded iron-formation immediately adjacent to the late quartz veins, and the chlorite- and arsenide-rich alteration zones adjacent to late quartz veins appear to overprint well-laminated arsenic-poor sulphide-iron-formation.

DEFINITIVE CHARACTERISTICS

The essential features of stratiform and nonstratiform iron-formation-hosted gold deposits are illustrated in Figure 15.3-4. Table 15.3-2 provides a detailed comparison between nonstratiform and stratiform sediment-hosted ores. Of the characteristics listed for nonstratiform deposits, numbers 1, 5, 9, and 12 are the most definitive. In other words, these deposits contain sulphide-rich, nonstratiform orebodies in which the sulphide minerals clearly replace other iron-rich minerals, typically magnetite in barren oxide-iron-formation, within or immediately adjacent to late structures. The most definitive characteristics of stratiform, Lupin-like, deposits are numbers 1, 3, 4, 5, 9, 12, and 13. In other words, these deposits contain well-laminated units of laterally continuous cherty, pyrrhotite-rich sulphide-iron-formation that are conformably interlayered with barren silicate- and/or carbonate-iron-formation and clastic sedimentary rocks. Furthermore, such ores lack obvious sulphidation textures and are not clearly controlled by late structures.

Many of the characteristics of selected deposits are summarized in Table 15.3-3. Figure 15.3-5 is an idealized stratigraphic section through the Lupin ore unit. This has been drawn to scale and illustrates inter-relationships among the different types of iron-formation, clastic sedimentary rocks, late quartz veins, alteration zones, and gold that may be typical of stratiform sediment-hosted deposits.

GENETIC MODELS

Numerous genetic models or working hypotheses have been proposed to best explain the critical features of gold deposits hosted by iron-formation. These fall into two main categories discussed below.

Syngenetic models

All components of a deposit (Fe, Si, Ca, S, As, Au, Ag, Cu, C, CO_2, W, etc.) were deposited from hydrothermal fluids during chemical sedimentation or early diagenesis. Localized remobilization of certain components (Si, Ca, As, W, etc.) during metamorphism and/or deformation in an essentially closed system is called upon to account for the typically vein-controlled distribution of some components.

Table 15.3-2. Comparison of characteristics of iron-formation-hosted gold deposits.

Features common to all deposits
1. Very strong spatial association between native gold and iron sulphide minerals
2. Gold-bearing quartz-rich veins and/or shear zones are present and locally abundant
3. Deposits occur in structurally complex settings
4. Ores contain only background contents of lead and zinc
Features diagnostic of nonstratiform deposits
1 Deposits are nonstratiform
2 Gold is commonly not restricted to sulphide-iron-formation or veins that crosscut iron-formation
3 Sulphide-iron-formation does not occur in laterally continuous units
4 Sulphide-iron-formation is not well laminated; iron sulphide minerals are commonly massive
5 Distributions of iron sulphide minerals and gold are clearly controlled by veins and/or late structures
6 Orebodies are typically less deformed than associated rocks
7 Iron sulphide minerals tend to be relatively undeformed and unmetamorphosed
8 Deposits not restricted to, but most abundant in greenschist facies
9 Sulphidation textures are common
10 Orebody scale alteration exists
11 Alteration products generally similar to those in "mesothermal vein" gold deposits
12 Oxide-iron-formation is typically the principal iron-formation lithology in the deposit
13 Pyrite is commonly the dominant iron sulphide mineral
14 Arsenic, if present, is characteristically directly correlated with gold
15 Silver contents of gold grains are typically low (Au-to-Ag ratios greater than 8.0)
16 Deposits are relatively common, generally small, and relative to stratiform deposits, are difficult to evaluate and mine
Features diagnostic of sediment-hosted (Lupin-like) stratiform deposits
1 Deposits are stratiform
2 Gold mostly restricted to iron-formation or to veins that crosscut sulphide-iron-formation
3 Sulphide-iron-formation occurs in several thin, but laterally continuous units that are conformably interlayered with barren silicate-iron-formation and/or carbonate-iron-formation and clastic sedimentary rocks
4 Sulphide-iron-formation is well laminated and chert-rich; iron sulphide minerals are typically finely layered
5 Distributions of iron sulphide minerals and gold are not clearly controlled by veins and/or late structures
6 Orebodies are as deformed or more deformed than associated rocks
7 Iron sulphide minerals show effects of deformation and metamorphism
8 Deposits occur in both greenschist and amphibolite facies terranes
9 Sulphidation textures are absent
10 Lack of orebody-scale alteration; localized vein-related alteration does occur
11 Vein-related alteration is commonly atypical of "mesothermal vein" gold deposits
12 Oxide-iron-formation is lacking in the deposits, irrespective of metamorphic grade
13 Pyrrhotite is typically the dominant iron sulphide mineral; in some cases early pyrrhotite has been replaced by pyrite
14 Arsenic is generally abundant adjacent to late quartz veins, but is not well correlated with gold
15 Silver contents of gold grains are moderately high (Au-to-Ag ratios ~ 3.0-7.0)
16 Deposits are rare, can be very large, and are less difficult to evaluate and mine than are the nonstratiform deposits

From the late 1960s through the early 1980s this essentially exhalative model was favoured for many gold deposits hosted by iron-formation (Sawkins and Rye, 1974; Hutchinson and Burlington, 1984). There is still some support for this model, particularly among those who have spent considerable time working with stratiform deposits (Nelson, 1986; Vial, 1988; Ladeira, 1991; Vieira et al., 1991a, b). Modern unequivocal examples of significant syngenetic gold concentrations lend further support to this model. Such concentrations occur within base metal-rich volcanic-associated massive sulphide deposits accumulating at Axial Seamount, within base metal-poor sulphide concentrations in sediment-covered portions of the Gorda Ridge (Escanaba Trough), and in subaerial hot springs associated with active geothermal zones in New Zealand and the western United States.

Epigenetic models

Some components of iron-formation were deposited during chemical sedimentation (Fe, Ca, some Si and CO_2, etc.), but others related to ore formation (S, Au, Ag, Cu, As, W, some Si and CO_2, etc.) were added during vein-related hydrothermal activity associated with much later deformation, metamorphism, and/or magmatism. Sulphidation of relatively Fe-rich host rocks adjacent to shear zones and/or veins is viewed as the principal ore-forming process. Extensive carbonatization may have preceded sulphidation in some deposits.

This model was favoured by most economic geologists up until the late 1960s and is currently advocated by many for most, if not all, gold deposits hosted by banded iron-formation (Phillips et al., 1984; Macdonald and Fyon, 1986; Colvine et al., 1988). Several potential sources of the

Table 15.3-3. Summary of characteristic features of selected iron-formation-hosted gold deposits.

Features	L	RL	J	H	C	MV	AE	NZ	CP	PC	SB	CL	DL	M
Type of deposit														
Stratiform	+	+	+	?	+	+	?	-	-	-	?	?	?	?
Probably stratiform	-	-	-	+	-	-	+	-	-	-	?	?	?	?
Nonstratiform	-	-	-	?	-	-	?	+	+	+	?	?	?	?
Probably nonstratiform	-	-	-	?	-	-	?	-	-	-	+	+	+	+
Sediment-hosted	+	+	+	+	-	-	-	+	+	-	-	+	-	-
Mixed volcanic-sedimentary	-	-	-	-	+	+	+	-	-	+	+	-	+	+
Iron-rich sedimentary rock														
Sulphide-iron-formation	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Oxide-iron-formation	-	-	-	-	-	-	-	+	+	+	+	+	+	+
Carbonate-iron-formation	-	-	-	+	+	-	+	?	?	?	+	-	-	?
Silicate-iron-formation	+	+	+	+	-	-	-	-	-	-	-	+	+	-
Lapa Seca	-	-	-	-	-	+	-	-	-	-	-	-	-	-
Ore host														
Sulphide-iron-formation	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Clastic sedimentary rocks	-	-	-	-	-	-	-	?	?	-	-	-	-	-
Mafic volcanic rocks	-	-	-	-	-	-	-	-	-	+	-	-	-	-
Felsic intrusions	-	-	-	-	-	-	-	+	-	+	-	-	-	-
Age														
Archean	+	+	+	-	+	+	+	+	+	+	+	?	+	+
Proterozoic	-	-	-	+	-	-	-	-	-	-	-	?	-	-
Associated minerals														
Pyrrhotite	++	+	++	++	+	++	+	+	++	++	?	++	++	++
Pyrite	+	++	+	+	++	+	++	++	-	++	++	+	+	?
Arsenopyrite	++	-	++	++	+	++	+	+	++	+	++	+	-	+
Löllingite	++	-	-	-	-	-	-	-	-	-	-	-	-	+
Quartz														
as chert	++	++	+	++	++	+	++	+	+	+	+	++	+	+
as veins	+	+	+	++	+	+	+	+	+	+	+	++	?	+
Chlorite	+	+	+	++	?	?	?	?	?	?	?	+	?	+
Hornblende	+	+	+	-	?	?	?	?	?	?	?	?	?	?
Grunerite	+	+	+	++	?	?	?	?	?	?	?	+	?	+
Fe-carbonate	-	-	?	++	++	++	++	++	?	?	++	++	-	-
Metamorphic grade														
Greenschist (G)	+	-	+	+	+	+	+	+	+	+	+	+	+	-
Amphibolite (A)	+	+	-	-	-	-	-	-	-	-	-	-	-	+
G-A transition	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Granulite	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Felsic intrusions														
Abundant within deposit	-	+	?	+	?	?	?	+	+	+	?	-	?	+
Abundant near deposit	+	+	+	+	?	?	+	+	+	+	?	-	?	+
Sulphidation textures	-	-	-	-	-	-	-	+	+	+	+	+	+	+
Au-to-Ag ratio (Au/Ag)	6.2	3.6	6.0	5.0	6.0	5.0	5.0	29.9	10.7	8.6	9.0	14.1	?	9.1

