Volcanogenic Massive Sulphide Deposits

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Abstract

Volcanogenic massive sulphide (VMS) deposits, also known as volcanic-associated, volcanic-hosted, and volcano-sedimentary-hosted massive sulphide deposits, are major sources of Zn, Cu, Pb, Ag, and Au, and significant sources for Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga, and Ge. They typically occur as lenses of polymetallic massive sulphide that form at or near the seafloor in submarine volcanic environments, and are classified according to base metal content, gold content, or host-rock lithology. There are close to 350 known VMS deposits in Canada and over 800 known worldwide. Historically, they account for 27% of Canada's Cu production, 49% of its Zn, 20% of its Pb, 40% of its Ag, and 3% of its Au. They are discovered in submarine volcanic terranes that range in age from 3.4 Ga to actively forming deposits in modern seafloor environments. The most common feature among all types of VMS deposits is that they are formed in extensional tectonic settings, including both oceanic seafloor spreading and arc environments. Most ancient VMS deposits that are still preserved in the geological record formed mainly in oceanic and continental nascent-arc, rifted-arc, and back-arc settings. Primitive bimodal mafic volcanic-dominated oceanic rifted arc and bimodal felsic-dominated siliciclastic continental back-arc terranes contain some of the world's most economically important VMS districts. Most, but not all, significant VMS mining districts are defined by deposit clusters formed within rifts or calderas. Their clustering is further attributed to a common heat source that triggers large-scale subseafloor fluid convection systems. These subvolcanic intrusions may also supply metals to the VMS hydrothermal systems through magmatic devolatilization. As a result of large-scale fluid flow, VMS mining districts are commonly characterized by extensive semi-conformable zones of hydrothermal alteration that intensifies into zones of discordant alteration in the immediate footwall and hanging wall of individual deposits. VMS camps can be further characterized by the presence of thin, but areally extensive, units of ferruginous chemical sediment formed from exhalation of fluids and distribution of hydrothermal particulates.

Résumé

Les gîtes de sulfures massifs volcanogènes (SMV) sont connus sous diverses appellations parmi lesquelles on peut mentionner les gîtes de sulfures massifs associés à des roches volcaniques, encaissés dans des roches volcaniques ou logés dans des assemblages volcano-sédimentaires. Ils constituent des sources considérables de Zn, Cu, Pb, Ag et Au, ainsi que des sources importantes de Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga et Ge. Ils consistent généralement en lentilles de sulfures massifs polymétalliques formées dans des milieux volcaniques sous-marins, au sein ou à proximité du fond océanique, et sont classés d'après leur contenu en métaux communs ou en or ou selon la lithologie des roches encaissantes. Près de 350 gîtes SMV ont été découverts au Canada et plus de 800, de par le monde. Dans l'histoire de la production minière du Canada, 27 % du cuivre, 49 % du zinc, 20 % du plomb, 40 % de l'argent et 3 % de l'or ont été extraits de gisements SMV. On trouve de tels gîtes aussi bien dans des terrains volcaniques sous-marins datant de 3,4 Ga que dans les fonds océaniques actuels où de nouveaux gîtes sont en cours de formation. La caractéristique la plus commune à tous les gîtes de SMV tient à leur formation dans des milieux tectoniques de distension, parmi lesquels on peut mentionner les fonds océaniques en expansion et les arcs. La plupart des anciens gîtes SMV conservés dans les archives géologiques se sont formés dans des milieux océaniques et continentaux d'arc naissant, d'arc de divergence et d'arrière-arc. Quelques-uns des districts à gisements SMV les plus importants dans le monde sur le plan économique se trouvent dans des terrains océaniques primitifs d'arc de divergence caractérisés par un volcanisme bimodal à dominante mafique, de même que dans des terrains continentaux d'arrière arc caractérisés par un volcanisme bimodal à dominante felsique et la présence de matériaux silicoclastiques. La plupart des principaux districts miniers à gisements SMV consistent en amas de gisements formés dans des rifts ou des caldeiras. Leur regroupement est attribuable à l'existence d'une source de chaleur commune qui donne naissance à de vastes réseaux de convection de fluides sous le plancher océanique. Les intrusions subvolcaniques qui produisent cette chaleur peuvent aussi fournir des métaux aux réseaux hydrothermaux des gîtes SMV par le biais d'un dégagement magmatique de matières volatiles. En raison de l'écoulement de fluides sur une grande étendue, les districts miniers à gisements SMV se caractérisent souvent par la présence de vastes zones semi-concordantes d'altération hydrothermale, qui gagnent en intensité pour devenir des zones d'altération discordantes, dans l'éponte inférieure et l'éponte supérieure immédiates des gisements. Ces districts se distinguent aussi par la présence d'unités minces mais étendues de sédiments chimiques ferrugineux qui résultent de l'exhalaison et de la diffusion de particules hydrothermales.

Definition

Volcanogenic massive sulphide (VMS) deposits are also known as volcanic-associated, volcanic-hosted, and volcano-sedimentary-hosted massive sulphide deposits. They typically occur as lenses of polymetallic massive sulphide that form at or near the seafloor in submarine volcanic environments. They form from metal-enriched fluids associated with seafloor hydrothermal convection. Their immediate host rocks can be either volcanic or sedimentary. VMS deposits are major sources of Zn, Cu, Pb, Ag, and Au, and significant sources for Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga, and Ge. Some also contain significant amounts of As, Sb, and Hg. Historically, they account for 27% of Canada's Cu production, 49% of its Zn, 20% of its Pb, 40% of its Ag, and

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3% of its Au. Because of their polymetallic content, VMS deposits continue to be one of the most desirable deposit types for security against fluctuating prices of different metals.

VMS deposits form at, or near, the seafloor through the focused discharge of hot, metal-rich hydrothermal fluids. For this reason, VMS deposits are classified under the general heading of "exhalative" deposits, which includes sedimentary exhalative (SEDEX) and sedimentary nickel deposits (Eckstrand et al., 1995). Most VMS deposits have two components (Fig. 1). There is typically a mound-shaped to tabular, stratabound body composed principally of massive (>40%) sulphide, quartz and subordinate phyllosilicates, and iron oxide minerals and altered silicate wall-rock. These stratabound bodies are typically underlain by discordant to semi-concordant stockwork veins and disseminated sulphides. The stockwork vein systems, or "pipes", are enveloped in distinctive alteration halos, which may extend into the hanging-wall strata above the VMS deposit.

VMS deposits are grouped according to base metal content, gold content, and host-rock lithology (Figs. 2, 3, 4). The base metal classification used by Franklin et al. (1981) and refined by Large (1992) and Franklin et al. (2005) is perhaps the most common. VMS deposits are divided into Cu-Zn, Zn-Cu, and Zn-Pb-Cu groups according to their contained ratios of these three metals (Fig. 2). The Cu-Zn and Zn-Cu categories for Canadian deposits were further refined by Morton and Franklin (1987) into Noranda and Mattabi types, respectively, by including the character of their host rocks (mafic vs. felsic, effusive vs. volcaniclastic) and characteristic alteration mineral assemblages (chlorite-sericite dominated vs. sericite-quartz ± carbonate-rich). The Zn-Pb-Cu category was added by Large (1992) in order to more fully represent the VMS deposits of Australia (Fig. 2). Poulsen and Hannington (1995) created a sim-

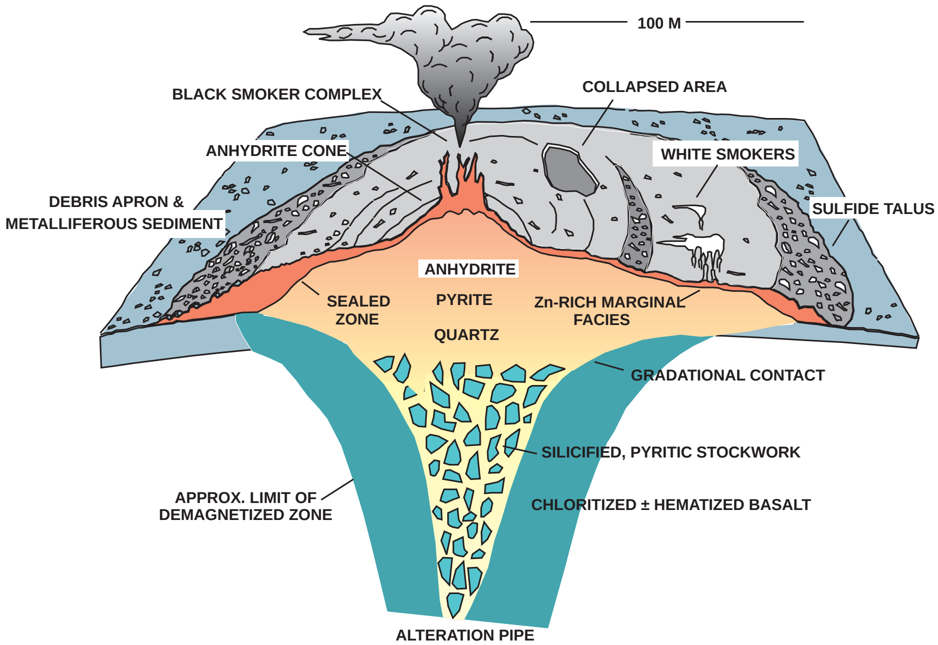

FIGURE 1. Schematic diagram of the modern TAG sulphide deposit on the Mid-Atlantic Ridge. This represents a classic cross-section of a VMS deposit, with concordant semi-massive to massive sulphide lens underlain by a discordant stockwork vein system and associated alteration halo, or "pipe". From Hannington et al. (1998).

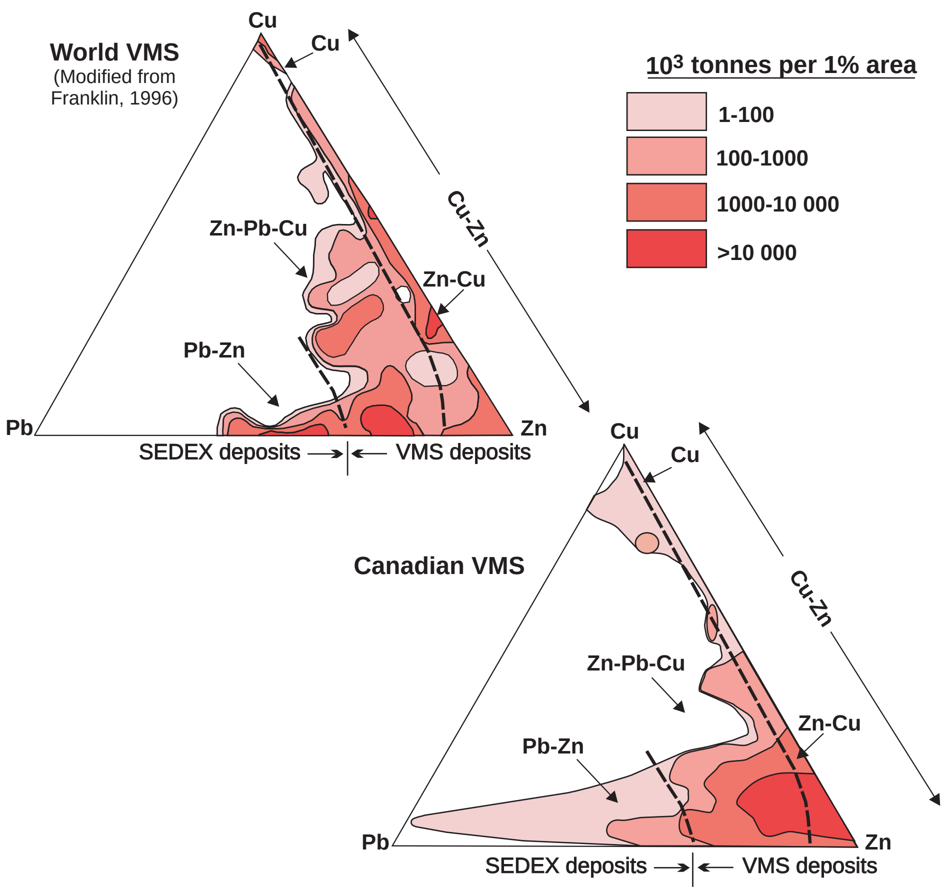

FIGURE 2. Base metal classification scheme of worldwide and Canadian VMS deposits as defined by Franklin et al. (1981) and modified by Large (1992) to include the Zn-Pb-Cu class. The preponderance of Cu-Zn and Zn-Cu VMS deposits in Canada is due to the abundance of Precambrian primitive oceanic arc settings. Worldwide, there is a larger proportion of felsic-hosted, more Pb-rich continental rift and continent margin arc settings.

ple bimodal definition of "normal" versus "Au-rich" VMS deposits (Fig. 3). This originally was intended to identify deposits that are transitional between VMS and epithermal deposits (e.g. Sillitoe et al., 1996) (Fig. 4). Further research has indicated a more complex spectrum of conditions for the generation of Au-rich VMS related to water depth, oxidation state, the temperature of the metal-depositing fluids, and possible magmatic contributions (e.g. Hannington et al., 1999a). In the classification of Poulsen and Hannington (1995) Au-rich VMS deposits are arbitrarily defined as those in which the abundance of Au in ppm is numerically greater than the combined base metals (Zn+Cu+Pb in wt.%, Fig. 3). A third classification system that is gaining acceptance is a five-fold grouping first suggested by Barrie and Hannington (1999), and later modified by Franklin et al. (2005). This system classifies VMS deposits by their host lithologies (Fig. 4), which includes all strata within a host succession defining a distinctive time-stratigraphic event (Franklin et al., 2005). These five different groups are bimodal-mafic, mafic-backarc, pelitic-mafic, bimodal-felsic, and felsic-siliciclastic. To this is added a sixth group of hybrid bimodal felsic, which represent a cross between VMS and shallow-water epithermal mineralization (Fig. 4). These lithologic groupings generally correlate with different submarine tectonic settings. There order here reflects a change from the most primitive VMS environments, represented by ophiolite settings, through oceanic rifted arc, evolved rifted arcs, continental back-arc to sedimented back-arc.

Geographical Distribution

There are close to 850 known VMS deposits worldwide with geological reserves of over 200,000 t. They are located in submarine volcanic terranes that range in age from the 3.4 Ga Archean Pilbara Block, Australia, to actively forming deposits in modern seafloor spreading and oceanic arc terranes (Fig. 5, Table 1). VMS-epithermal hybrids are also forming today in volcanically active shallow submarine (Manus Basin) and lacustrine environments. VMS deposits are recognized on every major continent except Antarctica, although Zn-Pb-Cu deposits are forming in the Bransfield Strait adjacent to the Antarctic Peninsula (Peterson et al., 2004). Cu and Au have been produced from Tertiary-age deposits hosted in ophiolites around the eastern Mediterranean and Oman for over 5000 years. Prior to 2002, VMS deposits are estimated to have supplied over 5 billion tonnes of sulphide ore (Franklin and Hannington, 2002). This includes at least 22% of the world's Zn production, 6% of the world's Cu, 9.7% of the world's Pb, 8.7% of its Ag, and 2.2% of its Au (Singer, 1995).

Over 350 deposits and major VMS occurrences containing geological reserves of more than 200,000 tonnes are known in Canada, of which only 13 are producing mines as of 2006 (Fig. 6, Table 2). Of these, Louvicourt, Bouchard-Hébert, Selbaie, and Konuto have been closed. VMS deposits are known to occur in every province and territory except Alberta and Prince Edward Island. The largest number of deposits is in Quebec (33%), followed in descending order by Manitoba (15%), Newfoundland (12%), British Columbia (10%), Ontario (9%), and New Brunswick (9%). The deposits in New Brunswick have had the highest aggregate metal value (Cu+Zn+Pb), followed by Quebec and then Ontario (Fig. 7).

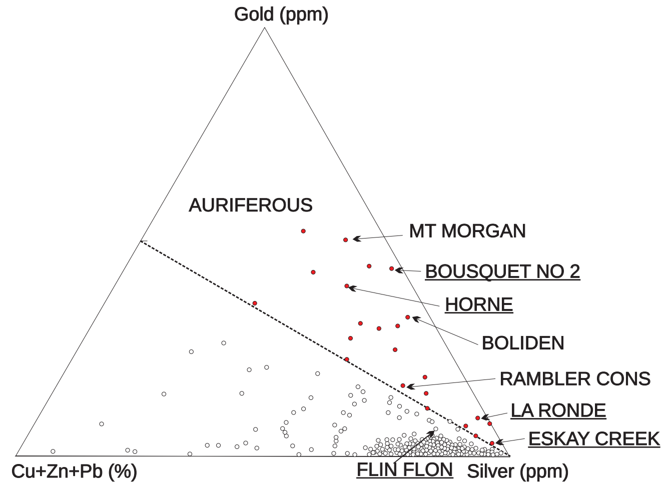

FIGURE 3. Classification of VMS deposits based on their relative base metal (Cu+Zn+Pb) versus precious metal (Au, Ag) contents. Some of Canada's better known auriferous deposits (underlined) are compared to international examples. Despite having produced 170 t of Au, the Flin Flon deposit is not considered an auriferous VMS deposit under this classification. Modified from Hannington et al. (1999c).