Explanation

L	Lupin	RL	Russell Lake	J	Jardine	H	Homestake
C	Cuiabá	MV	Morro Velho	AE	Agnico-Eagle	NZ	North ore zone, Geraldton
CP	Central Patricia	PC	Pickle Crow	SB	São Bento	CL	Cullaton B-zone
		DL	Dona Lake	M	Musselwhite		

Associated minerals: ++ Abundant; + Present in significant amounts; - Rare or not present; ? Unknown
Other categories: + Present; - Not present; ? Unknown

epigenetic ore-forming fluids have been proposed. Some suggest the fluids were metamorphically derived during devolatilization reactions associated with prograde metamorphism of deeper crustal rocks. Others believe the fluids were derived from late felsic magmas. A direct contribution from the mantle has also been proposed.

The epigenetic model is clearly appropriate for the vein (nonstratiform) type of iron-formation-hosted deposits. Such deposits are structurally controlled and related to late sulphidation of iron-formation that was initially gold- and sulphur-poor.

The genesis of stratiform ores is controversial, but this writer considers that synsedimentary concentration of gold, silver, and copper during deposition of sulphide-iron-formation on or just below the seafloor best accounts for many of the critical features of these deposits (Kerswill, 1993). The conformable interlayering of discrete units of gold-rich sulphide-iron-formation with barren silicate-iron-formation and clastic sedimentary rocks, the finely laminated character of the ores, their remarkable continuity, the strong positive correlation between gold and sulphur, the lack of clear evidence for structural control, and an absence of sulphidation textures suggest that both gold and sulphur were primary components of the deposits. Arsenic, tungsten, and much silica were, however, probably introduced during formation of the late quartz veins. Mobilization of synsedimentary gold during subsequent metamorphism and deformation, followed by its deposition in structurally favourable sites, were probably not essential for the genesis

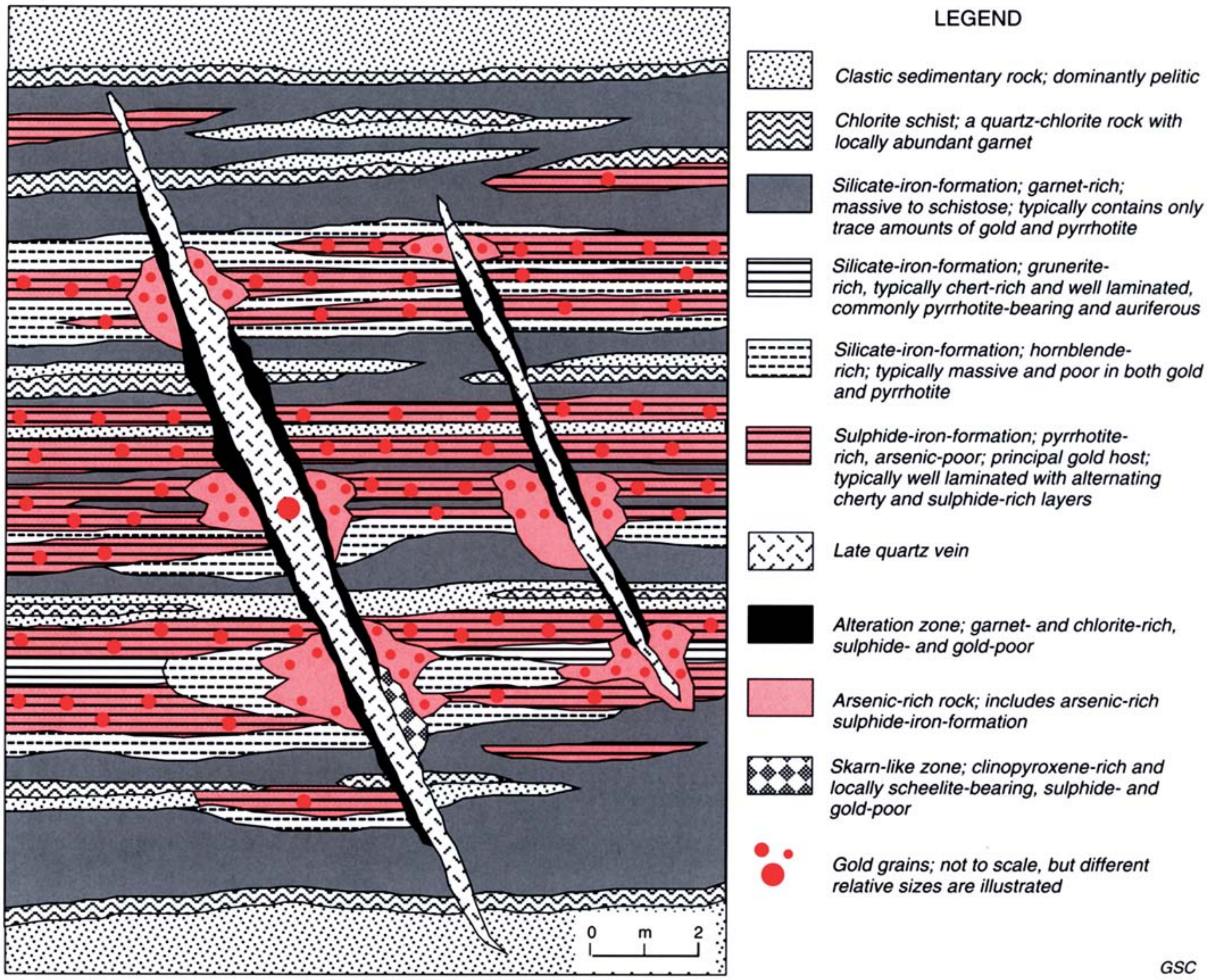


Figure 15.3-5. Idealized stratigraphic section through the Lupin ore unit showing the distributions of gold, sulphide-iron-formation, several varieties of silicate-iron-formation, chlorite schist, clastic sedimentary rocks, late quartz veins, arsenic-rich rock, chlorite- and garnet-rich alteration zones, and skarn-like zones.

Table 15.3-4. Comparison between iron-formation-hosted gold deposits in sediment dominate settings and skarn gold deposits.

	IRON-FORMATION GOLD	SKARN GOLD
Presence of calc-silicate minerals (garnet±hornblende±clinopyroxene)	Yes	Yes
Direct correlation between distribution of calc-silicate minerals and distributions of gold and sulphur	No	Yes
Typical compositions of diagnostic calc-silicate minerals (garnet and clinopyroxene)	Pyralspite, Hedenbergite	Ugrandite, Diopsidic
Significant ore occurs within an intrusion	No	Common
Calc-silicate minerals are zoned about an intrusion and/or major structure	No	Common
Much of the ore is discordant rather than stratiform	No	Yes
Much of the ore is clearly controlled by late structures and/or lithological contacts	No	Yes
Ores contain significant concentrations of bismuth and/or tellurium	No	Common
Presence of locally abundant tungsten as scheelite	Common	Uncommon
Presence of abundant magnetite in the ore	No	Common
Strong direct correlation between gold and arsenic	No	Common
Silicate mineral assemblages most commonly associated with ore	Prograde	Retrograde
Apparent timing of gold and sulphur introduction	Early	Late
Inferred genesis of calc-silicate minerals most commonly associated with ore	Metamorphic	Metasomatic

of the stratiform ores. Some gold in stratiform deposits may represent new gold introduced during formation of the late quartz veins rather than gold that has just been remobilized.

However, epigenetic models for the genesis of stratiform deposits continue to receive support. For example, recent work at the Homestake mine has led Caddey et al. (1991) to abandon the syngenetic model of Nelson (1986) in favour of epigenetic introduction of gold during reverse movement on high-angle shears synchronous with late quartz vein emplacement. Lhotka (1988) and Lhotka and Nesbitt (1989) have concluded from their investigations that Lupin is an epigenetic deposit in which all the gold, sulphur, and arsenic were introduced by the late quartz veins. Bullis (1990) also proposed a model for Lupin that is similar to that of Lhotka (1988). In the author's opinion much of the available evidence for stratiform deposits is most consistent with a syngenetic model.

RELATED DEPOSIT TYPES

Vein or nonstratiform type

Iron-formation-hosted gold deposits of the vein or nonstratiform type are similar to mesothermal gold deposits as discussed elsewhere in this volume (see subtype 15.2).

Stratiform type

Stratiform gold deposits, though possessing some of the features of mesothermal vein deposits and/or stratabound sulphide schist deposits, are more similar to some of the types of stratiform deposits discussed below.

Sedimentary-exhalative massive sulphides

Stratiform iron-formation-hosted deposits in sediment-dominated settings are similar to sedimentary exhalative (Sedex) deposits in that both types are stratiform, sediment-hosted, well laminated, and sulphide-rich. However, there are major differences in the metal contents; sedimentary exhalative deposits are base metal-rich and gold-poor, whereas the stratiform gold deposits are base metal-poor but gold-rich. The two deposit types may have formed in similar geological settings, but from hydrothermal fluids of different character; reduced, acidic, and relatively high temperature for sedimentary exhalative deposits, but reduced, alkaline, and only moderate temperature for stratiform gold ores. Sedimentary exhalative deposits range in age from Proterozoic to the present. Homestake, the largest of the stratiform sediment-hosted gold deposits, is Proterozoic, but Lupin and Jardine are Archean. As noted previously, the auriferous pyrrhotite-rich but lead- and zinc-poor sulphide accumulations in the Escanaba Trough may be similar to Lupin and other Lupin-like deposits.

Volcanic-hosted massive sulphides

Stratiform gold deposits of the mixed volcanic-sedimentary subtype are somewhat similar to volcanic-associated sulphide deposits. Numerous ancient, and several modern, deposits of the latter type contain significant gold, but the stratiform gold deposits are not enriched in lead and zinc and contain only minor concentrations of copper.

Iron-rich sedimentary rocks (Algoma type)

Both types of iron-formation-hosted gold deposits occur within Algoma-type banded iron-formation and thus share similarities with it. The sulphide-iron-formation in the stratiform deposits is probably a true sulphide facies iron-formation and was most likely deposited from hydrothermal fluids during chemical sedimentation or early diagenesis. However, most Algoma-type iron deposits contain abundant magnetite and are poor in both sulphur and gold. In the case of nonstratiform deposits, the sulphide-rich iron-formation within and adjacent to late veins and/or shear zones is a product of structurally and chemically controlled alteration processes related to metamorphism and/or deformation, and was clearly not originally a primary chemical sediment.

Skarns

Some features of stratiform iron-formation-hosted gold deposits in sediment-dominated settings are characteristic of reduced skarn deposits that are rich in tin and/or tungsten. Calc-silicate assemblages occur in both, pyrrhotite is the principal iron sulphide, ore units are typically thin, but laterally continuous, and ores are commonly restricted to beds hosted by clastic sedimentary rocks. However, the banded iron-formation-hosted deposits are only superficially similar to gold-rich skarns. Significant differences between these two deposit types are presented in Table 15.3-4. Unequivocal evidence for the pervasive metasomatism associated with skarn deposits is lacking in stratiform gold deposits. Indeed, evidence for skarn-like metasomatism is typically restricted to narrow gold- and sulphide-poor alteration zones immediately adjacent to late quartz veins. Most of the mineralogical and chemical features of the stratiform ores away from veins are adequately explained by prograde metamorphism of variably mixed clastic and chemical sediments containing different amounts of aluminous clays, Fe-rich silicate and/or carbonate minerals, abundant quartz, Fe-monosulphide minerals and gold.

EXPLORATION GUIDES

A number of largely empirical exploration guidelines that may be useful in the search for additional iron-formation-hosted gold deposits can be proposed. These include general guides for either stratiform- or vein-type targets, as well as specific guides for each type. Comparison between the guidelines and the characteristics of a target may help one determine whether the target is more likely to contain stratiform or nonstratiform mineralization. Early recognition of the most probable deposit type should permit more effective evaluation of the prospect. Although stratiform deposits can be very large and are more easily evaluated and mined than vein-type deposits, the favourable grade and tonnage characteristics of some nonstratiform deposits (see Fig. 15.3-1) make this deposit type an attractive target as well.

The most useful empirical exploration guide for any iron-formation-hosted gold deposit is the presence of abundant iron sulphide minerals (pyrrhotite and/or pyrite). These minerals are in some cases relatively uniformly disseminated in stratiform units, and in other cases are restricted to alteration zones adjacent to late structures. Units of well laminated, cherty, pyrrhotite-rich banded iron-formation are particularly favourable for the occurrence of stratiform ores in sediment-dominated target areas. Auriferous pyrrhotite-rich iron-formation in such deposits is typically interbedded with silicate- and/or carbonate-bearing iron-formation and pelitic sedimentary rocks. Carbonate-iron-formation may be a useful exploration guide for stratiform mineralization in terranes at relatively low metamorphic grade (Homestake, Morro Velho, Cuiabá, and Agnico-Eagle). Calc-silicate-bearing iron-formation may be the metamorphosed equivalent of carbonate-iron-formation within higher grade terranes (Lupin, Jardine, Bugow, and Musselwhite). Sulphidic, but gold-poor, black shales are consistently associated with stratiform iron-formation-hosted gold deposits in mixed volcanic-sedimentary settings (Agnico-Eagle, Cuiabá, and Morro Velho). Such rocks are not characteristic of sediment-hosted deposits, but pyrrhotite-rich gold-poor graphitic mudstone is a significant component of the Poorman Formation, which underlies the Homestake Formation at Homestake. Despite the apparent preferred occurrence of iron-formation-hosted gold ores in Archean rocks, the Proterozoic age of Homestake, the largest stratiform deposit, suggests that exploration, particularly for stratiform ores, need not be restricted to Archean terranes.

Oxide-iron-formation is a negative indicator for stratiform gold mineralization, but such rocks are the typical host of nonstratiform deposits. However, the presence of oxide-iron-formation does not mean that an area or region is unfavourable for the occurrence of stratiform mineralization. Although lateral transitions from sulphide-iron-formation to oxide-iron-formation have not been recognized in stratiform deposits, oxide-iron-formation is not uncommon in the vicinity of stratiform mineralization. Indeed, oxide-iron-formation is widespread near the Lupin mine and hosts numerous occurrences of the nonstratiform type. This suggests that the presence of nonstratiform mineralization may be useful in identifying areas with potential for stratiform mineralization.

Late quartz veins and/or shear zones are present in most known examples of iron-formation-hosted gold deposits. Thus they provide an obvious exploration guide, particularly if concentrations of iron sulphide minerals are spatially and genetically associated with the veins. Complex folds are characteristic of many iron-formation-hosted gold deposits and may be viewed as a positive feature in evaluating exploration targets. In nonstratiform deposits, the distributions of gold-bearing veins and sulphide-rich zones are commonly controlled by fold structures. In stratiform deposits, structural repetition and thickening of sulphide-iron-formation in fold hinges can significantly increase ore tonnage. However, the distributions of gold and sulphur in these deposits are not obviously controlled by such structures. This suggests that in the case of targets of possibly stratiform nature, fold limbs as well as fold hinges require testing.

Arsenic-bearing minerals can be viewed as useful empirical ore guides, because late quartz veins with associated arsenic constitute a volumetrically important component in many nonstratiform deposits and most sediment-hosted stratiform deposits (Bugow and SP in the Russell Lake area, Northwest Territories, are notable exceptions). However, in stratiform deposits, sulphur is consistently more reliable than arsenic as a guide for gold. This is largely because much stratiform mineralization is arsenic-poor. In some nonstratiform deposits, such as the North ore zone at Geraldton and the São Bento mine, gold is closely associated with arsenopyrite and the positive correlation between gold and arsenic is very strong. In many cases, the presence of abundant arsenic can be linked to a relatively late hydrothermal event in a setting containing abundant sedimentary rocks.

Zones or lithologies anomalously rich in nonsulphide minerals that may be products of alteration associated with gold mineralization can be viewed as possible ore hosts or as indicators of nearby mineralization. Such nonsulphide minerals include chlorite, carbonate, biotite, and sericite. The dolomite-rich Lapa Seca that is closely associated with the sulphide ore at Morro Velho is an excellent exploration guide.

The consistently high silver content of gold grains in stratiform ores, and the apparent ubiquitous presence of minor chalcopyrite in association with pyrrhotite in sediment-hosted stratiform ores, suggest that silver and copper may be useful pathfinders for stratiform mineralization. The significant difference in gold-to-silver ratios between stratiform (Au:Ag typically between 3.0 and 7.0) and nonstratiform (Au:Ag typically greater than 8.0) deposits indicates that variations in this ratio may be helpful in distinguishing styles or types of mineralization. A general consistency of gold-silver ratios within individual deposits suggests that anomalous ratios may help identify samples that should be reassayed.

Magnetic surveys are particularly useful in exploration for iron-formation-hosted gold deposits. The abundant pyrrhotite in occurrences of the sediment-hosted stratiform-type produces positive magnetic anomalies that generally can be distinguished from the background response of sulphide- and oxide-poor silicate-iron-formation, as well as from positive anomalies associated with the presence of oxide-iron-formation or mafic dykes. The replacement of magnetite by pyrite and/or pyrrhotite in vein deposits produces subtle negative magnetic anomalies associated with gold mineralization. Electromagnetic, self-potential, induced polarization, and resistivity surveys may prove useful in detecting sulphide concentrations.