Grade and Tonnage

The over 800 VMS deposits worldwide range in size from 200,000 tonnes to supergiant deposits containing more than 150 million tonnes (Franklin et al., 2005) (Table 3). Among the largest is Rio Tino, Spain's portion of the Iberian Pyrite Belt (IPB), with contained ore in excess of 1.535 Bt. The richest supergiant produced to date is Neves Corvo on the Portuguese side of the IPB, with ore in excess of 270 Mt, with 8.8 Mt of contained metal. At the average metal prices to date for 2006 (Cu=$1.75/lb, Zn=$1.25/lb, Ag=$6.00/oz), this orebody was originally worth in the order of 26 billion dollars (US). Other large districts are the Urals and Rudny Altai of Russia and Kazakhstan with over 70 Mt of contained metals each (Fig. 5). Canada has two supergiant VMS deposits (Windy Craggy and Brunswick No. 12) and two giant VMS deposits (Kidd Creek, and Horne), which are defined as being in the upper 1% of the world's VMS deposits with respect to total original reserves (Fig. 10A). In Canada, the largest VMS mining district is Bathurst, New Brunswick, which contained over 320 Mt of geological resource of massive sulphide containing 30 Mt of combined Zn, Cu, and Pb (Figs. 6, 10A). The 128 Mt Brunswick No. 12 deposit alone contained 16.4 Mt of metal (Table 2). This is followed by the 138.7 Mt Kidd Creek deposit containing 12.6 Mt of metal. The largest known Canadian VMS deposit is the 297 Mt Windy Craggy deposit, but it contains only 4.1 Mt of Cu, Co, and Au. The 50 Mt Horne deposit contains 2.2 Mt of Zn+Cu+Pb, along with over 330 t of Au, making it also a world-class gold deposit (Fig. 10B). The 98 Mt LaRonde VMS deposit contains 258 Mt of gold, and because of its high Au/base metal ratio (Au ppm/Zn+Cu+Pb% = 1.9) it is classified by its owner as a gold deposit rather than a VMS deposit.

Determining the mean and median metal concentrations for Canadian VMS deposits is difficult due to missing or

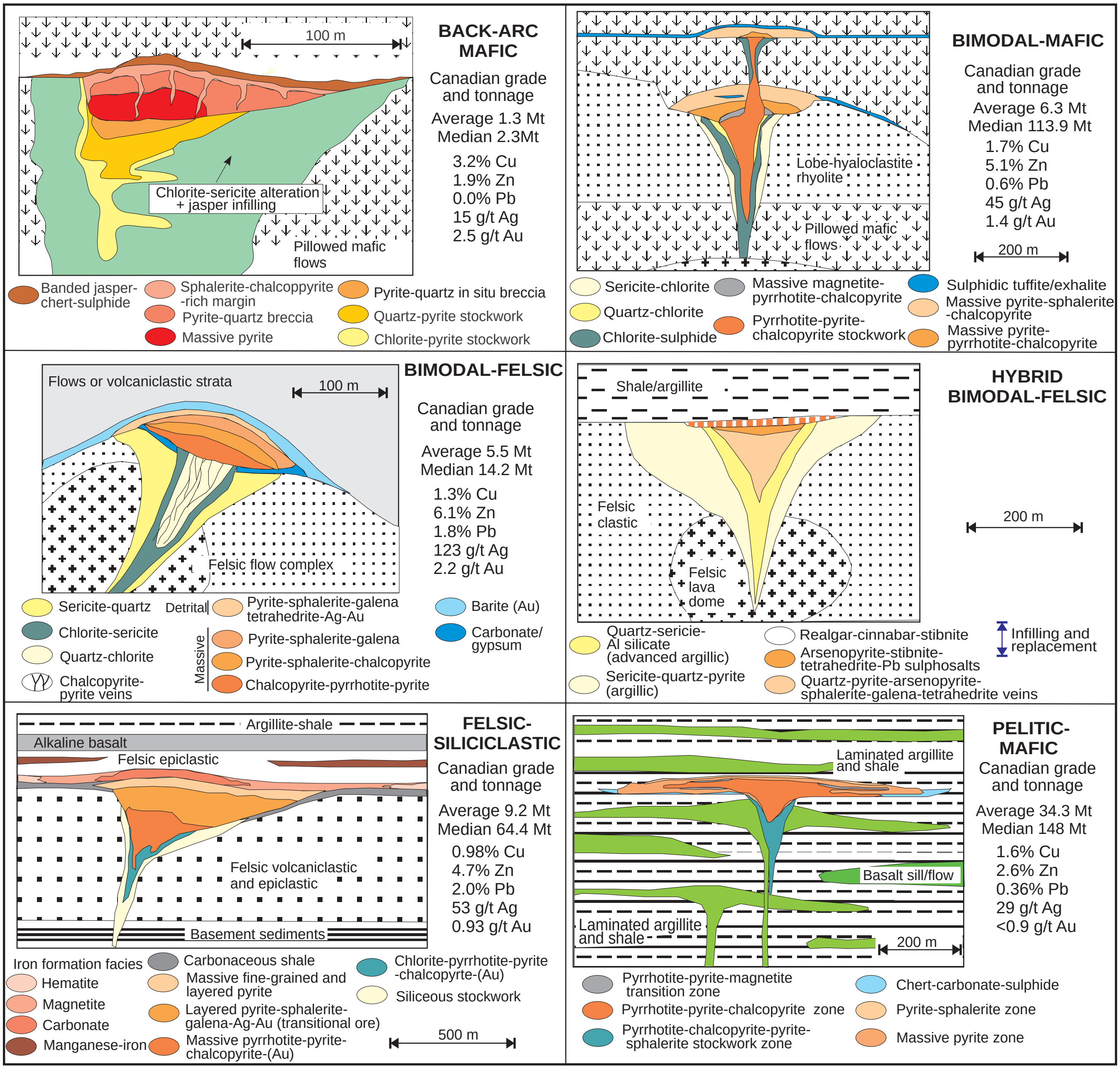

Figure 4. Graphic representation of the lithological classifications modified from Barrie and Hannington (1999) by Franklin et al. (2005), with the addition of the hybrid bimodal felsic as a VMS-epithermal subtype of bimodal-felsic. Average and median sizes for each type for representative Canadian deposits shown, along with average grade.

incomplete data for a large number of deposits. Pb grades are known for 34% of Canadian deposits, whereas 55% have known Au grades and 75% have known Ag grades. From the available production data, the mean and median (in brackets) size and grades for past and present producing Canadian deposits are 7 306 521 t grading 4.88% (4.12) Zn, 1.62% (0.70) Cu, 1.639% (1.00) Pb, 63 g/t (37) Ag, and 1.65 g/t (0.88) Au. Figure 9B shows the more meaningful breakdown of tonnage and grade for each of the five Canadian VMS types as defined by host lithology. Bimodal mafic deposits account for the greatest number and, therefore, the largest aggregate tonnage of the five deposit types, with both siliciclastic types accounting for the largest average tonnage. The mafic-siliciclastic deposit types have the highest average tonnage, with the number highly skewed by Windy Craggy. As expected, the three deposit types dominated by mafic volcanic and volcaniclastic rocks have the highest Cu grades, whereas the two felsic-dominated deposit types contain the highest Pb and Ag contents. The bimodal felsic deposit group contains the highest average gold. Mafic-ultramafic-dominated systems can also contain Se, Co, and Ni. The presence of immature sediments (i.e. black shale) within the footwall stratigraphy can also influence hydrothermal fluid composition, as is postulated for he Se-rich Wolverine and KZK deposits in the Finlayson Lake camp (Bradshaw et al., 2003). Possible contributions from devolatilizing subvol-

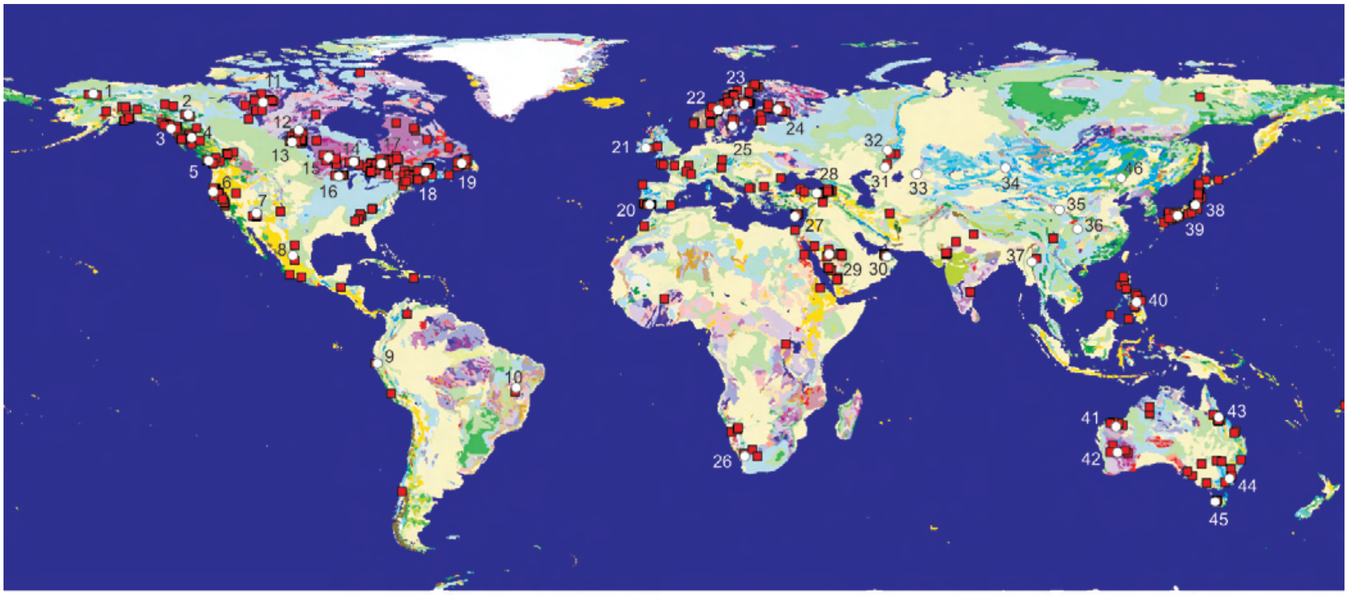

FIGURE 5. Geographical distribution of ancient VMS deposits, with major districts highlighted with respect to known aggregate geological reserves (see Table 1). Modified from Sinclair et al. (1999) and Franklin et al. (2005).

canic intrusions may also account for anomalous Se, Sn, In, Bi, Te, and possibly Au and Sb contents (Hannington et al., 1999c; Yang and Scott, 2003; Dubé et al., 2004).

Geological Attributes

Tectonic Environment

The most common feature among all types of VMS deposits is that they are formed in extensional tectonic settings, including both oceanic seafloor spreading and arc environments (Fig. 11). Modern seafloor VMS deposits are recognized in both oceanic spreading ridge and arc environments (Herzig and Hannington, 1995), but deposits that are preserved in the geological record formed mainly in oceanic and continental nascent-arc, rifted arc, and back-arc settings (Franklin et al. 1998; Allen et al., 2002) (Fig. 11). This is because during subduction-driven tectonic activity much of the ancient ocean-floor is subducted, leaving only a few ophiolite suites as remnant obducted ocean-floor. Examples of these include the Ordovician Bay of Islands ophiolite in Newfoundland and the Late Triassic Cache Creek terrane in British Columbia (Bédard and Hébert, 1996; Nelson and Mihalynuk, 2004).

Nascent, or early arc rifting, results from the initial foundering of older thickened oceanic crust, commonly

TABLE 1. Major world volcanogenic massive sulphide deposits and districts.

No.*	Deposit/District, Country	Tonnage (Mt)	No.*	Deposit/District, Country	Tonnage (Mt)
1	Brooks Range, Alaska	35	23	Skellefte, Sweden	70
2	Finlayson Lake, Yukon	20	24	Outokumpu-Pyhasalmi, Finland	90
3	Windy Craggy, BC & Green's Creek, Alaska	300	25	Bergslagen-Orijarvi, Sweden & Finland	110
4	Northern Cordillera, British Columbia	100	26	Preiska, South Africa	45
5	Myra Falls, British Columbia	35	27	Troodos, Cyprus	35
6	Shasta, California	35	28	Black Sea, Turkey	200
7	Jerome, Arizona	40	29	Saudi Arabia	70
8	Central Mexico	120	30	Semail, Oman	30
9	Tambo Grande, Peru	200	31	Southern Urals, Russia / Kazahkstan	400
10	Amazonian craton, Brazil	35	32	Central Urals, Russia	100
11	Slave Province, Northwest Territories, Nunavut	30	33	Rudny Altai, Kazahkstan / Russia	400
12	Ruttan, Manitoba	85	34	Altai Shan, Mongolia	40
13	Flin Flon-Snow Lake, Manitoba	150	35	North Qilian, China	100
14	Geco, Manitouwadge, Ontario	60	36	Sanjiang, China	50
15	Sturgeon Lake, Ontario	35	37	Bawdwin-Laochang, Burma /	40
16	Ladysmith-Rhinelander, Wisconsin/Michigan	80	38	Hokuroku, Japan	80
17	Abitibi, Ontario-Quebec	600	39	Besshi, Japan	230
18	Bathurst, New Brunswick	495	40	Phillipines arc	65
19	Dunnage Zone, Newfoundland	75	41-42	Pilbara, Yilgarn Western Australia	75
20	Iberian Pyrite Belt, Spain & Portugal	1575	43	Central Queensland, Australia	80
21	Avoca, Ireland	37	44	Lachlan Fold Belt, Australia	100
22	Trondhjeim, Norway	100	45	Mt. Read, Tasmania	200
			46	Sino-Korean Platform	40

* numbers refer to Figure 5; tonnage is approximate

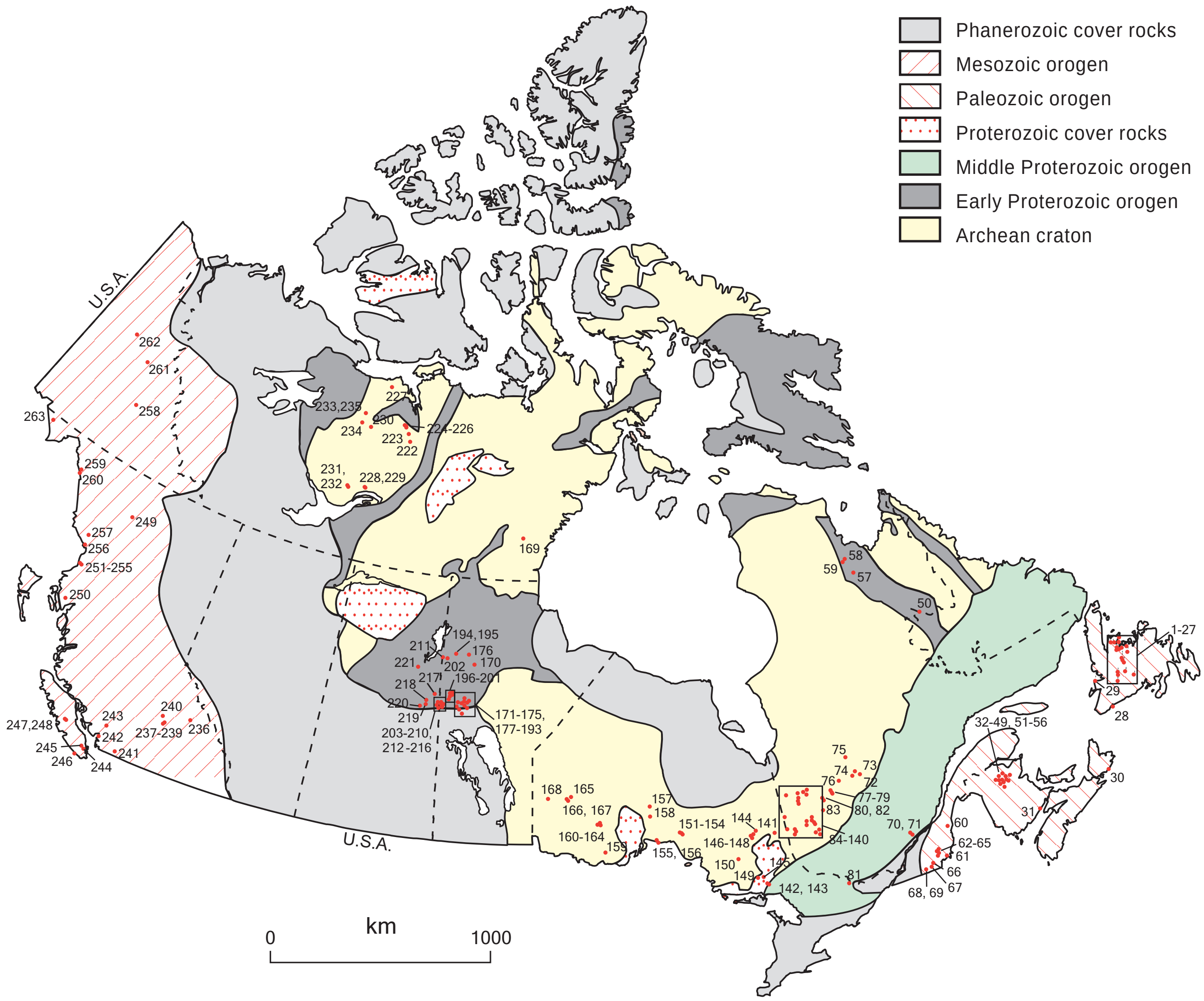

Figure 6. Distribution of VMS deposits in Canada by geologic province. Numbers correspond to deposits listed in the national VMS database (Appendix 1).

Table 2. Canadian volanogenic massive sulphide deposits presently in production (2005).