The recognition that syngenetic processes may have controlled the distributions of gold and sulphur in stratiform iron-formation-hosted gold deposits has considerable exploration significance. The principal implication is that exploration for such deposits should involve documenting and evaluating features of the primary depositional environment, particularly the distribution of sulphide-bearing iron-formation. In some cases, the detailed work involved in delineating and tracing particular units of sulphide-iron-formation is best attempted after potential problems related to the interpretation of complex fold patterns and metamorphic overprint have been resolved. Exploration for nonstratiform deposits should emphasize structural and metamorphic features.

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15.4 DISSEMINATED AND REPLACEMENT GOLD

K.H. Poulsen

INTRODUCTION

In all geological environments, gold deposits are commonly composed of either vein or disseminated ores, or combinations of the two. The term disseminated refers to ores in which veins are minor and gold is "finely dispersed in host rocks of variable composition where little or no fabric control on mineralization is apparent, at least at the hand specimen scale" (Romberger, 1986). Although this term is commonly applied to deposits inferred to have formed at shallow to intermediate crustal depths in younger terranes (Carlin-type, mantos, gold-rich volcanic-associated massive sulphides, etc.), there are also many important Canadian deposits in metamorphic terranes, particularly in Precambrian and younger greenstone belts (sensu lato), that consist dominantly of disseminated ores for which the origins are more obscure. Disseminated and replacement gold deposits comprise mainly stratabound, auriferous bodies of disseminated to massive sulphides, commonly pyritic, that are hosted either by micaceous and/or aluminous schists, derived from tuff and volcanic sandstone, or by carbonate-clastic sedimentary rocks; spatial associations with granitoid rocks are common. They have low contents of base metal sulphides and commonly less silver than gold. Important Canadian examples (Fig. 15-1) include the Hemlo deposit in Ontario, QR and Equity Silver deposits in British Columbia, and the Hope Brook deposit in the Chetwynd area, Newfoundland (Table 15.4-1). The Archean Big Bell and Sons of Gwalia deposits in Western Australia and the Late Proterozoic-Paleozoic Haile, Brewer, and Ridgeway deposits in South Carolina, U.S.A. are of similar type. Sediment-associated deposits such as Island Mountain, British Columbia and Ketza River and Brewery Creek, Yukon Territorry have broadly similar characteristics. The last of these is analogous to "Carlin-like" deposits in the U.S.A.

IMPORTANCE

Sulphide-rich disseminated and replacement gold deposits represent approximately 5% of Canada's historical gold production and reserves but, with significant production from three mines on the Hemlo deposit, they account for approximately 25% of current output.

SIZE AND GRADE

The disseminated gold deposits have a similar size range as other subtypes (Fig. 15.4-1). From the giant Hemlo deposit (three mines, 600 t gold) to the smaller Hope Brook deposit (50 t gold), the stated total deposit size is dependent on the number and size of individual orebodies that constitute the deposit. It is not uncommon for deposits of this subtype to comprise several lenticular orebodies.

GEOLOGICAL FEATURES

Setting

Disseminated and replacement gold deposits occur in host rocks of both volcanic and sedimentary derivation. This includes tuffaceous metavolcanic rocks in the Precambrian greenstone belts and Phanerozoic arc terranes, as well as clastic and carbonate sedimentary rocks such as those found in the deformed passive margins of ancestral North America. The best Archean examples of the volcanic-associated type occur in the Superior Province at Hemlo in Ontario (Fig. 15.4-2); the sulphide orebodies in the Red Lake district, Ontario (Madsen, Campbell-Dickenson) and Beattie, Quebec are similar in many respects. The Hope Brook deposit (Fig. 15.4-3A), hosted by Late Precambrian to Paleozoic La Poile Group in the Chetwynd district, Newfoundland, is the most directly analogous deposit in younger terranes, but the early Proterozoic MacLellan deposit in Manitoba possesses some similar attributes. Similar younger deposits include the Tertiary Equity Silver (Fig. 15.4-3B) and Mesozoic QR deposits in British Columbia, which occur in the volcanic and volcaniclastic rocks of accreted island arc terranes. Sulphide "replacement" orebodies such as those at Island Mountain, British Columbia and Ketza River, Yukon Territory are examples of sediment-associated deposits of this type. The former is hosted by the Late Precambrian to Paleozoic Barkerville carbonate and clastic rocks in the Kootenay terrane of the Cariboo district, and the latter by similar Cambrian strata in the Cassiar terrane. The Brewery Creek deposit in Yukon Territory also occurs in Paleozoic clastic rocks of the continental miogeocline.

Deposits of this type have notable similarities and significant differences in their geological settings at a district scale (Table 15.4-1). In most cases, the deposits occur in linear belts containing a diversity of lithological units with subparallel contacts (Fig. 15.4-2, 15.4-3). Mafic host rocks are regionally important at MacLellan deposit, Red Lake district, and QR deposit; are present at Hemlo and Cariboo districts, but are rare in the sequences at Hope Brook and Equity Silver deposits. Where they are present and well preserved, the mafic units are interpreted to be volcanic flows. Felsic rocks at these deposits can be ascribed to both volcanic and sedimentary origins. The host rocks at the Madsen deposit, Red Lake district, consist of intermediate

Poulsen, K.H.
1996: Disseminated and replacement gold; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 383-392 (also Geological Society of America, The Geology of North America, v. P-1).

to felsic volcaniclastic rocks; at Hemlo and Chetwynd districts, both volcaniclastic rocks and wacke are present. In the Cariboo district, quartz wacke and phyllite are dominant.

Intrusions form a significant proportion of the rocks in most of the districts containing disseminated gold deposits (Table 15.4-1). These take the form of stocks and dykes, ranging from mafic to felsic composition and from pre- to post-tectonic timing. Granodioritic plutons and associated dykes are present at Hemlo (Cedar Lake Pluton), where they have an inferred pre- to synkinematic timing (Fig. 15.4-2), whereas the granodioritic Faulkenham Lake stock at Madsen deposit, and the Chetwynd Granite at Hope Brook, are both postkinematic. Pre- to synkinematic mafic dykes are common at Hemlo and Hope Brook deposit. At Equity Silver, the deposit lies adjacent to a quartz-monzonite stock containing subeconomic porphyry style Cu-Mo mineralization and the ore zones are cut by unaltered dacite dykes (Fig. 15.4-4C). The Brewery Creek deposit is related to Late Cretaceous felsic dykes and QR to quartz monzonite porphyry, and a deeply buried intrusion is inferred at Ketza River on the basis of existing hornfelsed rocks. No intrusive activity can conclusively be linked to the Cariboo district deposits.

Regional dynamothermal metamorphism of low to medium grade has affected the rocks in all districts that contain deposits of this subtype. Middle to upper greenschist metamorphic conditions are inferred at Cariboo district and Hope Brook deposit; the Red Lake district; MacLellan, and Hemlo deposits occur in rocks at the transition from greenschist to amphibolite facies. Where rocks of the upper greenschist and amphibolite facies are present, the presence of diagnostic minerals, such as cordierite and andalusite at Red Lake, and co-existing sillimanite and kyanite at Hemlo, indicates that metamorphism was of low to moderate pressure.

Structure

In each of the districts cited, the rocks were penetratively deformed during regional metamorphism (Table 15.4-1), and this has resulted in at least one generation of tectonic fabrics that overprints the main lithological units. In most cases, a strong foliation, amplified in discrete fault zones (Fig. 15.4-2, 15.4-3A), strikes subparallel to the regional lithological trend. In most cases, minor folds have been noted to be contemporaneous with foliation, and the transposition of bedding into parallelism with foliation is

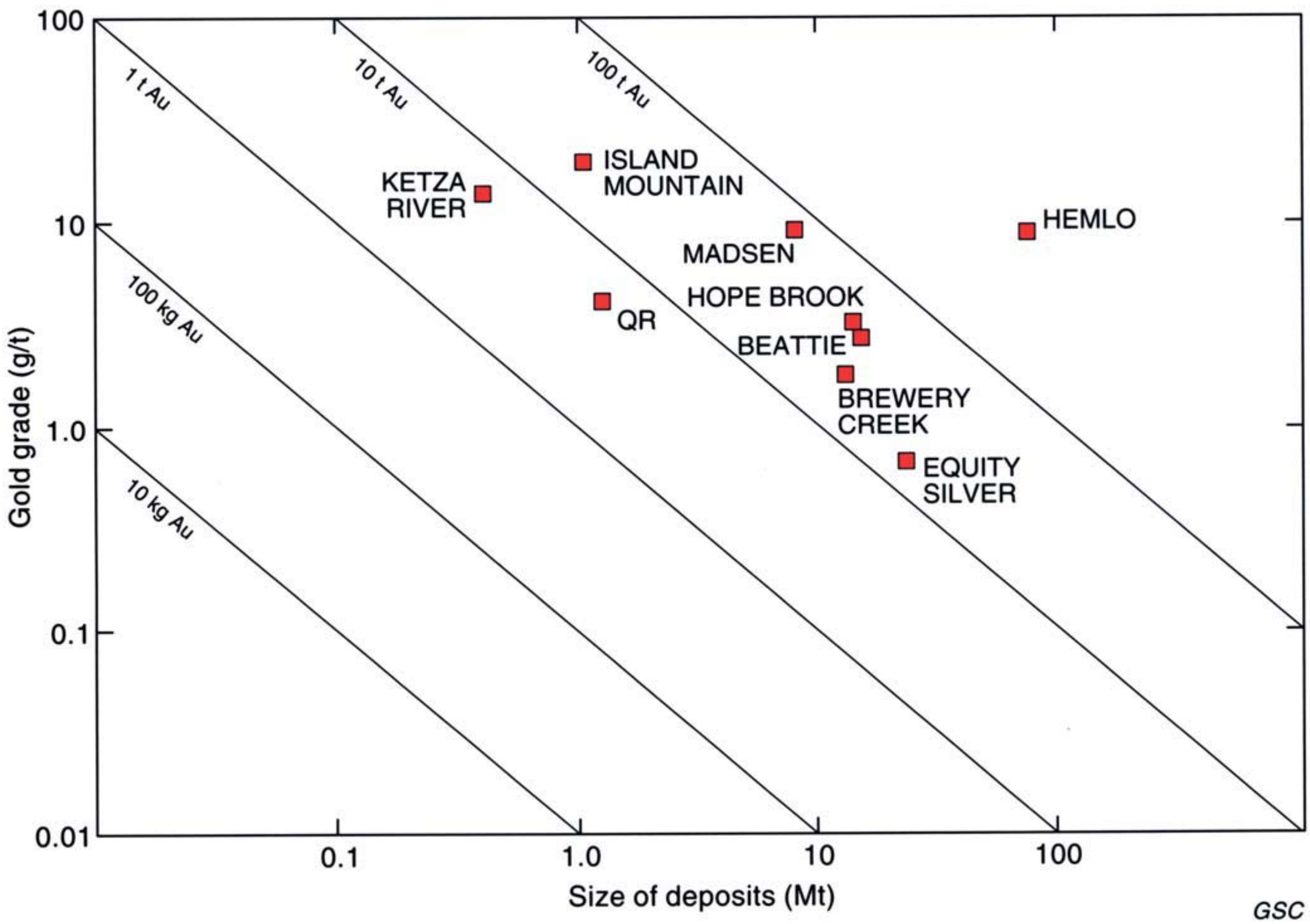

Figure 15.4-1. Tonnage-grade plot of selected Canadian disseminated and replacement gold deposits.

Table 15.4-1. Geological characteristics of selected Canadian disseminated and replacement gold deposits.

Deposit	Size	Age	Host rocks	Structure	Intrusions	Ore mineralogy	Gangue	Alteration
volcanic-associated:								
Hemlo	600 t Au	Archean	felsic tuff, wacke	intense E-W foliation	feldspar porphyry dykes	pyrite, molybdenite, sphalerite, arsenopyrite, stibnite, cinnabar, realgar	quartz, muscovite, biotite, microcline, barite, V-muscovite	kyanite, sillimanite, staurolite
Hope Brook	50 t Au	Paleozoic	wacke-tuff	intense NE-SW foliation	quartz-feldspar porphyry	pyrite, chalcopyrite, molybdenite	quartz, sericite	andalusite, paragonite, pyrophyllite
Equity Silver	25 t Au	Tertiary	Cretaceous lapilli tuff, tuff, conglomerate, sandstone	N-S folds	quartz monzonite stock; gabbro-monzonite complex	arsenopyrite, pyrite, chalcopyrite, tetrahedrite, sphalerite	quartz, chlorite, sericite	andalusite, pyrophyllite, corundum, tourmaline, scorzalite
QR	7 t Au	Mesozoic	Triasssic-Jurassic basalt, tuff, breccia, and siltstone	thrust and normal faults	early Cretaceous diorite	pyrite, chlalcopyrite, sphalerite; rare arsenopyrite, galena	epidote	carbonate, epidote, chlorite, calcite
Beattie	50 t Au	Archean	basalt flows, breccias	E-W foliation, local faults	porphyritic syenite stock and dykes	pyrite, arsenopyrite; trace chalcopyrite, sphalerite, galena, molybdenite	quartz, microcline	microcline
Madsen	84 t Au	Archean	felsic tuff	intense NE-SW foliation	adjacent quartz porphyry	pyrite, pyrrhotite, arsenopyrite, sphalerite, chalcopyrite, molybdenite	quartz, biotite, chlorite	andalusite, cordierite, garnet
MacLellan	10 t Au	Early Proterozoic	basalt, siltstone	intense E-W foliation	none	pyrite, pyrrhotite, arsenopyrite, galena, sphalerite	quartz, biotite	andalusite, staurolite, sillimanite
sediment-associated:								
Island Mountain	22 t Au	Mesozoic (?)	Paleozoic limestone beds in wacke	intense NW-SE foliation	none	pyrite, arsenopyrite; minor sphalerite-galena	quartz	sericite(?)
Ketza River	5.3 t Au	Mesozoic	Cambrian dolomitic limestone in argillite-quartzite hornfels	intersecting steep faults	inferred buried stock	pyrrhotite, pyrite, arsenopyrite; minor sphalerite, galena	siderite, calcite	silicification
Brewery Creek	27.5 t Au	Mesozoic	Paleozoic argillite, sandstone, and barite	adjacent normal faults	quartz monzonite porphyry	pyrite, arsenopyrite; stibnite in late veins; local realgar	quartz	sericite

an attribute of all the districts (Alldrick, 1983; Andrews et al., 1986; O'Brien, 1987; Muir and Elliot, 1987). Such transposition accounts for the "straightness" of the belts (e.g., Fig. 15.4-2) and is largely responsible for obscuring the primary relationships between the ore deposits and their host rocks. Linear fabrics, such as the axes of asymmetric minor folds and mineral and shape lineations, are also characteristic of these areas and are of consistent orientation within a district. Fold hinges and lineations with shallow plunge are present at Cariboo district, whereas moderate to steep plunges have been noted at Hemlo and Red Lake.

Nature and composition of orebodies

Disseminated and replacement gold orebodies are commonly stratabound at the scale of a district (Fig. 15.4-2, 15.4-3). This is attributable to the fact that they occur within, and along the strike of, well defined lithotectonic packages of rocks. Furthermore, they commonly occur at contacts between distinctive lithological units or solely within a particular unit. The lenticular to tabular shape of most orebodies is such that they are geometrically concordant with their host rocks (Fig. 15.4-3, 15.4-4). Individual deposits commonly comprise several subparallel orebodies that are arranged in a stacked fashion or along strike from one another. The long axes of orebodies (e.g., Fig. 15.4-5) are commonly parallel to other linear fabrics in a district. Ores within these deposits are sulphide-bearing, commonly schistose rocks in which the proportions of sulphides and the nature of the silicate hosts differ from orebody to orebody and from deposit to deposit (Table 15.4-1).

The Hemlo ores (Fig. 15.4-4A, 15.4-5) contain on average 8% pyrite (Harris, 1989), and occur principally in three rock types (Kuhns et al., 1986; Walford et al., 1986; Burk et al., 1986), namely quartz-microcline±barite±molybdenite schist, quartz-muscovite schist, and biotite schist. The ore types contain a wide variety of ore minerals (Table 15.4-1) that reflect chemical enrichment of Au, Mo, Sb, As, Hg, Tl, V, and Ba (Harris, 1989). The mercury minerals are located centrally within the "A" orebody where the ore is thickest (Fig. 15.4-5) and, although they occur mainly in a late paragenesis, their distribution suggests a cogenetic relationship with the gold orebody.

The Hope Brook ores are composed almost entirely of fine grained quartz with minor sericite and about 5% pyrite; chalcopyrite is a minor but common constituent (McKenzie, 1986). They occur within a wider zone of strong silicification in the structural hanging wall of a barren pyritic zone, the "pyritic cap" (Fig. 15.4-4B).