Deposit	Location	(1) Mt	Cu wt.%	Zn wt.%	Pb wt.%	Ag g/t	Au g/t	Age
Brunswick No. 12	Bathurst, New Bruswick	229.8	0.46	7.66	3.01	91	0.46	Ordovician
Kidd Creek	Abitibi, Ontario	149.3 (181 mined + all resources)	2.89	6.36	0.22	92	0.05	Archean
LaRonde (incl. LaRonde II)	Abitibi, Quebec	88.1	0.32	1.71		40.9	5.07	Archean
Selbaie	Abitibi, Quebec	47.3	0.98	1.98		20	0.9	Archean
Myra Falls Gp.,Buttle Lake	Wrangellia, British Columbia	29.3	1.83	6.25	0.55	49	2.01	Devonian
Trout Lake	Trans-Hudson Orogen, Manitoba	20	1.83	5.59		17.4	1.73	Paleoproterozic
Louvicourt	Abitibi, Quebec	19.3	3.1	1.71		28.7	0.83	Archean
Triple 7	Trans-Hudson Orogen, Manitoba	14.5	3.32	5.78		37.7	2.71	Paleoproterozic
Bouchard-Hébert	Abitibi, Quebec	10.2	2.11	4.79		15	1.4	Archean
Callinan	Trans-Hudson Orogen, Manitoba	9.16	1.41	3.59		23.5	2.08	Paleoproterozic
Duck Pond*	Central Volcanic Belt,	5.2	3.24	5.97	1.1	61.5	0.88	Ordovician
Perseverence Group *	Abitibi , Quebec	5.1	1.24	15.82		29.4	0.38	Archean
Eskay Creek	Stikine, British Columbia	4	0.33	5.4	2.2	998	26.4	Jurassic
Bell Allard	Abitibi, Quebec	3.2	1.5	13.77		43.5	0.76	Archean
Chisel North	Trans-Hudson Orogen, Manitoba	2.8	0.15	9.36	0.4	22	0.4	Paleoproterozic
Konuto	Trans-Hudson Orogen,	1.28	5.27	1.44		10.6	2.09	Paleoproterozoic

* In preproduction (2006)

(1) Includes production and estimated reserves where applicable.

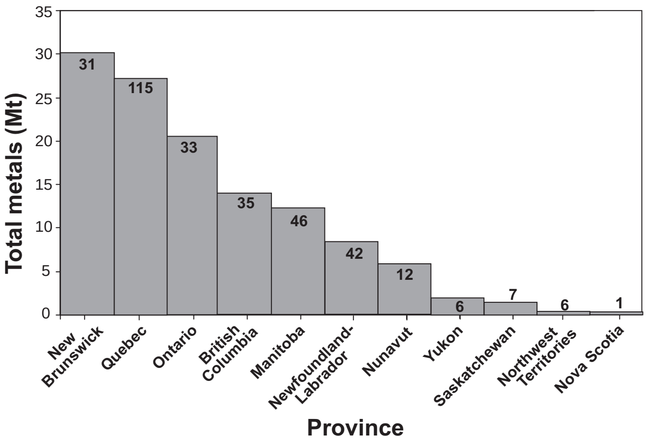

Figure 7. Histogram of the total tonnage of base metals from known VMS deposits per province; also shown are the number of deposits. The aggregate tonnage was calculated by total metals represent divided by geological reserves (proven, possible, and probable; non 43-101 compliant).

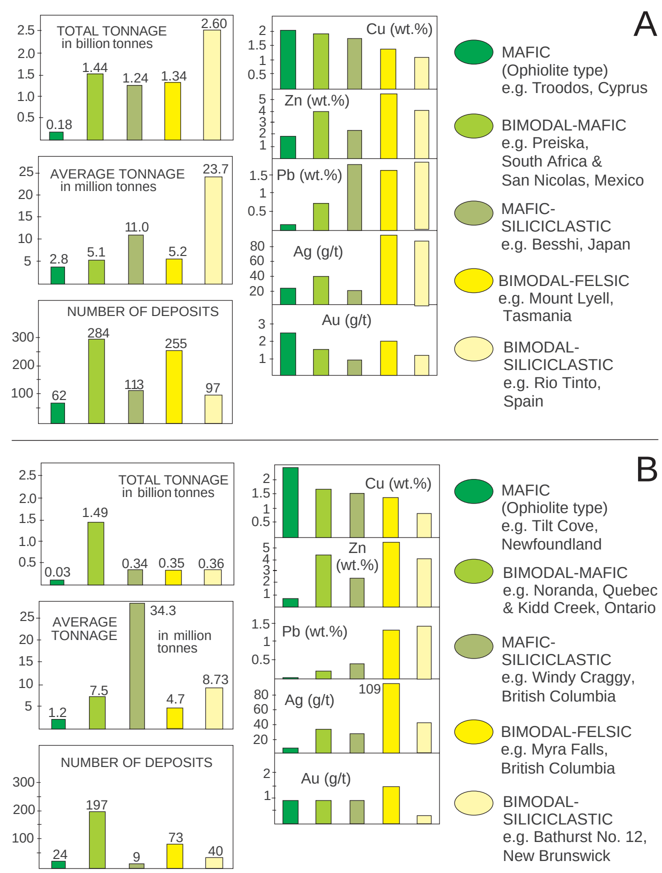

Figure 9. Statistics for VMS deposits grouped by lithologic class (Barrie and Hannington, 1999): **(A)** worldwide deposits; **(B)** Canadian deposits.

along transform fault sutures (Bloomer et al., 1995). These early suprasubduction terranes are most commonly observed in the ancient rock record at the base of oceanic arc assemblages in which VMS deposits are spatially associated with isolated extrusive rhyolite complexes near the top of thick basalt and basaltic andesite successions. The best Canadian example of these bimodal mafic-dominated caldera settings is the Paleoproterozoic host succession to the Anderson, Stall, and Rod VMS deposits in the Snow Lake camp, Manitoba (Bailes and Galley, 1999). The komatiite-basalt-rhyolite setting for the Archean Kidd Creek deposit is interpreted to be an early primitive arc setting possibly linked to an underlying mantle plume (Wyman et al., 1999), or a rare example of a non-arc VMS setting associated with partial lithospheric melting above a mantle plume (cf. Iceland).

In the idealized evolutionary stages of arc terrane formation, extension of the principal arc assemblage is another common period of VMS formation (Fig. 11). This results in

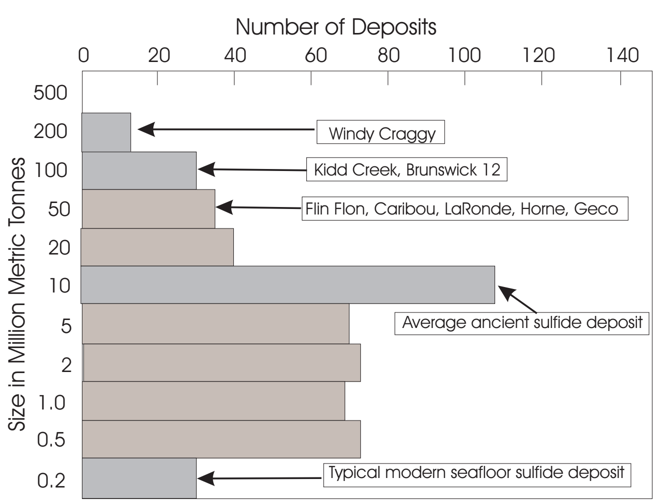

Figure 8. Global (proven, possible, and probable; non 43-101 compliant) size distribution for VMS deposits, with deposits over 50 Mt considered "very large" (Table 1), those over 100 Mt considered "giant", and those over 150 Mt defined as "supergiant". Atlantis II Deep, Red Sea, is considered the largest modern example of a seafloor massive sulphide deposit. Best known examples of Canadian very large, giant, and supergiant deposits are shown. Modified from Hannington et al. (1995).

the formation of calderas in which bimodal mafic extrusive successions predominate. This is perhaps the most common arc environment for VMS formation in oceanic arc settings. Bimodal mafic-dominated VMS-hosting calderas include the Archean Noranda and the Paleoproterozoic Flin Flon mining camps (Gibson and Watkinson, 1990; Syme and Bailes, 1993). Rifting of continental margin arcs, in contrast, results in the development of more volcaniclastic-rich bimodal felsic extensional settings. Examples include the Sturgeon Lake camp in the Archean Wabigoon terrane of Ontario (Morton et al., 1990; Whalen et al., 2004) and the Devonian Buttle Lake VMS camp in the Wrangellia Terrane of British Columbia (Barrett and Sherlock, 1996a). Outside Canada, the Paleoproterozoic Skellefte mining district in Sweden (Allen et al., 1996a) and the Cambrian Mount Read VMS district in Tasmania (Corbett, 1992) are other examples of rifted continental margin arc settings. Continued extension in both oceanic and continental margin arc settings results in the development of back-arc basins. In oceanic arc settings, mature back-arc ophiolites also can host VMS deposits. Canadian examples include the Paleoproterozoic Birch-Flexar-Coronation camp on the Saskatchewan side of the Flin Flon mining district (Wyman et al., 1999) and Betts Cove, Newfoundland (Swinden et al., 1988; Bédard et al., 1998). Well known examples outside Canada include the Tethyan ophiolites in Cyprus (Troodos), Oman (Semail), and Turkey (Ergani) (Galley and Koski, 1999, and references therein).

Table 3. Examples of large-tonnage volcanogenic massive sulphide deposits of the World (Canadian deposits in red).

NAME	COUNTRY	Orogen	Mtonnes Ore (Geol.)	CU %	PB %	ZN %	AU (g/t)	AG (g/t)	Orebody Age (est. Ma)
SUPERGIANT									
Rio Tinto (Stockwork)	Spain	Hercynian	1200.00	0.15		0.15		7.00	320
Rio Tinto (Massive)	Spain	Hercynian	335.00	0.39	0.12	0.34	0.36	22.00	320
Kholodnina	Russia	Baikal-Vitim	300.00	0.04	0.79	5.2			750
Windy Craggy (Cu,Co)	Canada	N.Cordilleran	297.40	1.38		0.25	0.22	3.83	220
Neves Corvo Group	Portugal	Hercynian	270.00	1.59	0.15	1.41		9.87	320
Gai East	Russia	Uralides (Hercynian)	269.00	1.2		0.7	1.10	7.70	395
Aljustrel Group (total)	Portugal	Hercynian	250.00	1.2	1.2	3.2	1.00	38.00	320
Brunswick #12	Canada	Appalachian	229.80	0.46	3.01	7.66	0.46	91.00	465
Gai	Russia	Uralides (Hercynian)	205.00	1.4	0.06	0.5	1.10	7.90	395
La Zarza	Spain	Hercynian	164.00	1.2	1.1	2.5	1.80	47.00	320
Ducktown	USA	Grenvillean? (Oecee)	163.34	1		0.9	0.30	3.00	1000
GIANT									
Kidd Creek	Canada	Abitibi (Kenoran)	147.88	2.31	0.22	6.18	0.01	87.00	2714
Horne - No. 5 Zone	Canada	Abitibi (Kenoran)	144.00	1		0.9	1.40		2698
Ozernoe	Russia	Baikal-Vitim	130.00	0.01	1.2	6.2			500
Ridder-Sokol	Kazakhstan	Altaides (Hercynian)	125.00	0.3	2	4	2.50	10.00	400
Zyryanov	Kazakhstan	Altaides (Hercynian)	125.00	0.4	2.7	4.5	0.13	20.00	395
Gacun	China	Yidun, Indosinian (Tethyan)	124.00	0.72	4.62	6.66	0.46	157.00	200
Masa Valverde	Spain	Hercynian	120.00	0.5	0.6	1.3	0.80	38.00	320
Sibai	Russia	Uralides (Hercynian)	115.00	1	0.04	1.56	0.60	16.00	392
Tharsis	Spain	Hercynian	110.00	0.5	0.6	2.7	0.70	22.00	320
Yubileinoe	Russia	Uralides (Hercynian)	107.00	1.9	0.1	1.2	2.50	16.00	392
Uchaly	Russia	Uralides (Hercynian)	106.00	1.1		3.8	1.10	15.50	392
Madneuli	Georgia	Caucasian (Tethyan)	102.60	1.29		1.8	0.73	4.31	70
VERY LARGE									
Mount Lyell	Australia	Tasman	98.57	1.17	0.01	0.04	0.39	7.20	495
Rouez	France	Caledonian	90.74	0.6		1.5	1.50	21.00	600
Aznalcollar	Spain	Hercynian	90.00	0.51	0.85	1.8	0.48	37.00	320
LaRonde (incl.LaRonde-II)	Canada	Abitibi (Kenoran)	88.00	0.3		1.7	5.07	40.90	2710
Skorpion	Namibia	Gariep	85.00		0.71	8.05			752
Podolsk	Russia	Uralides (Hercynian)	84.10	2.01	0.13	1.3	1.49	27.60	392
Murgul	Turkey	Pontides (Tethyan)	83.14	0.76	0.05	0.03	0.05	3.70	175
Ruttan	Canada	Trans-Hudson	82.80	1.37	0.08	1.63	0.49	13.11	1900
Tambo Grande 3	Peru	S.Cordilleran	82.00	1	0.3	1.4	0.80	25.00	104
San Nicolas	Mexico	C.Cordilleran	79.90	1.34		2.27	0.53	30.00	136
Pyhasalmi	Finland	Svecokarelian	75.70	0.9	0.06	1.9	0.20	14.00	1921
Sotiel	Spain	Hercynian	75.20	0.56	1.34	3.16	0.21	24.00	320
Los Frailes	Spain	Hercynian	70.00	0.34	2.25	3.92		62.00	320
Heath Steele	Canada	Appalachian	69.90	0.98	0.89	2.69	0.54	47.00	465
Ulaan	Mongolia	Kazakh-Mongol(Hercyn.)	68.00		1.2	2	0.21	53.00	380
Caribou	Canada	Appalachian	64.69	0.51	1.6	4.29	1.89	51.00	465
Crandon	USA	Trans-Hudson	63.50	1		6.5			1870
Flin Flon	Canada	Trans-Hudson	62.93	2.2		4.1	2.85	43.20	1875
Zincgruvan(+Knalla)	Sweden	Svecokarelian	60.00		3.2	10.4		69.00	1890
Tishin	Kazakhstan	Altaides (Hercynian)	60.00	0.5	0.9	5.3	0.90	15.00	395
Geco	Canada	West.Superior (Kenoran)	58.40	1.86	0.15	3.45		50.06	2720
Tambo Grande 1	Peru	S.Cordilleran	56.20	1.6	0.3	1	0.50	26.00	104
Deerni (Cu-Co)	China	Indosinian (Tethyan)	54.00	1.23		1.57	0.42	4.73	260
Horne-H&G Orebodies	Canada	Abitibi (Kenoran)	53.70	2.2			6.10	13.00	2700
Mount Morgan	Australia	Tasman	50.00	0.7	0.05	0.1	4.70	0.60	385
Outokumpu(Cu,Zn,Co)	Finland	Svecokarelian	50.00	3.3	0.005	1.07	0.07	9.00	1970
Artem'yev	Kazakhstan	Altaides (Hercynian)	50.00	1.4	1.6	2.2	1.20	143.00	375
Lousal	Portugal	Hercynian	50.00	0.7	0.8	1.4	0.70	21.00	300
LARGE									
Britannia	Canada	N.Cordilleran	49.31	1.08	0.033	0.26	0.34	4.03	150
Novo-Leninogorsk	Kazakhstan	Altaides (Hercynian)	48.00	0.16	1.43	4.04	1.54	32.80	395
Preiska	South Africa	Namaqua	47.00	1.7		3.8	0.00		1300
Anyox-Hidden Creek	Canada	N.Cordilleran	45.95	1.37			0.17	9.92	195
Hanaoka Mine (total)	Japan	Japan arcs(Tethyan)	43.50	1.2	1.5	4.7	0.40	68.00	15
Aguas Tenidas	Spain	Hercynian	41.00	1.3	0.91	3.1	0.50	37.00	320
Hongtoushan	China	Sino-Korean Platform	40.00	1.75		2.4	0.77	32.40	3000
Maleev	Kazakhstan	Altaides (Hercynian)	40.00	2.3	1.3	7.5	0.75	75.00	390
Orlovskoye	Kazakhstan	Altaides (Hercynian)	40.00	2.4	0.5	2.1	0.80	47.00	392
Ashele (#1)	China	Altayshan (Hercynides)	34.00	2.51		2.98	0.57	104.03	375
Xiaotieshan	China	Tarim-NorthQilian (Caled.)	34.00	1.26	3.39	5.33	2.28	126.20	440
Arctic (Brooks Range,Ak)	USA	N.Cordilleran	32.93	4	0.8	5.5	0.70	55.00	365
Rosebery	Australia	Tasman	32.70	0.58	4.4	14.5	2.70	145.00	495
Liwu	China	Yidun, Indosinian (Tethyan)	31.00	2.5		0.62			430
Belousov	Kazakhstan	Altaides (Hercynian)	30.00	2.6	2.4	9.2	2.00	119.00	395
Lokken (Hoydal)	Norway	Caledonian	30.00	2.3	0.02	1.8	0.29	19.00	450
Jerome- United Verde	USA	Yavapai	30.00	4.8		0.2	1.37	49.70	1800
Bald Mountain	USA	Appalachian	29.98	1.03	<0.05	1.12	0.51	14.40	430
Besshi	Japan	Japan arcs(Tethyan)	29.95	2.6		0.3	0.70	21.00	210
Selbaie	Canada	Abitibi (Kenoran)	29.90	1.21		1.91	0.63	37.02	2730
Myra Falls Group	Canada	N.Cordilleran	29.32	1.83	0.55	6.25	2.00	49.00	365
Garpenberg (+Lappberget)	Sweden	Svecokarelian	29.00	0.3	3.3	5.3	0.65	98.00	1890
Bisha	Eritrea	Pan African	28.60	1.52		4.63	1.68	46.80	850
Vihanti	Finland	Svecokarelian	28.10	0.48	0.36	5.12	0.49	25.00	1910
Falun	Sweden	Svecokarelian	28.10	3	1.5	4	3.00	20.00	1875
Safyanovka	Russia	Uralides (Hercynian)	27.50	3.04		1.4	1.32	25.00	392
McIlvenna Bay	Canada	Trans-Hudson	27.23	0.9	0.1	3.27	0.34	16.43	1900
Mattagami Lake	Canada	Abitibi (Kenoran)	25.60	0.42		5.1	0.30	21.60	2725
Las Cruces (primary)	Spain	Hercynian	25.20	1.25	1.69	3.63	0.38	38.00	320
Granduc	Canada	N.Cordilleran	25.06	1.79	0.021	0.1	0.17	10.63	190
Korbalikhinsk	Russia	Altaides (Hercynian)	25.00	1.46	2.01	9.81			375
Greens Creek	USA	N.Cordilleran	25.00	0.32	5.1	13.9	5.61	706.00	220