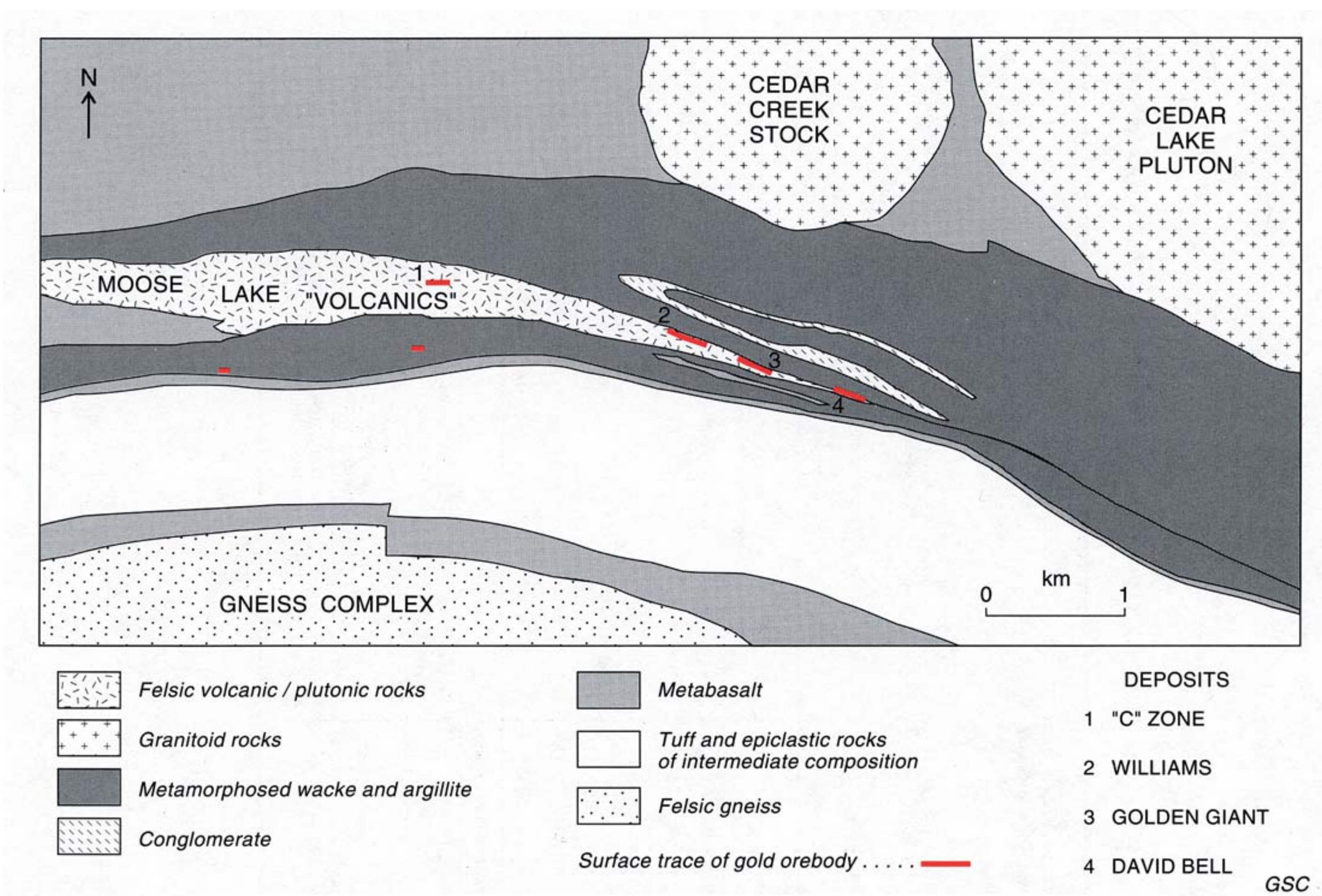

Figure 15.4-2. Geological setting of the Hemlo gold deposits (adapted after Patterson, 1985).

At Equity Silver silver-copper-gold-antimony ores occur in three separate orebodies (Fig.15.4-3B). The ores of the Main zone and its northern extension, the Waterline zone, are composed of pyrite-chalcopyrite-tetrahedrite and arsenopyrite finely disseminated in the matrix of volcanic breccia and closely associated with andalusite, blue scorzalite, tourmaline, and dumortierite (Wojdak and Sinclair, 1984). The Southern Tail ores (Fig. 15.4-3B, 15.4-4C) also are composed mainly of pyrite, arsenopyrite, chalcopyrite, and tetrahedrite, but are coarser grained fracture fillings and are related to sericitic alteration that overprints aluminous alteration.

Horwood (1940) described the Madsen orebodies as "lenses of sheared tuff with sulphide mineralization". He noted an early barren phase of massive pyrite overprinted by "orebodies" containing "variable quantities of pyrite, pyrrhotite, arsenopyrite, sphalerite, chalcopyrite, magnetite and gold".

The MacLellan ores are quartz-biotite-sulphide schists containing four successive generations of veinlets (Gagnon and Sampson, 1989). Gold and silver occurs predominantly in third generation quartz-arsenopyrite veinlets whereas veinlets of the fourth generation contain quartz, galena, sphalerite, pyrite, and arsenopyrite.

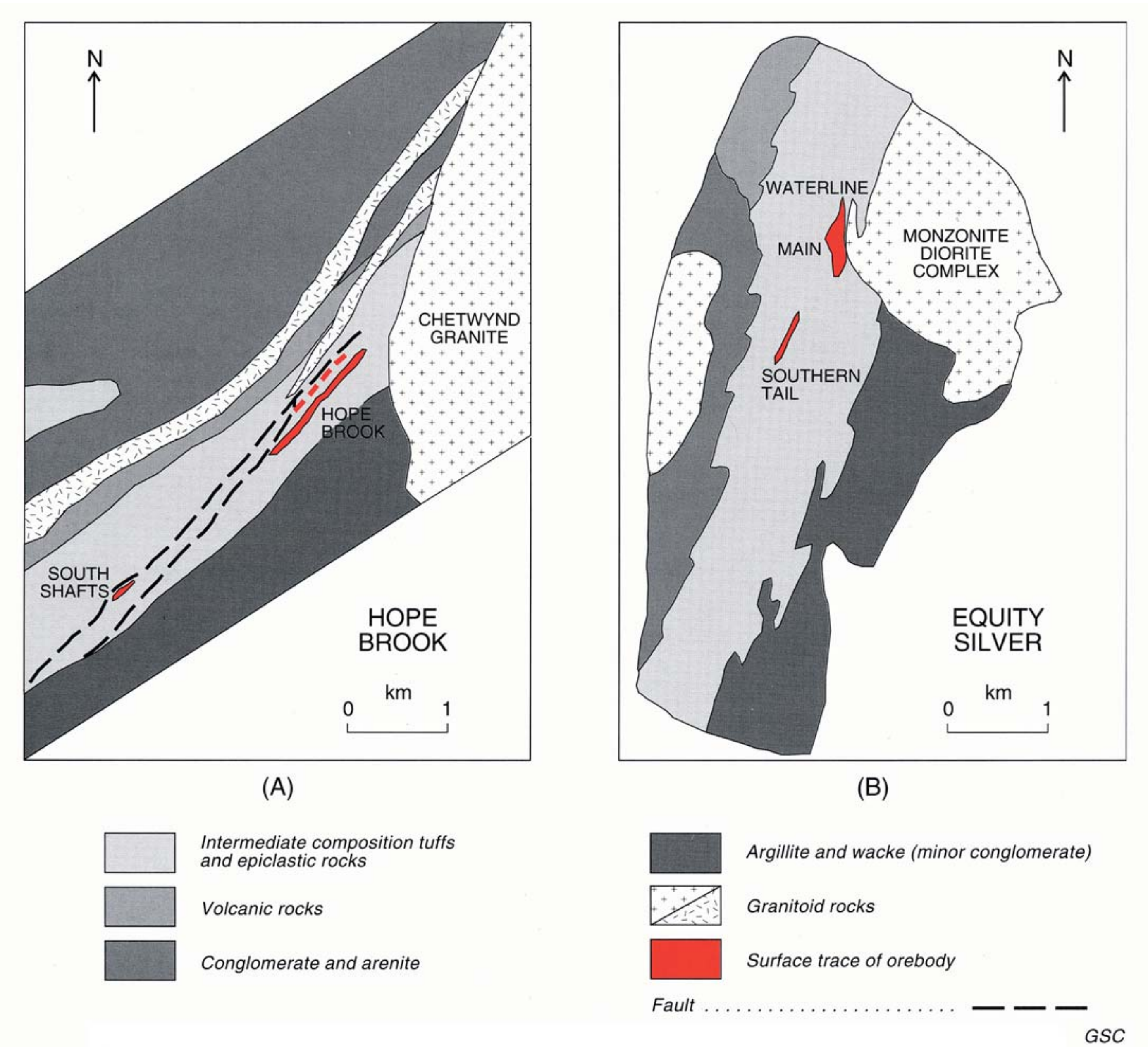

Figure 15.4-3. Geological setting of **A)** Hope Brook (adapted after McKenzie, 1986; O'Brien, 1987), and of **B)** Equity Silver (after Cyr et al., 1984).