* Modified from Franklin et al., 2005

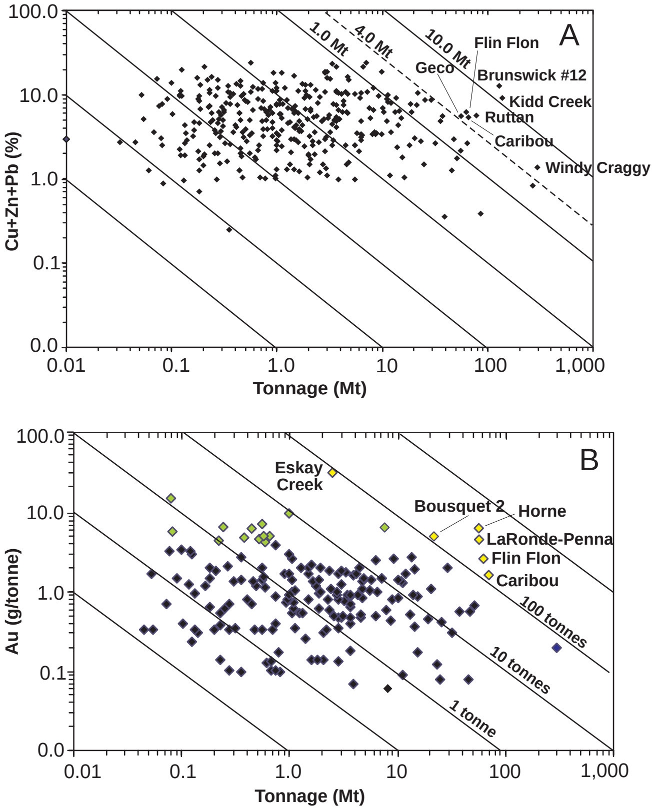

Figure 10. Distribution of Canadian VMS deposits with respect to **(A)** aggregate base metal grade versus tonnes and **(B)** contained Au versus tonnes; most auriferous Au deposits contain >4 g/t Au (green diamonds). Those containing over 1000 tonnes of Au (yellow diamonds) include both auriferous VMS deposits and those with moderate Au grades but large tonnages. Giant and supergiant VMS deposits are identified by name. From National VMS database (Appendix 1).

Continental back-arc settings contain some of the world's most economically important VMS districts. These environments are dominated by bimodal siliciclastic rocks ± iron formation and include the Ordovician Bathurst camp of New Brunswick (van Staal et al., 2003) and Finlayson Lake (Piercey et al., 2001). Examples outside Canada include the Archean Golden Grove camp in Western Australia (Sharpe and Gemmell, 2002), the Paleoproterozoic Bergslagen district of Sweden (Allen et al., 1996b), the Cambro-Ordovician Mount Windsor district of Queensland (Doyle and McPhie, 2000), the Devono-Mississippian Iberian Pyrite Belt (Carvalho et al., 1999), and parts of the Devonian Southern Urals VMS districts of Russia and Kazakhstan (Herrington et al., 2002; Franklin et al., 2005).

Other extensional environments may form in post-accretion and/or successor arc settings. Crustal thickening of an accreted ocean-floor-arc assemblage can result in modification of the angle of descent of the subducting slab, cessation of subduction along a section of plate boundary, or a change in the direction of approach of the colliding plates (Ziegler, 1992; Hamilton, 1995). This process results in the generation of strike-slip basins in the older arc assemblages. Magmatism associated with these successor arc basins may be associated with mineralized porphyry systems (Richards, 2003), and the basins may be infilled with both subaqueous and subaerial bimodal volcanic rocks. This can result in the formation of multiple mineral deposit types, including epithermal and VMS deposits. A good example of this is the Lower Jurassic Hazelton Group in British Columbia, which hosts the Eskay Creek Au-rich VMS deposit (Barrett and Sherlock, 1996b; Nelson and Mihalynuk, 2004). When these strike-slip fault systems propagate into a continental margin setting, such as in the modern day Guaymas Basin, Gulf of California, the strike-slip basins begin to infill with terrigenous sediment. They can host mafic siliciclastic-hosted VMS deposits, such as the Triassic Windy Craggy and Green's Creek deposits in British Columbia and Alaska, respectively (Peter and Scott, 1999). These are known as Besshi-type deposits from the type locality in the fore-deep accretionary wedge outboard of the Miocene Japanese islands. Other mafic siliciclastic-hosted VMS deposits occur along modern sedimented seafloor spreading systems such as Middle Valley, on the Juan de Fuca Ridge off the British Columbia coast (Goodfellow et al., 1999).

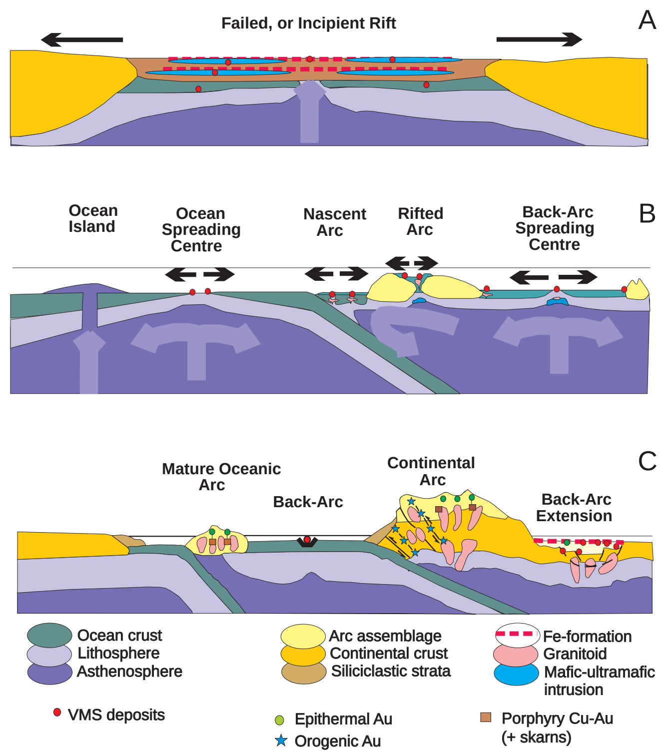

Figure 11. There are three principal tectonic environments in which VMS deposits form, each representing a stage in the formation of the Earth's crust. **(A)** Early Earth evolution was dominated by mantle plume activity, during which numerous incipient rift events formed basins characterized by early ocean crust in the form of primitive basalts and/or komatiites, followed by siliciclastic infill and associated Fe-formation and mafic-ultramafic sills. In the Phanerozoic, similar types of incipient rifts formed during transpressional, back-arc rifting (Windy Craggy). **(B)** The formation of ocean basins was associated with the development of ocean spreading centers along which mafic-dominated VMS deposits formed. The development of subduction zones resulted in oceanic arc formation with associated extensional domains in which bimodal mafic, bimodal felsic, and mafic-dominated VMS deposits formed. **(C)** The formation of mature arc and ocean-continent subduction fronts resulted in successor arc and continental volcanic arc assemblages that host most of the felsic-dominated and bimodal siliciclastic deposits. Thin black arrows represent direction of extension and thick, pale arrows represent mantle movement. Modified from Groves et al., 1998

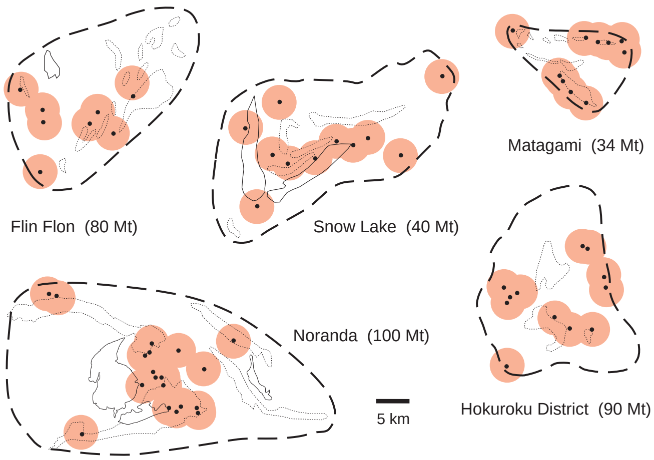

Figure 12. A same-scale comparison of selected VMS districts. A 5 km diameter circle around each deposit shows the hypothetical area of influence of proximal-scale alteration about each deposit, all encircled by a dashed line defining the proposed extent of a regional-scale alteration system for each camp based on the presence of known felsic volcanic and synvolcanic formations/intrusions (thin black lines). The Noranda example corresponds closely to the observed alteration. Modified from Sangster (1980).

District-Scale Environments

Most, but not all VMS deposits, occur in clusters that define major mining camps. Sangster (1980) used the distribution of VMS deposits within well known mining districts in Canada to indicate that there was a first-order regional control on their distribution (Fig. 12). In general, the deposit clusters are restricted to either linear rifts or calderas. These features are generated by regional thinning of the basement, decompression melting of the underlying mantle, and generation of mafic magmas (Fig. 13). In ocean spreading-ridge settings, these magmas rise to within a few thousand metres of the seafloor to form elongate gabbroic sills that parallel the seafloor-spreading axes (Stinton and Detrick, 1992). Where pre-existing ocean-floor or arc lithosphere is present, these mafic magmas, at temperatures of 1000 to 1400°C, may underplate the crust, producing intermediate to felsic partial melts and bimodal mafic intrusive/extrusive assemblages. The associated gabbro-diorite-tonalite-trondhjemite intrusive complexes may rise to within 2 to 3 km of the seafloor (Galley, 2003, and references therein). Where extension is taking place in thicker (20-30 km) crust, such as in a continental back-arc setting, magmas may form mid-crustal intrusions. These melts may not intrude into their comagmatic volcanic assemblages but may remain in the underlying basement rocks. These different scenarios result in multiple forms of district-scale alteration and deposit characteristics for a VMS district.

The presence of either mafic or composite high-level subvolcanic intrusions within a rift or caldera setting will drive a subseafloor hydrothermal-fluid convection system (Galley, 1993; Alt, 1995) (Fig. 14). Connate seawater in the porous crust is first heated, causing it to become buoyant. As this heated water rises up synvolcanic fault structures, cold seawater is drawn in above the cooling intrusion. These originally cold, near neutral pH fluids are progressively heated during their downward migration, interacting with the surrounding rocks at progressively higher temperatures. The isotherms above cooling sill complexes are generally horizontal, resulting in the formation of a stratified, district-scale semi-conformable alteration zone controlled in extent by the strike length of the underlying intrusion (Spooner and Fyfe, 1973; Munha and Kerrich, 1980; Lagerblad and Gorbatchev; 1985; Gibson and Watkinson, 1990; Galley, 1993; Alt, 1995; Brauhart et al., 1998; Bailes and Galley, 1999) (Fig. 14). The distribution of the resulting alteration mineral assemblages mimics that of regional metamorphic facies (Spooner and Fyfe, 1973; Alt, 1995; Hannington et al., 2003) (Fig. 15). Hydrothermal fluid reaction zones immediately overlying the intrusions can be altered to amphibolite-facies assemblages, including Fe-Ca-rich amphibole, clinozoisite, Ca-plagioclase, and magnetite (Figs. 15, 16A,B,C). Above this are Na-Ca-rich greenschist-facies assemblages characterized by albite, quartz, chlorite, actinolite, and epidote. Closer to

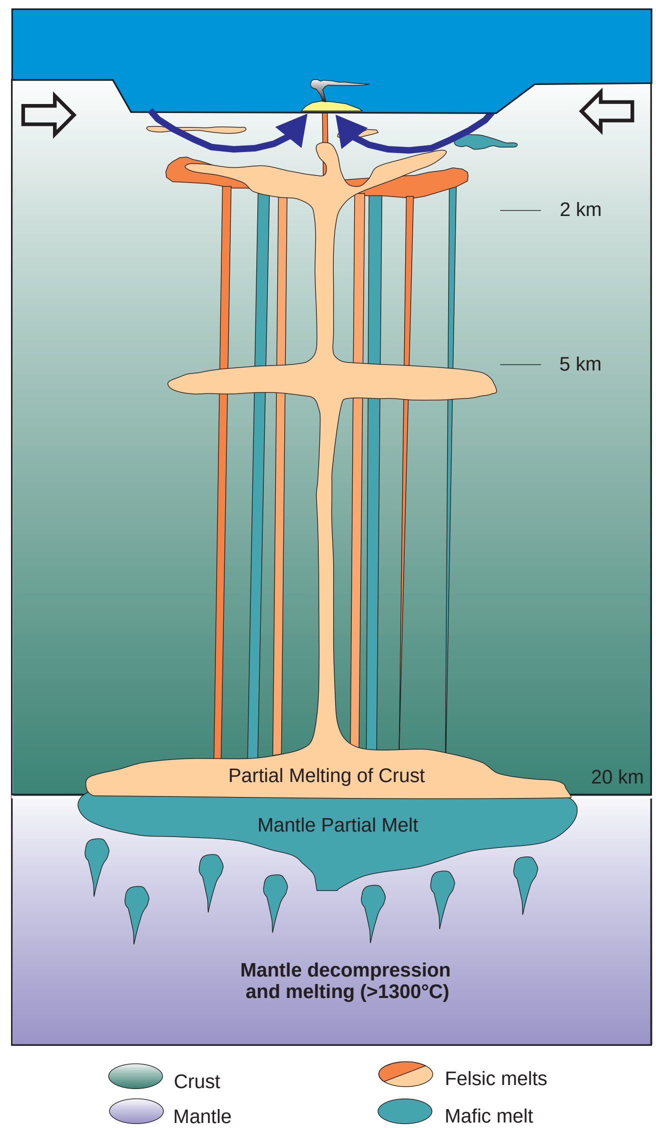

Figure 13. VMS environments are characterized by tectonic extension at various scales (open arrows). Extension resulted in crustal thinning, mantle depressurization, and the generation of basaltic melts. Depending on crustal thickness and density, these mafic melts ponded at the base of the crust, resulting in partial melting and generation of granitoid melts. These anhydrous, high-temperature melts quickly rose to a subseafloor environment (<3 km below seafloor), where their heat initiated and sustained convective hydrothermal cells that formed VMS deposits (black arrows).

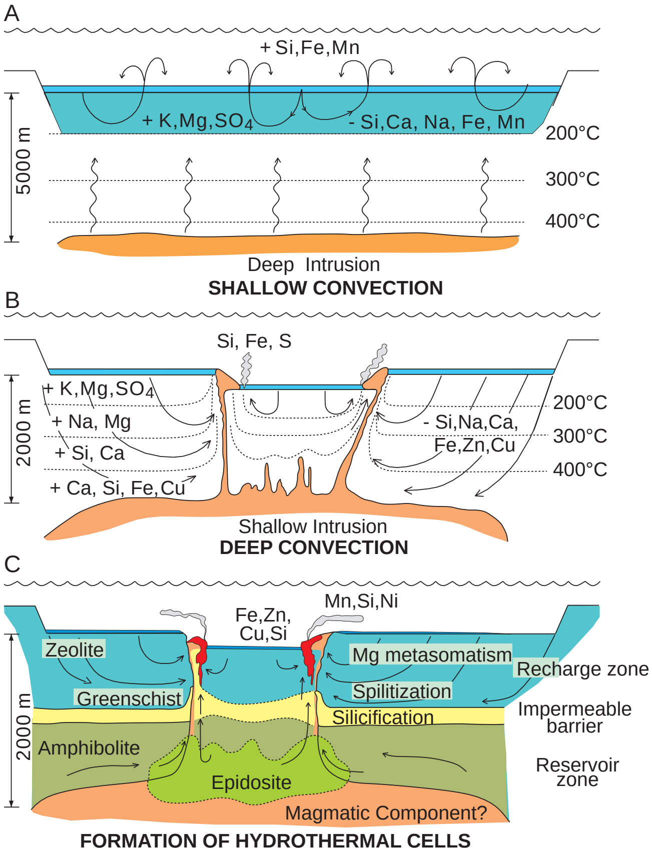

FIGURE 14. The development and maturation of a generic subseafloor hydrothermal system involves three stages. **(A)** The relatively deep emplacement of a subvolcanic intrusion below a rift/caldera and the establishment of a shallow circulating, low-temperature seawater convection system. This results in shallow subseafloor alteration and associated formation of hydrothermal exhalative sediments. **(B)** Higher level intrusion of subvolcanic magmas and resultant generation of a deep-seated subseafloor seawater convection system in which net gains and losses of elements are dictated by subhorizontal isotherms. **(C)** Development of a mature, large-scale hydrothermal system in which subhorizontal isotherms control the formation of semiconformable hydrothermal alteration assemblages. The high-temperature reaction zone next to the cooling intrusion is periodically breached due to seismic activity or dyke emplacement, allowing focused upflow of metal-rich fluids to the seafloor and formation of VMS deposits. From Galley (1993).

the seafloor are zeolite-clay and related subgreenschist mineral assemblages characterized by K-Mg-rich smectites, mixed-layer chlorites, and K-feldspar. In some regional hydrothermal systems, the low-temperature alteration assemblages closest to the seafloor are dominated by carbonate species due to precipitation from shallowly circulating seawater (Fig. 16D). These chemical and mineralogical changes in the ancient rock record can be further revealed by mapping shifts in bulk rock oxygen and hydrogen isotope compositions of the different zones (Green et al., 1983; Taylor and South, 1985; Aggarwal and Longstaffe, 1987; Cathles, 1993; Paradis et al., 1993). These stratified alteration zones can have a strike length of 5 to 50 km and a thickness of 1 to 3 km in caldera settings (Fig. 15). The size and areal morphology of the alteration system is a reflection of the size and areal morphology of the VMS deposit cluster (Fig. 12). The distribution of VMS deposits within this cluster depends on synvolcanic fault distribution relative to the underlying intrusions (Eastoe et al., 1987; Gibson and Watkinson, 1990; Brauhart et al., 1998; Galley, 2003). Faults that acted as conduits for volcanic feeder systems were the focal point for ascent of high-temperature, acidic metal-laden hydrothermal fluids that formed VMS deposits. These fault systems may have remained active through several cycles of volcanic and hydrothermal activity. This may have resulted in several periods of VMS formation at different stratigraphic levels within the rift or caldera structure.

Mafic-dominated, bimodal mafic, and bimodal felsic host rocks are dominated by effusive volcanic successions and accompanying, large-scale hypabyssal intrusions (Fig. 17). This high-temperature subseafloor environment supported high-temperature (>350°C) hydrothermal systems, from which may have precipitated Cu, Cu-Zn, and Zn-Cu- (Pb) VMS deposits with variable Au and Ag contents. Areally extensive, 1 to 5 m thick, Fe-rich “exhalites” (iron formations) may mark the most prospective VMS horizons (Spry et al., 2000; Peter, 2003) (Fig. 18A). These exhalite deposits consist of a combination of fine volcaniclastic material, chert, and carbonates. They formed during the immature and/or waning stages of regional hydrothermal activity when shallowly circulating seawater stripped Fe, Si, and some base metals at <250°C and precipitated them on the seafloor through extensive, but diffuse, low-temperature hydrothermal venting. Formation of exhalites on a basalt-dominated substrate was commonly accompanied by silicification and/or chloritization of the underlying 200 to 500 m of strata (Fig. 18B). Examples of this are observed in the Noranda, Matagami Lake, and Snow Lake VMS camps (Kalogeropoulos and Scott, 1989; Liaghat and MacLean, 1992; Bailes and Galley, 1999). In felsic volcaniclastic-dominated terranes, the generation of Fe-formation exhalites was accompanied by extensive K-Mg alteration of the felsic substrate, as recorded in the Bergslagen district of Sweden (Lagerblad and Gorbatschev, 1985) and in the Iberian Pyrite Belt (Munha and Kerrich, 1980).

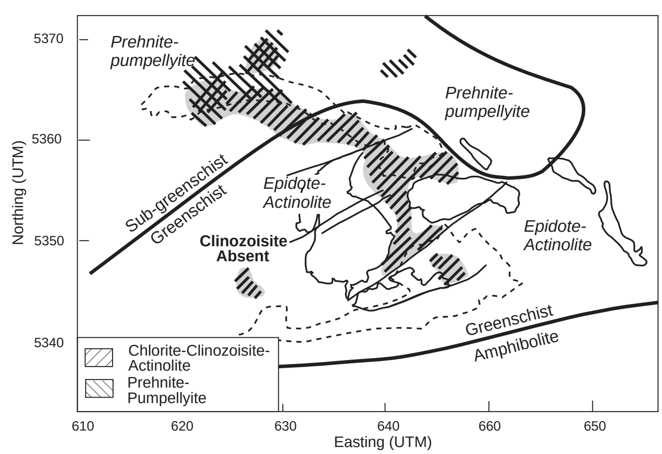

FIGURE 15. Comparison of regional greenschist-facies hydrothermal alteration in the Noranda Volcanic Complex with previously mapped metamorphic isograds (solid lines from Dimroth et al., 1983; Powell et al., 1993). The distribution of greenschist-facies hydrothermal alteration (shaded) suggests that interpreted metamorphic zonation is at least partly a product of early synvolcanic hydrothermal processes. Note that epidote and chlorite in the pre-cauldron sequence are distinct from those of the mine sequence volcanic rocks, even though they are well within the epidote-actinolite subfacies and have been metamorphosed at the same pressure and temperature. Modified from Hannington et al. (2003).

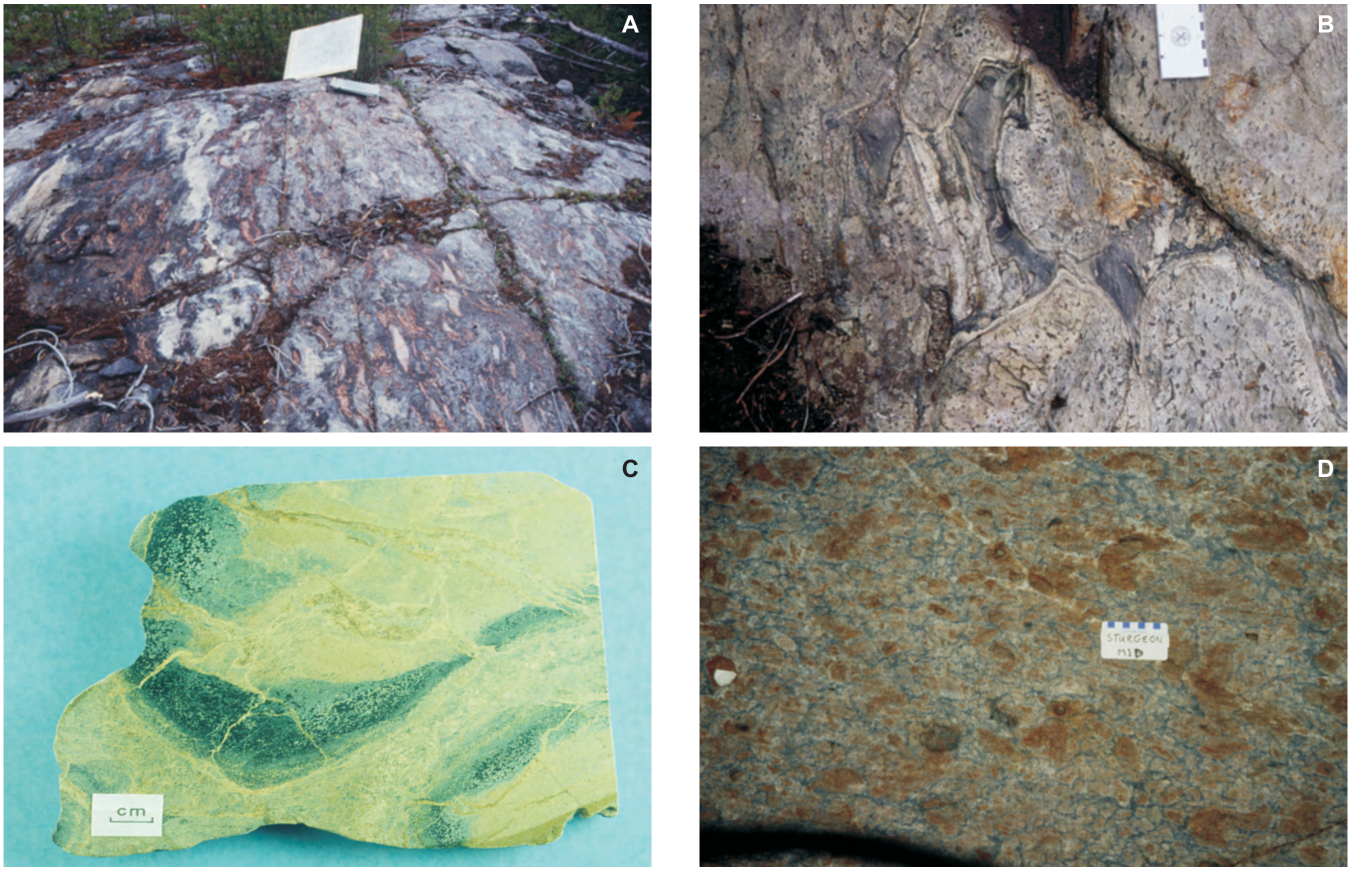

Figure 16. (A) High-temperature hydrothermally altered mafic volcaniclastic turbidite (left) overlain by a strongly silicified mafic debris flow 1200 m below the Chisel-Lost-Ghost VMS horizon, Snow Lake. This is a regional-scale reaction zone overlain by a high-temperature zone of silica precipitation. **(B)** Strongly silicified pillows with pipe vesicles infilled with actinolite, epidote, and magnetite, and interpillow hyaloclastite completely replaced by the same assemblage. This alteration facies directly overlies the subvolcanic Mooshla intrusion, Bousquet VMS camp, Quebec. **(C)** Epidosite typical of the root zones of VMS hydrothermal upflow zones in which high fluid/rock ratios have resulted in leaching of lithophile, chalcophile, and low field strength elements from the strata. **(D)** Chloritoid-rich zone below the Mattabi deposit, Sturgeon Lake, where Fe-rich hydrothermal fluids overprinted a previously formed carbonate-rich regional alteration zone.

Mafic, felsic, and bimodal siliciclastic volcanic assemblages tend to host volumetrically smaller mafic and/or felsic sill-dyke complexes, and generally contain Zn-Cu-Co and Zn-Pb-Cu-Ag VMS deposits, respectively. More Cu-rich deposits, such as Neves Corvo in the Iberian Pyrite Belt, may also be present in settings proximal to discrete extrusive complexes. The district-scale semiconformable hydrothermal systems consist of low-temperature mineral assemblages, with Mg-K smectite and K-feldspar alteration overlain by extensive units of low-temperature Fe-Si-Mn deposits. Other types of iron formation in VMS districts are interpreted to be products of plume fallout from high-temperature hydrothermal venting, or collection of hypersaline brines within fault-controlled depressions on the seafloor (Peter, 2003). Iron formation horizons can extend for tens of kilometres, as in the Bathurst VMS camp in New Brunswick (Peter and Goodfellow, 1996) (Fig. 18C), the Paleoproterozoic Bergslagen district (Allen et al., 1996b), the Devono-Mississippian Iberian Pyrite Belt in Spain and Portugal (Carvalho et al., 1999), and the Mississippian Finlayson Lake camp, Yukon (Peter, 2003). Mineralogical variations within these regionally extensive iron formations, from oxide through carbonate to sulphide, are indicative of proximity to more focused, higher temperature hydrothermal vent complexes and also reflect stratification of the water column in the basin. The mineralogical variations are accompanied by changes in element ratios such as Fe, Mn, B, P, and Zn (exhalative component) versus Al and Ti (detrital clastic component) (Peter and Goodfellow, 1996).

Deposit-Scale Environments

VMS deposits consist of a massive to semimassive stratabound sulphide lens, and most are underlain by a sulphide-silicate stockwork vein system (Figs. 1, 4). Within this broad framework, there is a spectrum of deposit sizes, morphologies, and compositions, depending on the nature of the synvolcanic faulting, footwall and host-rock lithology, water depth, size and duration of the hydrothermal system, temperature gradients, and degree of preservation. Individual massive sulphide lenses can be over 100 m thick, tens of metres wide, and hundreds of metres in strike length. The 135 Mt Kidd Creek deposit begins at the present erosion surface and extends for over 2000 m downplunge (original strike length), with the five composite orebodies over 500 m wide and individual lenses up to 100 m thick. The stratabound sulphide mound component of a VMS deposit may have a number of morphologies and variable internal structure (e.g. Fig. 1). Observations of modern seafloor hydrothermal vent complexes in effusive, flow-dominated terranes indicate that the deposits begin to form as a series of

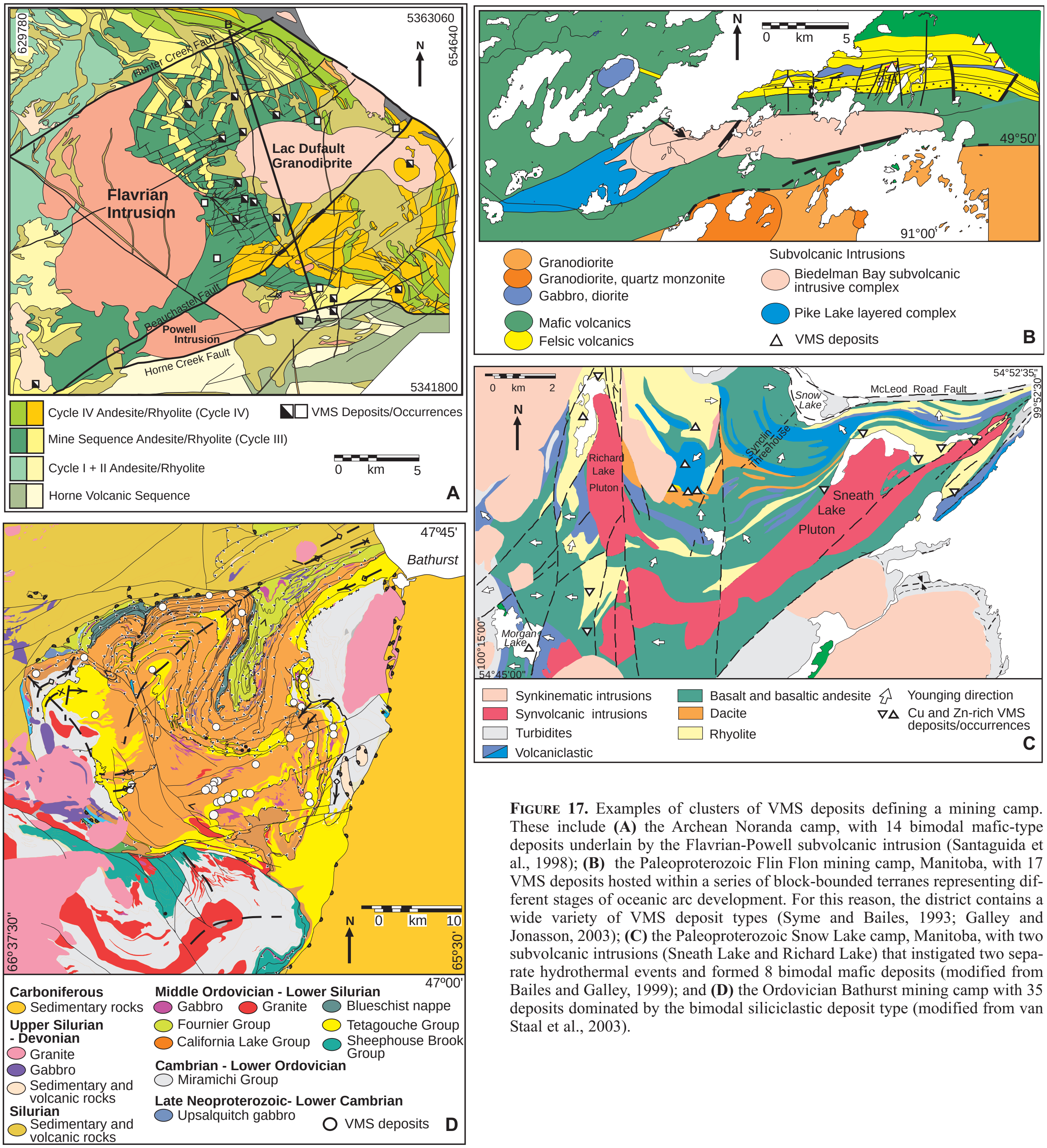

FIGURE 17. Examples of clusters of VMS deposits defining a mining camp. These include **(A)** the Archean Noranda camp, with 14 bimodal mafic-type deposits underlain by the Flavrian-Powell subvolcanic intrusion (Santaguida et al., 1998); **(B)** the Paleoproterozoic Flin Flon mining camp, Manitoba, with 17 VMS deposits hosted within a series of block-bounded terranes representing different stages of oceanic arc development. For this reason, the district contains a wide variety of VMS deposit types (Syme and Bailes, 1993; Galley and Jonasson, 2003); **(C)** the Paleoproterozoic Snow Lake camp, Manitoba, with two subvolcanic intrusions (Sneath Lake and Richard Lake) that instigated two separate hydrothermal events and formed 8 bimodal mafic deposits (modified from Bailes and Galley, 1999); and **(D)** the Ordovician Bathurst mining camp with 35 deposits dominated by the bimodal siliciclastic deposit type (modified from van Staal et al., 2003).

sulphide-silicate-sulphate chimneys (Fig. 19A). These become structurally unstable with continued growth and collapse, and coalesce to form a breccia mound (Fig. 19A,C). Continued circulation of hydrothermal fluids within this breccia mound results in sealing from seawater by a silica, clay, and/or sulphate cap. Progressive deposition of metal sulphides within the mound results in the formation of a complexly textured, semimassive to massive sulphide mound. The flow of hydrothermal fluid through the mound structure commonly results in remobilization of previously deposited metals along a chemical and temperature gradient perpendicular to the seawater interface. This process is referred to as zone refining (Eldridge et al., 1983) and results in a chalcopyrite±pyrrhotite-rich core and a sphalerite±pyrite±galena-rich outer zone (Fig. 20). In extreme cases, much of the base and precious metals can be remobilized out of the sulphide mound and carried into the seawater column by venting hydrothermal fluids and spent fluids (hot seawater). Massive pyritic cores and thin, base- and precious-metal-enriched outer margins are a characteristic of VMS

Figure 18. **(A)** Mine contact tuff exhalite horizon (between white lines) that overlies the silicified andesites of the Waite Formation, Noranda, Quebec. **(B)** Silicified basaltic andesite of the Upper Amulet Formation., Noranda, Quebec, as an example of pervasive silica precipitation that occurred in mafic flows directly underlying tuffaceous exhalite units in many Precambrian VMS camps. **(C)** Banded magnetite-chert Fe-formation overlying the Austin Brook massive sulphide deposit, Bathurst camp (photo by J.M. Peter).

deposits that have had a protracted thermal history (e.g. Hannington et al., 1998; Petersen et al., 2000).