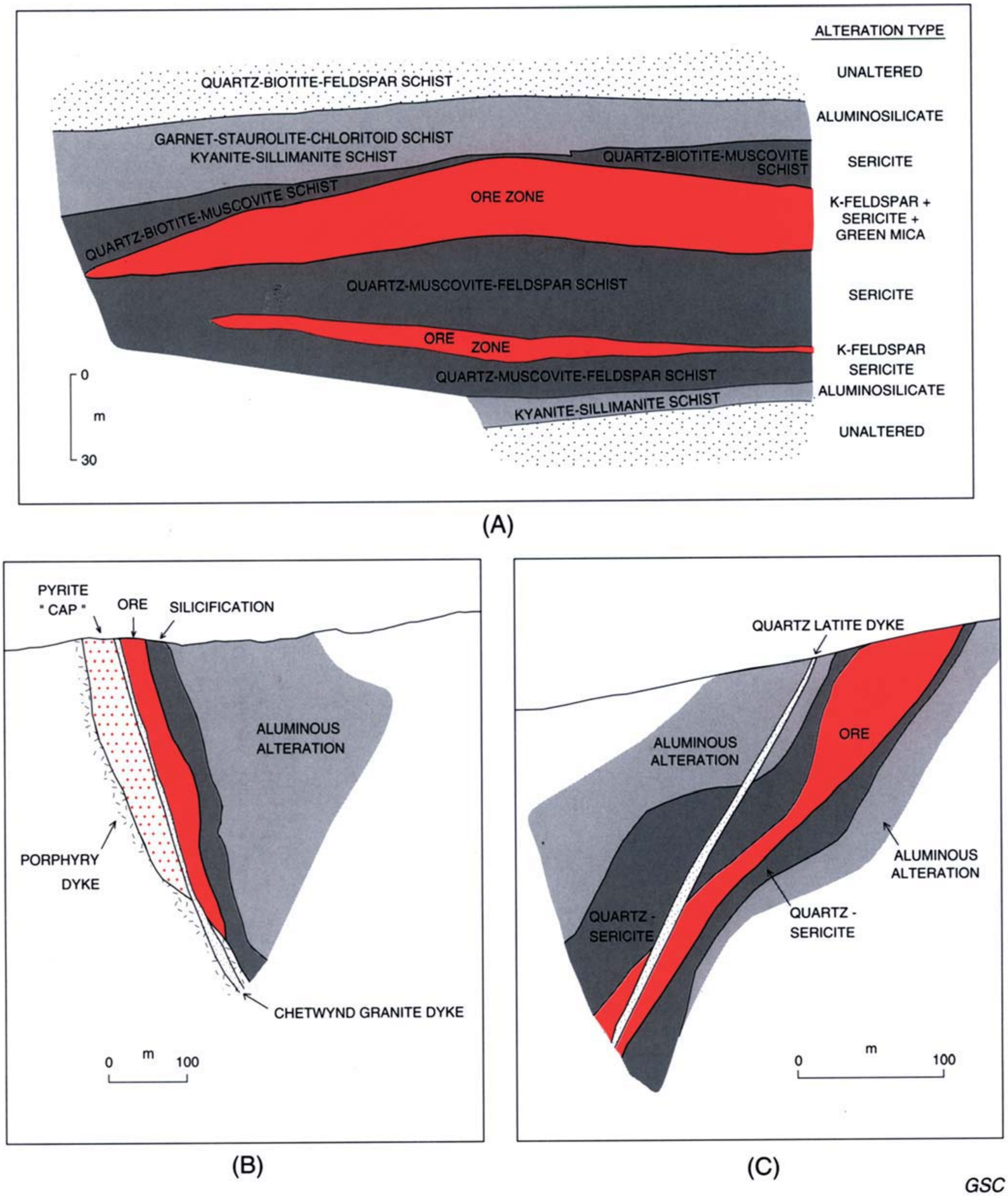

Figure 15.4-4. Distribution of alteration minerals in, and adjacent to, disseminated and replacement gold orebodies, which are shown in red: **A)** Plan of the Golden Giant mine, Hemlo (after Kuhns, 1986), **B)** Cross-section of the Hope Brook deposit, Chetwynd (after McKenzie, 1986), **C)** Cross-section of the Southern Tail zone of the Equity Silver deposit (after Wojdak and Sinclair, 1984).

The immediate host of the sulphide ores of the Cariboo district is siliceous, sericitic, dolomitic limestone. Ore lenses are disseminated to massive accumulations of fine grained pyrite, and lesser arsenopyrite, sphalerite, galena, and pyrrhotite (Alldrick, 1983). Similar pyrite-pyrrhotite-arsenopyrite ores at Ketza River are hosted by dolomitic limestone.

Alteration

All deposits in this category occur in regionally metamorphosed terranes in which minerals that are normally attributable to hydrothermal alteration are also part of the mineral assemblage of metamorphosed, but unaltered, rocks. This is particularly true because, in some cases, the deposits occur in rocks that are of an original pelitic composition. Nonetheless, anomalous abundances of some minerals, coupled with enrichment and depletion of selected trace elements, have been noted at the various deposits. These are likely the products of hydrothermal alteration, although their direct relationship to gold deposition has rarely been demonstrated. Unlike the quartz-carbonate vein gold deposits that occur in the same types of metamorphic terranes, the disseminated deposits are not noted for abundant carbonate alteration; the QR deposit is an exception (Melling and Watkinson, 1988). They do, however, display evidence of sericitic alteration like those of the vein type, but also show a notable spatial association with rocks that contain peraluminous mineral assemblages (Table 15.4-1) or in some cases, potassic alteration.

Sericitic alteration is a common feature of most deposits of this type. The sericite, or muscovite and/or biotite in higher grade metamorphic assemblages, occurs with quartz in mineral assemblages containing few phases, and in abundances that preclude formation by metamorphism of an unaltered protolith. For example, quartz-muscovite schists at Hemlo (Fig. 15.4-4A) are devoid of Na, Mg, and Ca (Kuhns et al., 1986) and are almost certainly hydrothermally altered. Similarly, the Hope Brook orebody (Fig. 15.4-4B) is enclosed in a silicified zone composed entirely of quartz and minor sericite (McKenzie, 1986).

Potassic alteration, in the form of abundant microcline, in part barium-rich, occurs in quartz-microcline rocks that host and envelop the ore (Fig.15.4-4A) at Hemlo (Kuhns et al., 1986; Harris, 1989). It is also an important constituent of other smaller, disseminated deposits in volcanic rocks, such as Beattie, Lac Shortt, and Bachelor Lake in the Abitibi belt of Quebec.

Aluminous mineral assemblages are distinctive features of the rocks adjacent to many of the volcanic-associated gold deposits of this type. A 200 m wide zone of aluminous alteration (Fig. 15.4-4B), containing abundant andalusite, pyrophyllite, paragonite, and local alunite,

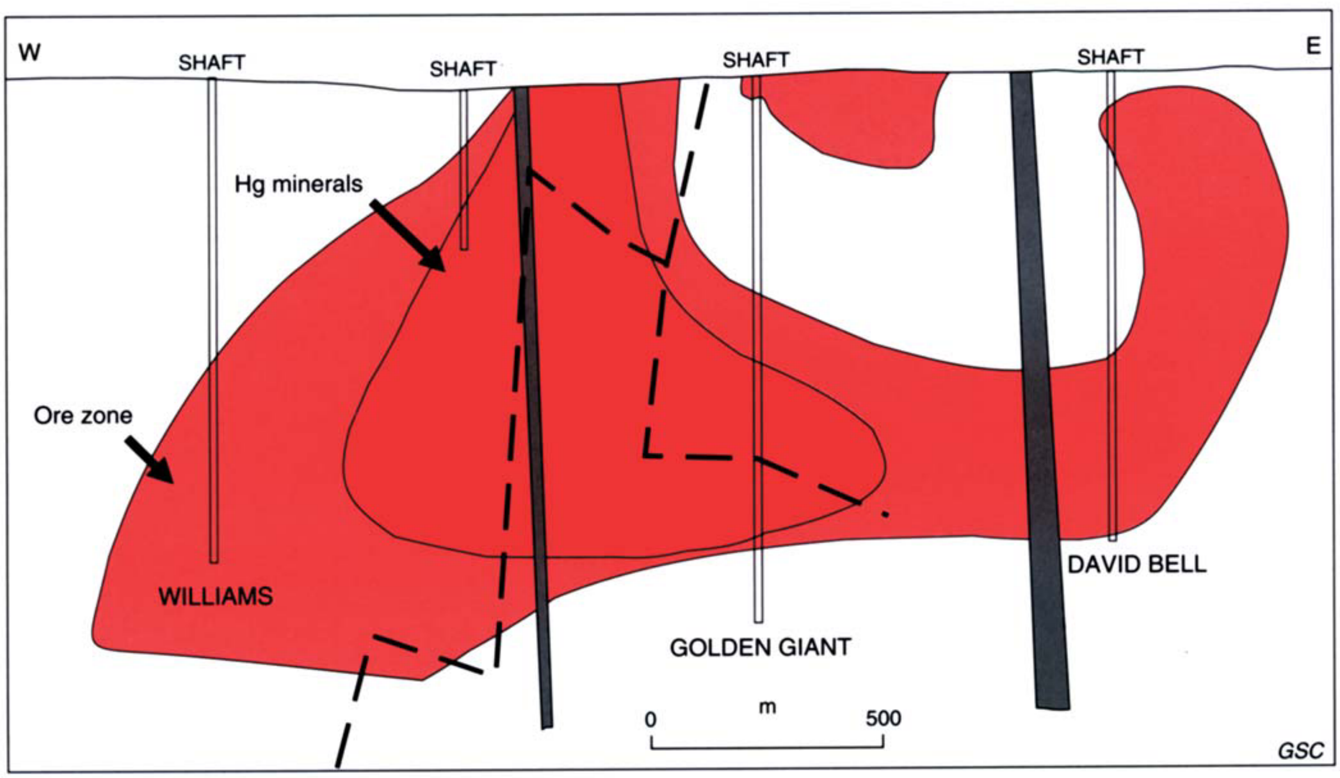

Figure 15.4-5. Vertical longitudinal projection (looking north) of the westward-plunging Hemlo "A" orebody (pink) through the Williams, Golden Giant, and David Bell mines, illustrating the distribution of mercury minerals (red) (after Harris, 1989). Diabase dykes (grey) crosscut the orebody.