Although many VMS deposits have a clastic component, this is usually subordinate to the massive sulphide facies. In many cases, such as the hanging-wall orebody at Buttle Lake, British Columbia (Barrett and Sherlock, 1996a), Kidd Creek, Ontario (Hannington et al., 1999b), and Louvicourt, Quebec, these subordinate clastic facies contain a mixture of sulphide and host-rock fragments (Fig. 19D). Interbedded sulphide and silicate-rich layers form from erosion and periodic collapse of a sulphide mound to form sand- to breccia-sized deposits. Examples where these clastic sulphide components are a dominant part of the deposit include Eskay Creek and Tulsequah Chief, British Columbia (Barrett and Sherlock, 1996a; Sebert and Barrett, 1996), and Buchans, Newfoundland (Walker and Barbour, 1981). In other cases, finely bedded ore lenses may result from high-temperature plume fallout of sulphide particles intermixing with hydrothermal silica, talc, and Mg-smectites, plus ambient background pelagic sedimentation (Peter, 2003, and references therein). Similar finely banded ores can also be a product of dynamic recrystallization of sulphides during regional deformation events. VMS deposits readily accommodate strain during regional deformation because of the ductile nature of massive sulphide bodies, and can therefore display much higher degrees of recrystallization and remobilization than the surrounding volcanic and sedimentary strata.

In some cases, VMS deposits do not form on the seafloor but develop as a result of shallow subseafloor replacement. This occurs when hydrothermal fluids infill primary pore space in either extrusive, autoclastic, volcaniclastic, or epiclastic successions below an impermeable cap. At the Ansil deposit in the Archean Noranda VMS camp, a succession of laminated felsic ash flows/turbidites infilled a small fault-bounded rift on the felsic flow complex. Hydrothermal fluid seepage up the rift margins resulted in unit-by-unit replacement of the laminated volcaniclastic layers by pyrite, sphalerite, and silica (Fig. 21A). This sulphide-impregnated unit was in turn replaced by massive pyrrhotite-chalcopyrite during a second stage of subseafloor replacement (Galley et al., 1996) (Fig. 21B). Some exceptionally large massive sulphide deposits have formed within volcanic depressions infilled with autoclastic and heterolithologic debris flow and talus deposits. These include the Horne No. 5 lens (Kerr and Gibson, 1993) Kidd Creek (Hannington et al., 1999b), and several orebodies at Buttle Lake (Barrett and Sherlock, 1996a) (Fig. 21C).

Most Canadian VMS deposits are characterized by discordant stockwork vein systems that commonly underlie the massive sulphide lenses, but may also be present in the immediate stratigraphic hanging-wall strata (Fig. 21D). These stockwork vein systems occur at the centre of more extensive, discordant alteration zones. They form by interaction between rising hydrothermal fluids, circulating seawater, and subseafloor rocks. The alteration zones and attendant stockwork vein systems may extend vertically below a deposit for several hundred metres. Proximal hanging-wall alteration can manifest itself as a semi-conformable halo up to tens of metres thick (Brunswick No 12, Bathurst) or may continue above the deposit for tens to hundreds of metres as a discordant alteration zone (Ansil, Noranda). In some cases, the proximal alteration zone and attendant stockwork vein mineralization connects a series of stacked massive sulphide lenses (Amulet, Noranda; LaRonde, Bousquet) representing synchronous and/or sequential phases of ore formation during successive breaks in volcanic activity.

In plan view, proximal alteration zones may form a halo up to twice the diameter of the massive sulphide lens (Fig. 22), but with deposits such as Chisel Lake, Snow Lake

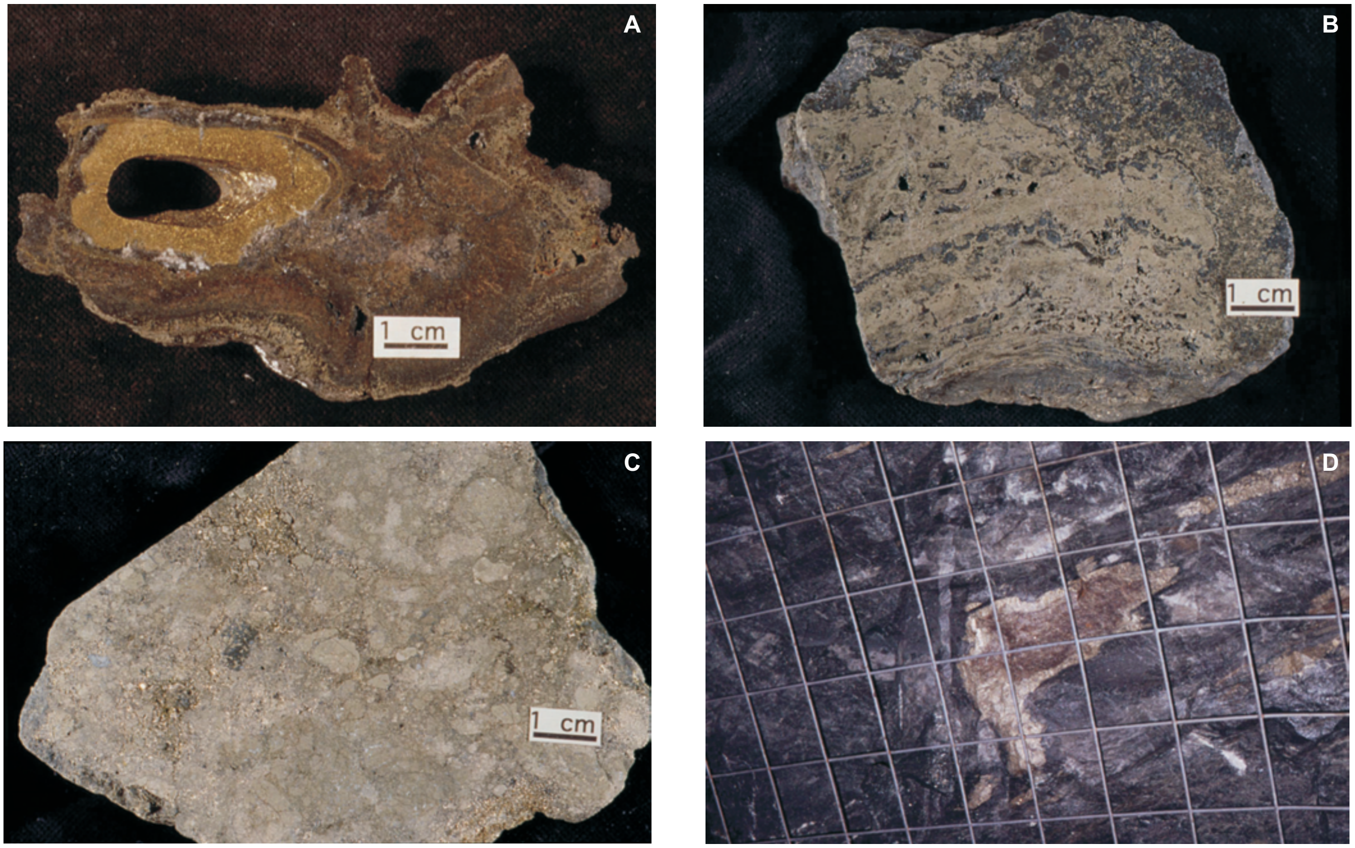

Figure 19. (A) Example of a zoned sulphide chimney from the Endeavour Ridge vent field (I.R. Jonasson). **(B)** Typical textures from a massive sulphide mound, Main vent field, Juan de Fuca Ridge. Mineralogical banding is due to incremental chimney growth, with ovoids representing worm casts. Fragment cemented by later sulphide growth during mound collapse and subsequent invasion by hydrothermal fluid. **(C)** Clastic sandy sulphide ore from Cretaceous Aarja deposit, Semail ophiolite, Oman. This common texture is created by repeated mound collapse resulting from anhydrite dissolution and recementing with later sulphide (photo by I.R. Jonasson). **(D)** Pyrite-sphalerite clast as part of a proximal debris flow, Louvicourt, Val d'Or. 15 cm metal grid for scale.

camp, or Eskay Creek, British Columbia, footwall alteration can be volumetrically extensive and many times the diameter of the massive sulphide lens (Galley et al., 1993). The morphology of proximal alteration zones can vary widely, but generally they tend to widen in proximity to the paleoseafloor surface, suggesting more intensive interaction between shallowly circulating, or connate, seawater and an ascending hydrothermal fluid. The internal mineralogical zonation of the alteration zones is indicative of these mixing phenomena. A Fe-chlorite-quartz-sulphide±sericite± talc mineral assemblage is commonly associated with the core of stockwork vein mineralization, which becomes increasingly quartz- and sulphide-rich towards the lower contact of the massive sulphide lens. In some cases, talc and/or magnetite occur at the base of the massive sulphide lens and the top of the alteration pipe, as at several of the Matagami district VMS deposits, the Ansil deposit in the Noranda camp, and the Late Triassic Chu Chua deposit in the Slide Mountain terrane of British Columbia. The core zone is cloaked in a wider zone of Fe-Mg-chlorite-sericite, including phengite in the part of this zone that encompasses the immediate hanging wall to the massive sulphide lens. Outboard from this is a zone rich in sericite, phengite, Mg-chlorite, ±albite, ±carbonate, and ±barite. This outer zone may also encompass a portion of the hanging-wall strata above, and lateral to, the massive sulphide lens.

In shallow-water environments (i.e. <1,500 m water depth), boiling may have occurred either in the upflow zone or in the immediate subseafloor. Depending on the extent of boiling, this can result in vertically extensive pyritic stock-

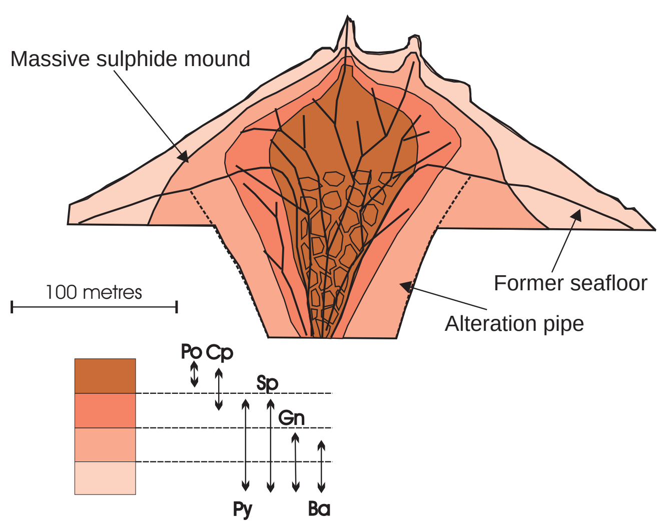

Figure 20. Mineral zonation commonly observed within VMS deposits; this zoning is largely a function of hydrothermal fluid temperature and composition. Temperature gradient results in the zoning of sulphide minerals within both the discordant stockwork zone and the conformable sulphide mound. From Lydon (1984).

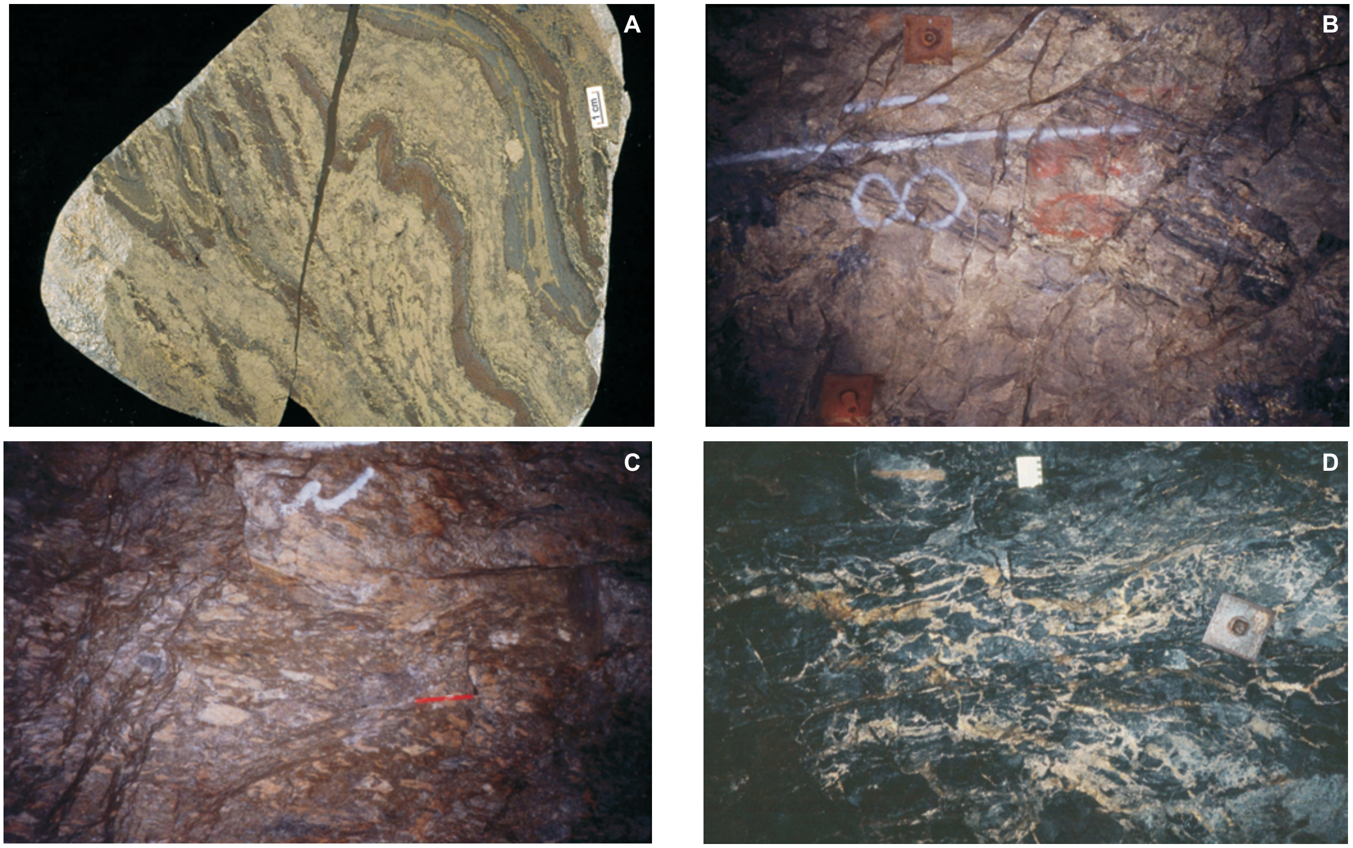

Figure 21. **(A)** Finely bedded tuff partially replaced by massive pyrrhotite-chalcopyrite at the Ansil deposit, Noranda. 15 cm metal plates for scale. **(B)** Cranston tuff unit with lit-par-lit replacement and in-filling by firstly by pyrite-sphalerite, followed by pyrrhotite-chalcopyrite, Ansil deposit, Noranda. **(C)** Rhyolite clasts cemented by pyrite-sphalerite rich sulphide groundmass, Louvicourt deposit, Val d'Or. 12 cm red magnet for scale. **(D)** Well developed pyrrhotite-chalcopyrite vein stockwork zone with intense chlorite alteration of the rhyolite wallrocks, Ansil deposit, Noranda.

work zones, possibly with widespread and intense sericite-quartz-pyrite alteration. The extensive sericite-rich alteration system that underlies the Eskay Creek auriferous VMS deposit may be a product of extensive subsurface boiling of hydrothermal fluids, which resulted in the formation of low-temperature (<200°C) Sb-Hg-As-Pb sulphosalt-rich ore lenses (Sherlock et al., 1999). More advanced argillic alteration may be produced by acidic magmatic volatiles, and this alteration can lead to distinctive aluminosilicate-rich mineral assemblages when metamorphosed to greenschist grade. In the case of the LaRonde deposit, Quebec, "classic" mound-type Zn-Cu-Au massive sulphide lenses are associated with extensive zones of metamorphosed argillic alteration containing pyrite-chalcopyrite-bornite-gold stockwork systems. This may be the result of shallow subsurface boiling and separation of a volatile-rich fluid or focused input of oxidized magmatic fluids (Dubé et al., 2004).

In less extreme cases, distal, low-temperature hydrothermal alteration assemblages associated with VMS deposits may be difficult to distinguish from regional greenschist-facies metamorphic mineral assemblages. When both proximal and regional semiconformable alteration zones are affected by amphibolite-grade regional or contact metamorphism, the originally strongly hydrated alteration mineral assemblages change into a coarse-grained quartz-phyllosilicate-aluminosilicate assemblages that are very distinct from the surrounding unaltered strata (Fig. 23). It then becomes possible to use the systematic variations in these coarse-grained metamorphic mineral assemblages as vectors towards the core of the proximal alteration system or upsection towards the paleo-seafloor (Hodges and Manojlovic, 1993).

Genetic/Exploration Models

Exploration models for VMS systems have several common themes despite the large variety of submarine environments in which the deposits can form. The generation of a VMS-hosting volcanic complex is a response to focused heat flow caused by tectonic extension, mantle depressurization, and the resultant formation of high-temperature mantle melts, crustal partial melts, and common bimodal volcanic succession. The large majority of VMS deposits in Canada form in either bimodal mafic or bimodal felsic volcanic terranes dominated by basalt-basaltic andesite and rhyolite-rhyodacite. Prospective VMS-hosting arc terranes are characterized by bimodal volcanic successions that have a tholeiitic to transitional tholeiitic-calc alkaline composition. The felsic volcanics are characterized by low Zr/Y (<7) and low $(La/Yb)_N$ (<6) ratios, with elevated high field strength element contents (Zr >200 ppm, Y >30 ppm, and elevated LREE and HREE) typical of high-temperature, reduced magmas derived from partially hydrated crust (Barrie et al., 1993; Barrie, 1995; Lentz, 1998). The lower viscosities of the high-temperature felsic magmas result in rapid ascent

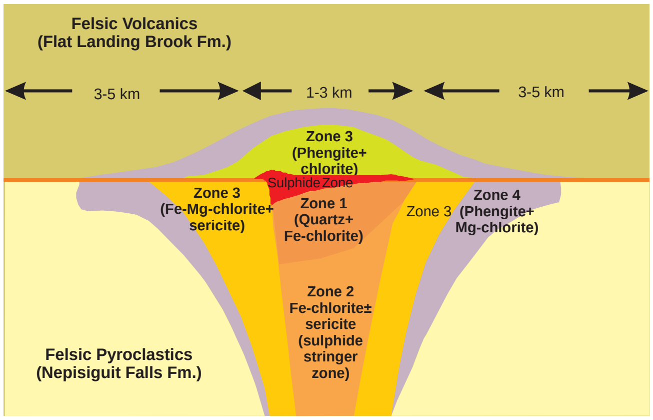

Figure 22. A schematic composite section through a VMS alteration system in the Bathurst mining camp as an example of a VMS proximal alteration zone metamorphosed to greenschist-grade mineral assemblages. From Goodfellow et al. (2003).

with minimal heat loss into subseafloor settings where hydrothermal convection can be initiated. For this reason, most prospective VMS environments are characterized by high-level sill-dyke swarms, discrete felsic extrusive centres, and large (>15 km long and 2000 m thick) subvolcanic composite intrusions. The absence of substantial subvolcanic intrusions in some camps may be due to poor preservation as a result of folding and faulting.

The interaction of large volumes of volcanic strata with seawater within these high-heat extensional environments results in the formation of district-scale alteration zones that extend over the strike length of the VMS-hosting extensional feature (spreading ridge, rift, or caldera). Stacked alteration zones can have an aggregate thickness of 2000 to 3000 m, and may be intruded by resurgent phases of the underlying subvolcanic intrusion. Subvolcanic intrusions themselves can display textural features indicating high-level devolatilization and high-temperature magmatic hydrothermal alteration (quartz-epidote-magnetite-ferroactinolite-sulphides). In some cases, this devolatilization may contribute metals to the overlying convective hydrothermal system (Large et al., 1996; Lydon, 1996; Galley, 2003, and references therein). Regional semiconformable alteration systems resemble regional metamorphic zones (zeolite, greenschist, amphibolite), with increasing grade towards the heat source. Most Canadian VMS districts have been affected by regional metamorphism, which has resulted in recrystallization of the original alteration minerals to greenschist and/or amphibolite assemblages. In camps such as Noranda, Bousquet, Sturgeon Lake, Manitouwadge, Snow Lake, Leaf Rapids, and the western Stikine (Tulsequah Chief), regional metamorphism or local contact metamorphism of alteration minerals has produced distinctive coarse-grained mineral assemblages characterized by such minerals as phlogopite, cordierite, anthophyllite, muscovite, staurolite, garnet, andalusite, and kyanite. The metamorphosed alteration can be distinguished from essentially isochemical regional metamorphic mineral assemblages by the losses and gains of various elements during fluid-rock interactions (Fig. 15).

Submarine volcanic stratigraphy that is prospective for VMS mineralization commonly contains ferruginous exhalative horizons as an indication of subseafloor hydrothermal activity. Precambrian VMS-related exhalites are commonly composed of finely bedded, sulphide-rich tuffaceous material. More extensive Algoma-type oxide facies Fe-formations are also common in VMS-prospective back-arc environments of all ages. Both types of exhalite may form proximal to massive sulphide deposits or extend for strike lengths of several kilometres to tens of kilometres (Spry et al., 2000; Peter, 2003). Proximity to a hydrothermal source in these formations is indicated by positive inter-element correlation between hydrothermal components (Eu, Fe, Mn, Pb, Zn, Cd, Au, Ca, Sr, Ba, P, and CO_2) versus clastic components (Si, Ti, Al, Mg, K, and Zr), increasing chondrite normalized EuEu* (hydrothermal input), and decreasing Ce/Ce* (seawater input) towards the source (Peter and Goodfellow, 1996; Peter, 2003). Vertical and horizontal facies vary from oxide through silicate to carbonate, which in some cases, also may reflect proximity to focused hydrothermal activity (Peter, 2003).

Key Exploration Criteria

The following are the major exploration criteria for Canadian VMS deposits and key attributes of VMS-hosting volcanic complexes.

The deposits occur in volcanic belts from Late Archean to Eocene in which extension is indicated by relatively primitive (tholeiitic to transitional) bimodal volcanism in nascent-arc, rifted-arc, and back-arc environments. Some obducted seafloor-spreading centres and rifted continental margins are also prospective.

VMS formation occurs during periods of major ocean-closing and terrane accretion. These include the Late Archean (2.8-2.69 Ga), Paleoproterozoic (1.92-1.87 Ga), Cambro-Ordovician (500-450 Ma), Devono-Mississippian (370-340 Ma), and Early Jurassic (200-180 Ma).

In effusive flow-dominated settings in oceanic arc and continental margin arcs, VMS deposits can be associated with 15 to 25 km long, mafic to composite synvolcanic intrusions. These intrusions are Na-rich and depleted in low field strength elements and have low airborne radiometric responses but commonly show magnetic halos due to surrounding zones of high-temperature fluid interaction. Exploration should be focused up to 3000 m upsection in the comagmatic volcanic suites in the hanging wall of the intrusions. Rhyolites with high Zr (>300 ppm), negative chondrite-normalized Eu anomalies, $(La/Yb)_N$ values of less than 7, $(Gd/Yb)_N$ values of less than 2, and Y/Zr ratios of less

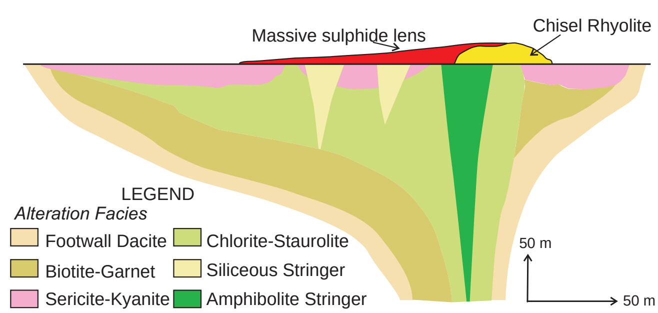

Figure 23. A stylized cross-section through the proximal alteration zone at the Chisel deposit, Snow Lake mining camp, illustrating the changes in mineral assemblages that occur when the terrane undergoes lower to middle amphibolite-grade regional metamorphism. From Galley et al. (1993).

than 7 define high-temperature (>900°C) felsic volcanic environments favourable for VMS formation. The presence of synvolcanic dyke swarms and exhalite horizons are indicative of areas of high paleo-heat flow.

In continental back-arc, bimodal siliciclastic-dominated settings aeromagnetic surveys can be used to identify aerially extensive iron formations to target hydrothermally active paleo-seafloor horizons. Variations in the mineralogy of the iron formations and varying element ratios can serve as vectors toward high-temperature hydrothermal centres. Volumetrically minor sill-dyke complexes also may identify higher temperature hydrothermal centres.

In upper greenschist-amphibolite metamorphic terranes, distinctive, coarse-grained mineral suites commonly define VMS alteration zones. These include chloritoid, garnet, staurolite, kyanite, andalusite, phlogopite, and gahnite. More aluminous mineral assemblages commonly occur closer to a high-temperature alteration pipe. Metamorphic mineral chemistry, such as Fe/Zn ratio of staurolite, is also a vector to ore. These largely refractory minerals have a high survival rate in surficial sediments, and can be used through heavy mineral separation as further exploration guides in till-covered areas.

Mineralogy and chemistry can be used to identify large-scale hydrothermal alteration systems in which clusters of VMS deposits may form. Broad zones of semiconformable alteration will show increases in Ca-Si (epidotization-silicification), Ca-Si-Fe (actinolite-clinozoisite-magnetite), Na (spilitization), or K-Mg (mixed chlorite-sericite±K-feldspar). Proximal alteration associated with discordant sulphide-silicate stockwork vein systems includes chlorite-quartz-sulphide- or sericite-quartz-pyrite±aluminosilicate-rich assemblages and is typically strongly depleted in Na and Ca due to high-temperature feldspar destruction. In addition to geochemical analysis, X-ray diffraction, PIMA, and oxygen isotope analysis can assist in vectoring towards higher temperature, proximal alteration zones and associated VMS mineralization. Although PIMA has been used most effectively on alteration systems that contain minerals with a high reflective index, there has been some success in identifying greenschist-facies minerals within Precambrian VMS hydrothermal systems (Thompson et al., 1999)

Knowledge Gaps

Researchers have gathered an impressive amount of knowledge over the last ten years with respect to how, and where, VMS deposits form within various geodynamic regimes. This is due to a combination of studies of modern seafloor environments and detailed and regional-scale studies of ancient VMS environments. These studies have allowed us to place VMS depositional environments within the context of diverse supra-subduction settings that can be identified in deformed and metamorphosed terranes through lithostratigraphic facies evaluation and lithogeochemical analyses. Prospective settings for subseafloor hydrothermal systems can now be determined through identification of synvolcanic intrusions that trigger the systems, geochemical variations in altered rocks and chemical sedimentary horizons, and the use of mineralogy, geochemistry, and isotope geology. The fundamental ingredient for the efficient use of these tools is an appropriate level of understanding of the architecture of the volcanic terranes. Mapping at 1:20 thousand scale and complementary geochronological studies of the Flin Flon, Snow Lake, Leaf Rapids, and Bathurst mining camps were key to understanding the evolution of the various VMS-hosting arc assemblages and at what period of time in this evolution the deposits formed. Detailed lithostratigraphic mapping was essential in unraveling deformation histories and understanding the structural repetitions of prospective ore horizons. At larger scales, we still need a better understanding of the longevity of hydrothermal systems and the character and scale of fluid flow into both volcanic and sedimentary hanging-wall strata. We also need a better understanding of how to prospect for VMS environments through thick drift cover using novel heavy mineral analysis and selective leach methods. Successful exploration under cover requires improved understanding of the processes of secondary and tertiary remobilization of metals and trace elements from a VMS deposit and its associated alteration system.

Some Areas of High Mineral Potential in Canada

The recognition of new classes of high-sulphidation and shallow-water VMS deposits and their genetic association with differentiated magmatic suites in both calc-alkaline and alkaline volcanic arcs opens up new terranes and volcanic environments to exploration that were previously considered non-prospective for VMS. These environments include arc fronts and successor magmatic arcs in addition to primitive rifted-arc and back-arc terranes. Calc-alkaline to alkaline terranes, such as the Triassic Nicola Group and the Lower Jurassic Hazelton Group in British Columbia, should be revisited for atypical VMS deposits. Evolved parts of Archean greenstone terranes, in particular >2.8 Ga terranes in which there was involvement of early sialic crust, should also be considered in this context, e.g. Frotet-Troilus Domain, Grand Nord, North Caribou, and western Slave subprovinces.

Incipient rift environments of the Paleoproterozoic Trans-Hudson Orogen: The presence of large volumes of iron formation and associated VMS mineralization in the Labrador Trough is evidence of extensive hydrothermal systems generated in these 2.1 to 2.0 Ga rift systems on both margins of the orogen. Why did these not develop large VMS deposits as in other Fe-formation-rich environments (e.g. Manitouwadge)?

Intrusions associated with Ni-Cu-PGE mineralization represent large volumes of magma, commonly emplaced at shallow crustal levels as part of volcano-plutonic complexes. If emplaced in a subaqueous environment, these terranes should be highly prospective for mafic siliciclastic or mafic-dominated VMS deposits. These may include the submarine volcanic stratigraphy above the Fox River and Bird River sills in Manitoba and possibly the Bad Vermilion anorthositic complex in southwestern Ontario.

Intra-continental back-arc environments have been recognized as highly prospective for VMS deposits. Where are the continental back-arc environments in the Superior, Slave, and Grenville provinces? Have we explored enough in the >2.8 or <1.5 Ga terranes?

Terranes affected by thin-skinned fold-thrust tectonics present special challenges for exploration but are also highly prospective for VMS deposits. The potential for new exploration targets in areas such as the Central Volcanic Belt of Newfoundland is high, and the lessons learned in the Iberian Pyrite Belt with respect to exploring in such terranes can be applied in these and other similar terranes in Canada.

The so-called oceanic terranes of British Columbia, such as the Triassic Slide Mountain and Cache Creek terrane, should be re-evaluated for their VMS potential in light of the possibility that they represent back-arc and not ocean-basin environments. The presence of boninite and subvolcanic tonalite-trondhjemite intrusions ± rhyolites in these terranes would be key indicators of possible arc-back-arc systems. Boninite, in particular, is an indication of a depleted mantle source typical of nascent to back-arc regimes (Crawford et al., 1989; Stern et al., 1995; Kerrich at al., 1998; Piercey et al., 2001).

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References

Aggarwal, P.K., and Longstaffe, F.J., 1987, Oxygen isotope geochemistry of metamorphosed massive sulfide deposits of the Flin Flon-Snow Lake Belt, Manitoba: Contributions to Mineralogy and Petrology, v. 96, p. 314-325.

Allen, R.L., Lundström, I., Ripa, M., Simeonov, A., Christofferson, H., 1996a, Facies analysis of a 1.9 Ga, continental margin, back arc, felsic caldera province with diverse Zn-Pb-Ag (Cu-Au) sulfide and Fe oxide deposits, Bergslagen region, Sweden: Economic Geology, v. 91, p. 979-1008.

Allen, R. L., Weihed, P., and Svesen, S-A, 1996b, Setting of Zn-Cu-Au-Ag massive sulfide deposits in the evolution and facies architecture of a 1.9 Ga marine volcanic arc, Skellefte district, Sweden: Economic Geology, v. 91, p. 1022-1053.

Allen, R.L., Weihed, P., and Global VMS Research Project Team, 2002, Global comparisons of volcanic-associated massive sulphide districts, *in* Blundell, D.J., Neubauer, F., and Von Quadt, A., eds., The Timing and Location of Major Ore Deposits in an Evolving Orogen: Geological Society of London Special Publication 204, p. 13-37.

Alt, J.C., 1995, Subseafloor processes in mid-ocean ridge hydrothermal systems, *in* Humphris, S., ed., Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions: American Geophysical Union Monograph 91, p. 85-114.

Bailes, A.H., and Galley, A.G., 1999, Evolution of the Paleoproterozoic Snow Lake arc assemblage and geodynamic setting for associated volcanic-hosted massive sulfide deposits, Flin Flon Belt, Manitoba, Canada: Canadian Journal of Earth Science, v. 36, p. 1789-1805.

Barrett, T.J., and Sherlock, R.L, 1996a, Volcanic stratigraphy, lithogeochemistry, and seafloor setting of the H-W massive sulfide deposit, Myra Falls, Vancouver Island, British Columbia: Exploration and Mining Geology, v. 5, p. 421-458.

——— 1996b, Geology, lithogeochemistry, and volcanic setting of the Eskay Creek Au-Ag-Cu-Zn deposit, northern British Columbia: Exploration and Mining Geology, v. 5, p.339-368.

Barrie, C.T., 1995, Zircon thermometry of high-temperature rhyolites near volcanic-associated sulfide deposits: Geology, v. 23, p. 169-172.

Barrie, C.T., and Hannington, M.D., 1999, Introduction: Classification of VMS deposits based on host rock composition, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings: Reviews in Economic Geology, v. 8, p. 2-10.

Barrie, C.T., Ludden, J.N., and Green, A.H., 1993, Geochemistry of volcanic rocks associated with Cu-Zn and Ni-Cu deposits in the Abitibi Subprovince: Economic Geology, v. 88, p. 1341-1358.