occupies the structural hanging wall of the Hope Brook deposit (McKenzie, 1986; Stewart, 1990). Units of kyanite-sillimanite schist flank the Hemlo orebody (Fig. 15.4-4A), and the ore zones at Equity Silver are enveloped by a zone (Fig. 15.4-4C) containing abundant andalusite and minor pyrophyllite (Wojdak and Sinclair, 1984). Ferromagnesian aluminous minerals also occur in significant proportions adjacent to several of the deposits (Table 15.4-1). Chloritoid is notable at Hemlo, staurolite at Hemlo and Madsen, and cordierite at Hope Brook and Madsen (Durocher, 1983; McKenzie, 1986).

The distribution and significance of the alteration types with respect to ore is, in most cases, difficult to assess. This is primarily because of the uncertainty in distinguishing mineral assemblages that are attributable solely to isochemical metamorphism of unaltered pelitic rocks from those that are products of high temperature metasomatism or of metamorphism of hydrothermally altered rocks. The possibility that ore has been dislocated from its wall rocks by faults during postore deformation is an added complication at some deposits. Nonetheless, zoning patterns have been documented at some deposits (Fig. 15.4-4), and they illustrate the importance of sericitic, silicic, potassic, and aluminous alteration. Potassic and sericitic alteration at Hemlo and in association with the southern Tail Zone at Equity Silver are closer to ore than the peripheral aluminous type, whereas at Hope Brook sericite occurs throughout the aluminous alteration zone which envelops silicified rocks, but which is thickest in the structural hanging wall of the deposit.

The sericitic and aluminous alteration observed at many of the volcanic-associated deposits in this category are similar, in many respects, to those ascribed to seafloor alteration (Mathieson and Hodgson, 1984). Also, the alteration pattern is comparable to that of certain porphyry deposits and epithermal gold deposits of acid-sulphate type (Schmidt, 1985; Ririe, 1990).

Definitive characteristics

As a group, these deposits possess the following definitive characteristics:

1) they are sulphidic gold deposits in which ore distribution is not dictated by vein quartz;
2) they are commonly stratabound at the district and deposit scale and are commonly hosted by clastic rocks of volcanic and/or sedimentary origin;
3) with few exceptions, granitoid rocks, both as dykes and stocks, are present in the ore environment;
4) with few exceptions, they have low contents of base metals (less than one per cent combined metal) and gold contents exceeding those of silver; arsenopyrite is a common constituent.
5) orebodies in volcanic environments are closely associated with zones of potassic alteration or zones of silicification enclosed by aluminous alteration; sericitic alteration is ubiquitous.

GENETIC MODEL

Although the deposits of this type conform to a reasonably coherent descriptive model, they do not necessarily all have a common genesis. The failure to establish consistent genetic models for these deposits stems mainly from the difficulty in distinguishing the effects of ore-forming processes from those of regional metamorphism and deformation in the absence of significant veins that could be used as tectonic markers. The most commonly proposed models for these deposits are of two types: those that relate the deposits directly to deformation and metamorphism, and those that view the deposits to be pretectonic entities (e.g., porphyry-related mantos, epithermal, or volcanic exhalative) which, in some cases, were merely redistributed by overprinting deformation and metamorphism.

The historically accepted genetic model for these deposits is that of "replacement" of wall rocks during deformation and metamorphism (e.g., Cooke, 1946). At one time or another, such a model has been applied to all of the deposits described above. In its modern application (e.g., Phillips, 1985; Colvine et al., 1988), their formation is considered to be identical in timing, and in fluid source, to that of "mesothermal" quartz-carbonate vein deposits, the only difference being one of depositional setting. The disseminated ores of the type at Madsen and Hemlo are considered to represent a deeper, hotter, and more ductile depositional environment than that of quartz vein deposits. A point in favour of such a model is that, in many cases, the disseminated ores strongly resemble vein-type ores in their bulk chemical composition, particularly the associated trace metal suite (As, Sb, Te) and gold:silver ratios. Furthermore, many gold mines contain both types of orebodies; the controversial East South "C" orebodies in the Campbell-Dickenson deposit at Red Lake are well studied examples in which sulphide ores at deep levels grade into vein ores at higher structural levels in the same deposit (Mathieson and Hodgson, 1984), and the Cariboo deposits are known for both their vein and "replacement" ores. Therefore, such dynamothermal replacement models do not treat disseminated greenstone gold deposits as a subtype separate from quartz-carbonate veins, but rather as a variation in a unified model of "mesothermal and hypothermal" lode gold deposits, the differences being attributable to crustal level of ore deposition.

Alternative models portray disseminated and replacement gold deposits as a separate class of pretectonic deposits of epigenetic origin. Such models typically are analogous to those for porphyry and epithermal deposits in younger geological environments. Porphyry and intrusion-related models are attractive for at least some of the disseminated deposits identified here, particularly if one considers the inferred relationships among porphyry deposits, overlying epithermal deposits and peripheral gold-bearing mantos in younger terranes. For example, McKenzie (1986) used the gold-copper-barium geochemical association and the development of extensive advanced argillic alteration to argue in favour of an epithermal model for the Hope Brook deposit. Similarly the Au-Hg-Sb-As metal association at Hemlo suggests an epithermal affiliation, whereas the high Mo concentrations and the presence of substantial potassic alteration favour a porphyry affiliation (Schmidt, 1985; Kuhns, 1986). A key unresolved question in this regard is whether the Moose Lake "Volcanics" at Hemlo (Fig. 15.4-2), a unit of fine grained quartz-phyric felsite, is indeed of extrusive origin or merely a deformed hypabyssal intrusion. The presence of Cu-Mo stockwork mineralization in granodiorite adjacent to, and of approximately the same age as, Au-Ag-Cu-Sb ore at Equity Silver also strongly favours a genetic relationship between the two. Although strongly deformed, the Island Mountain "replacement orebodies" resemble other mantos (e.g., Ketza River) in both form and setting (F. Robert and B.E. Taylor, pers. comm., 1988) and the Brewery Creek deposit is broadly similar to Carlin-type and Carlin-like deposits in the western U.S.A. which, in turn, locally display clear relationships to intrusions.

RELATED DEPOSIT TYPES

Auriferous volcanic-associated massive sulphide deposits

There are several superficial similarities in the geological characteristics of disseminated and replacement gold deposits in volcanic rocks with auriferous volcanic-associated massive sulphide deposits (see subtype 6.3). Although they share common aluminosilicate alteration and a primarily sulphidic nature, the case for volcanic exhalative origins for deposits of the former type (e.g., Valliant and Bradbrook, 1986) is, however, not particularly strong. In no cases (e.g., Hemlo, Hope Brook, Equity Silver, etc.) have exhalative units been convincingly identified, and related intrusions tend to be post- rather than synvolcanic in timing. A common point in the genesis of the deposits discussed here and auriferous massive sulphides may lay, however, in the fact that, like the stockwork zones beneath exhalative deposits, they are subsurface zones of veining and replacement. One distinction between auriferous volcanogenic massive sulphide deposits (subtype 6.3) and those of "disseminated and replacement" type may be their composition: the former tend to have lower gold:silver ratios than the latter.

EXPLORATION GUIDES

On a regional scale, disseminated gold deposits occur at major lithological contacts which mark a distinctive change in volcanic and sedimentary facies. Furthermore, these contacts are, in part, of deformational origin in that they commonly coincide with zones of intense layer transposition. At a local scale, the presence of aluminous mineral assemblages in rocks in which they are not normally expected may be a useful exploration guide. The sulphide contents of many of these deposits are sufficient to produce geophysical responses and, owing to the disseminated nature of the sulphides, induced polarization methods should be the most effective. Lithogeochemical anomalies for trace elements such as Sb, As, and Hg have locally been shown to correlate with orebodies of this type (Durocher, 1983; Kuhns, 1986; Harris, 1989), but no single element, or suite of elements, is diagnostic of all of the deposits of this subtype. For those deposits like Hemlo, in which potassic alteration is important, gamma-ray spectrometry has proven to be a useful tool for mapping hydrothermal alteration.

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Authors' addresses

J.A. Kerswill
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

K.H. Poulsen
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

François Robert
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

B.E. Taylor
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

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