Bédard, J.H., and Hébert, R., 1996, The lower crust of the Bay of Islands ophiolite, Canada: Petrology, mineralogy, and the importance of syntexis in magmatic differentiation in ophiolites and at ocean ridges: Journal of Geophysical Research, v. 101, p. 25105-25124.

Bédard, J.H., Lauzière, K., Tremblay, A., and Sangster, A., 1998, Evidence from Betts Cove ophiolite boninites for forearc seafloor-spreading: Tectonophysics, v. 284, p. 233-245.

Bloomer, S.H., Taylor, B., MacLeod, C.J., Stern, R.J., Fryer, P., Hawkins J.W., Johnson, L., 1995, Early arc volcanism and the ophiolite problem: A perspective from drilling in the Western Pacific: Geophysical Monograph 88, p. 1-30.

Bradshaw, G.D., Rowins, S.M., Peter, J.M., and Taylor, B.E., 2003, Genesis of the Wolverine deposit, Finlayson Lake district, Yukon: A transitional style of polymetallic massive sulfide mineralization in an ancient continental margin setting: The Gangue, p. 1-7.

Brauhart, C.W., Groves, D.I., and Morant, P., 1998, Regional alteration systems associated with volcanogenic massive sulfide mineralization at Panorama, Pilbara, Western Australia: Economic Geology, v. 93, p. 292-302.

Carvalho, D., Barriga, F.J.A.S., and Munha, J., 1999, Bimodal-siliciclastic systems - The case of the Iberian Pyrite Belt, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings: Reviews in Economic Geology, v. 8, p. 375-402.

Cathles, L.M., 1993, Oxygen isotope alteration in the Noranda Mining District, Abitibi Greenstone Belt, Quebec: Economic Geology, v. 88, p. 1483-1511.

Corbett, K.D., 1992, Stratigraphic-volcanic setting of massive sulfide deposits in the Cambrian Mount Read volcanics, western Tasmania: Economic Geology, v. 87, p. 564-586.

Crawford, A.J., Falloon, T.J., and Green D.H., 1989, Classification, petrogenesis and tectonic setting of boninite, *in* Crawford, A.J., ed., Boninites and Related Rocks: Unwin Hyman, London, p. 2-48.

Dimroth, E., Imreh, L., Goulet, N., and Rocheleau, M., 1983, Evolution of the south-central segment of the Archean Abitibi Belt, Quebec; Part II, Tectonic evolution and geomechanical model: Canadian Journal of Earth Sciences 20, p. 1355-1373.

Doyle, M.G., and McPhie, J, 2000, Facies architecture of a silicic intrusion-dominated volcanic centre at Highway-Reward, Queensland, Australia: Journal of Volcanology and Geothermal Research, v. 99, p. 79-96.

Dubé, B., Mercier-Langevin, P., Hannington, M.D., Davis, D.W., and LaFrance, B., 2004, Le gisement de sulfures massifs volcanogènes aurifères LaRonde, Abitibi, Québec: alteration, mineralisation genèse et implications pour l'exploration: Ministère de Resources Naturelles, Québec, Open File Report MB 2004-03, 112 p.

Eastoe, C.J., Solomon, M., and Walshe, J.L., 1987, District-scale alteration associated with massive sulfide deposits in the Mount Read volcanics, Tasmania: Economic Geology, v. 82, p. 1204-1238.

Eckstrand, O.R., Sinclair, W.D., and Thorpe, R.I., eds. 1995, Geology of Canadian Mineral Deposit Types, Geology of Canada, No. 8, Decade of North American Geology (DNAG): Geological Society of America, Part 1, p. 183-196.

Eldridge, C. W., Barton, P.B., and Ohmoto, H., 1983, Mineral textures and their bearing on formation of the Kuroko orebodies: Economic Geology Monograph, v. 5, p. 241-281.

Epp, M., and Crocket, J.H., 1999, Geology and geochemistry of the Potterdoal Cu-Zn deposit, Munro township, Ontario, *in* Hannington, M.D., and Barrie, C.T., eds., The Giant Kidd Creek Volcanogenic Massive Sulfide Deposit, Western Abitibi Subprovince, Canada: Economic Geology Monograph 10, p. 593-612.

Franklin, J.M., 1996, Volcanic-associated massive sulphide base metals, *in* Eckstrand, O.R., Sinclair, W.D., and Thorpe, R.I., eds., Geology of Canadian Mineral Deposit Types: Geological Survey of Canada, Geology of Canada, no. 8, p. 158-183.

Franklin, J.M., and Hannington, M.D., 2002, Volcanogenic massive sulfides through time: Geological Society of America, 2002 Annual Meeting, Abstracts with Programs, v. 34, p. 283.

Franklin, J.M., Lydon, J.W., and Sangster, D.F., 1981, Volcanic-associated massive sulfide deposits; in Skinner, B.J., ed., Economic Geology 75th Anniversary Volume: Society of Economic Geologists, p. 485-627.

Franklin, J.M., Hannington, M.D., Jonasson, I.R., and Barrie, C.T., 1998, Arc-related volcanogenic massive sulphide deposits: Proceedings of Short Course on Metallogeny of Volcanic Arcs, January 24-25, Vancouver: British Columbia Geological Survey Open-File 1998-8, p. N1-N32.

Franklin, J.M., Gibson, H.L., Jonasson, I.R., and Galley, A.G., 2005, Volcanogenic Massive Sulfide Deposits, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., eds., Economic Geology 100th Anniversary Volume: The Economic Geology Publishing Company, p. 523-560.

Galley, A.G., 1993, Semi-conformable alteration zones in volcanogenic massive sulphide districts: Journal of Geochemical Exploration, v. 48, p. 175-200.

——— 2003, Composite synvolcanic intrusions associated with Precambrian VMS- related hydrothermal systems: Mineralium Deposita, v. 38, p. 443-473.

Galley, A.G., and Jonasson, I.R., 2003, Classification and tectonic environments of VMS deposits in the Flin Flon mining camp, Manitoba: Geological Association of Canada/Mineralogical Association of Canada Annual General Meeting, Program with Abstracts (CD-ROM).

Galley, A.G., and Koski, R.A., 1999, Setting and characteristics of ophiolite-hosted volcanogenic massive sulfide deposits, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings: Reviews in Economic Geology, v. 8, p. 215-236.

Galley, A.G., Bailes, A.H., and Kitzler, G., 1993, Geological setting and hydrothermal evolution of the Chisel Lake and North Chisel Zn-Pb-Ag-Au massive sulphide deposit, Snow Lake, Manitoba: Exploration and Mining Geology, v. 2, p. 271-295.

Gibson, H.L., and Watkinson, D.H., 1990, Volcanogenic massive sulphide deposits of the Noranda Cauldron and Shield Volcano, Quebec, *in* Rive, M., Verpaelst, P., Gagnon, Y., Lulin, J.M., Riverin, G., and Simard, A., eds., The Northwestern Quebec Polymetallic Belt: Canadian Institute for Mining and Metallurgy, Special Volume 43, p. 119-132.

Goodfellow, W.D., Zierenberg, R.A., and ODP 196 Shipboards Science Party, 1999, Genesis of massive sulfide deposits at sediment-covered spreading centers, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings: Reviews in Economic Geology, v. 8, Society of Economic Geologists, p. 297-324.

Goodfellow, W.D., McCutcheon, S.R., and Peter, J.M., 2003, Massive sulfide deposits of the Bathurst Mining Camp, New Brunswick and Northern Maine: Introduction and summary of findings, *in* Goodfellow, W.D., McCutcheon, S.R., and Peter, J.M., eds., Massive Sulfide Deposits of the Bathurst Mining Camp, New Brunswick, and northern Maine: Economic Geology Monograph 11, Society of Economic Geologists, p. 1-16.

Green, G.R., Ohmoto, H., Date, J., and Takahashi, T., 1983, Whole-rock oxygen isotope distribution in the Fukazawa-Kosaka area, Hokuroko district, Japan, and its potential application to mineral exploration, *in* Ohnoto, H., and Skinner, B.J., ed., The Kuroko and Related Volcanogenic Massive Sulfide Deposits: Economic Geology Monograph 5, Society of Economic Geologists, p. 395-511.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, H., Hagemann, S.G., and Robert, F., 1998, Orogenic gold deposits - a proposed classification in the context of their crustal distribution and relationship to other gold deposit types: Ore Geology Reviews, v. 13, p. 7-27.

Hamilton, W.B., 1995, Subduction systems and magmatism: Geological Society of London Special Publication, v. 81, p. 3-28.

Hannington, M.D., Jonasson, I.R., Herzig, P.M., and Petersen, S., 1995, Physical and chemical processes of seafloor mineralization at mid-ocean ridges, *in* Humphris, S., ed., Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions: American Geophysical Union, Geophysical Monograph v. 91, p. 115-157.

Hannington, M.D., Galley, A.G., Herzig, P.M., and Petersen, S., 1998, Comparison of the TAG mound and stockwork complex with Cyprus-type massive sulfide deposits; Proceedings of the Ocean Drilling Program, Scientific Results Volume 158, College Station, TX, p. 389-415.

Hannington, M.D., Barrie, C.T., and Bleeker, W., 1999a, The giant Kidd Creek volcanogenic massive sulfide deposit, western Abitibi Subprovince, Canada, *in* Hannington, M.D., and Barrie, C.T., eds., The Giant Kidd Creek Volcanogenic Massive Sulfide Deposit, Western Abitibi Subprovince, Canada: Economic Geology Monograph 10, p. 1-30.

Hannington, M.D., Bleeker, W., and Kjarsgaard, I., 1999b, Sulfide mineralogy, geochemistry and ore genesis of the Kidd Creek deposit: Part II. The bornite zone, *in* Hannington, M.D., and Barrie, C.T., eds., The Giant Kidd Creek Volcanogenic Massive Sulfide Deposit, Western Abitibi Subprovince, Canada: Economic Geology Monograph 10, p. 225-266.

Hannington, M.D., Poulsen, K.H., Thompson, J.F.H., and Sillitoe, R.H., 1999c, Volcanogenic gold in the massive sulfide environment, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings: Reviews in Economic Geology 8, p. 325-356.

Hannington, M.D., Santaguida, F., Kjarsgaard, I.M., and Cathles, L.M., 2003, Regional greenschist facies hydrothermal alteration in the central Blake River Group, western Abitibi subprovince, Canada: Mineralium Deposita, v. 38, p. 393-422.

Herrington, R.J., Armstrong, R.N., Zaykov, V.V., Maslennikov, V.V., Tessalina, S.G., Orgeval, J.J., and Taylor, R.N.A., 2002, Massive sulfide deposits in the South Urals; geological setting within the framework of the Uralide Orogen, *in* Brown, D., Juhlin, C., and Puchkov, V., eds., Mountain Building in the Uralides; Pangea to the Present: Geophysical Monograph. 132, p. 155-182.

Herzig, P.M., and Hannington, M.D., 1995, Polymetallic massive sulfides at the modern seafloor: A review: Ore Geology Reviews, v. 10, p. 95-115.

Hodges, D.J., and Manojlovic, P.M., 1993, Application of lithogeochemistry to exploration for deep VMS deposits in high grade metamorphic rocks: Journal of Geochemical Exploration, v. 48, p. 201-224.

Kalogeropoulos, S.I., and Scott, S.D., 1983, Mineralogy and geochemistry of tuffaceous exhalites (Tetsusekiei) of the Fukazawa mine, Hokuroko District, Japan: *in* Ohnoto, H., and Skinner, B.J., eds., The Kuroko and Related Volcanogenic Massive Sulfide Deposits: Economic Geology Monograph 5, p. 412-432.

Kalogeropoulos, S.I., and Scott, S.D., 1989, Mineralogy and geochemistry of an Archean tuffaceous exhalite: the Main Contact Tuff, Millenbach mine area, Noranda, Quebec: Canadian Journal of Earth Sciences, v. 26, p. 88-105.

Kerr, D.J., and Gibson, H.L., 1993, A comparison between the volcanology and geochemistry of volcanic successions hosting the Horne mine deposit and smaller intra-cauldron deposits of the mine sequence: Economic Geology, v. 88, p. 1419-1443.

Kerrich, R., Wyman, D., Fan, J., and Bleeker, W., 1998, Boninite series - low Ti-tholeiite associations from the 2.7 Ga Abitibi greenstone belt: Earth and Planetary Science Letters, v. 164, p. 303-316.

Lagerblad, B., and Gorbatschev, R., 1985, Hydrothermal alteration as a control of regional geochemistry and ore formation in the central Baltic Shield: Geologische Rundschau, v. 74, p. 33-49.

Large, R.R., 1992, Australian volcanic-hosted massive sulphide deposits: features, styles and genetic models: Economic Geology, v. 87, p. 471-510.

Large, R.R., Doyle, M., Raymond, O., Cooke, D., Jones, A., and Heaman, L., 1996, Evaluation of the role of Cambrian granites in the genesis of world class VHMS deposits in Tasmania: Ore Geology Reviews, v. 10, p. 215-230.

Lentz, D.R., 1998, Petrogenetic evolution of felsic volcanic sequences associated with Phanerozoic volcanic-hosted massive sulfide systems: the role of extensional geodynamics: Ore Geology Reviews, v. 12, p. 289-327.

Liaghat, S., and MacLean, W.H., 1992, The Key Tuffite, Matagami mining district: Origin of the tuff components and mass changes: Exploration and Mining Geology, v. 1, p. 197-207.

Lydon, J.W., 1984. Some observations on the morphology and ore textures of volcanogenic sulfide deposits of Cyprus: Geological Survey of Canada, Current Research, Paper 84-01A, p. 601-610.

——— 1996, Characteristics of volcanogenic massive sulfide deposits: Interpretations in terms of hydrothermal convection systems and magmatic hydrothermal systems: Instituto Tecnologico Geominero de Espana, Boletin geologico y minero, v. 107, p. 15-64.

Morton, J.L., and Franklin, J.M., 1987, Two-fold classification of Archean volcanic-associated massive sulfide deposits: Economic Geology, v. 82, p. 1057-1063.

Morton, R.L., Hudak, G.J., Walker, J.S., and Franklin, J.M., 1990, Physical volcanology and hydrothermal alteration of the Sturgeon Lake caldera complex, *in* J.M. Franklin, Schneiders, B.R., and Koopman, E.R., eds., Mineral Deposits in the Western Superior Province, Ontario: Open File 2164, Geological Survey of Canada, p. 74-94.

Munha, J., and Kerrich, R., 1980, Sea water-basalt interaction in spilites from the Iberian Pyrite Belt: Contributions to Mineralogy and Petrology, v. 73, p. 191-200.

Nelson, J., and Mihalynuk, M., 2004, Mega-terranes and deep structures: tectonics and the potential for major new mineral deposits in British Columbia: Mineral Exploration Roundup, Program with Abstracts, p. 26.

Paradis, S., Taylor, B.E., Watkinson, D.H., and Jonasson, I.J., 1993, Oxygen isotope zonation and alteration in the Noranda mining district, Abitibi greenstone belt, Quebec: Economic Geology, v. 88, p. 1512-1525.

Peter, J.M., 2003, Ancient iron-rich metalliferous sediments (iron formations): Their genesis and use in the exploration for stratiform base metal sulphide deposits, with examples from the Bathurst Mining Camp, *in* Lentz, D.R., ed., Geochemistry of Sediments and Sedimentary Rocks: Evolutionary Considerations to Mineral Deposit-Forming Environments, GEOtext 4: Geological Association of Canada, p. 145-173.

Peter, J.M., and Goodfellow, W.D., 1996, Mineralogy, bulk and rare earth element geochemistry of massive sulfide-associated hydrothermal sediments of the Brunswick Horizon, Bathurst Mining Camp, New Brunswick: Canadian Journal of Earth Sciences, v. 33, p. 252-283.

Peter, J.M., and Scott, S.D., 1999, Windy Craggy, northwestern British Columbia: The world's largest Besshi-type deposit, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings: Reviews in Economic Geology, v. 8, p. 261-295.

Petersen, S., Herzig, P.M., and Hannington, M.D., 2000, Third dimension of a presently forming VMS deposit: TAG Hydrothermal Mound, Mid-Atlantic Ridge, 26°N: Mineralium Deposita, v. 35, p. 233-259.

Petersen, S., Schwarz-Schampera, U., Herzig, P., Hannington, M., and Jonasson, I., 2004, Hydrothermal precipitates associated with bimodal volcanism in the Central Bransfield Strait, Antarctica: Mineralium Deposita, v. 39, p. 358-379.

Piercey, S.J., Murphy, D.C., Mortensen, J.K., and Paradis, S., 2001, Boninitic magmatism in a continental margin setting, Yukon-Tanana terrane, southeastern Yukon, Canada: Geology, v. 29, p. 731-734.

Poulsen, H., and Hannington, M., 1995, Auriferous Volcanogenic Sulfide Deposits, *in* Eckstrand, O.R., Sinclair, W.D., and Thorpe, R.I., eds. Geology of Canadian Mineral Deposit Types, Geology of Canada, no. 8, Decade of North American Geology (DNAG): Geological Society of America, Part 1. p. 183-196.

Powell, W.G., Carmichael, D.M., and Hodgeson, C.J., 1993, Relative timing of metamorphism and tectonism during the evolution of the southern Abitibi greenstone belt. *in* Caty, J.L., ed., L'Exceptionnel potentiel mineral du Quebec, une realite a decouvrir; resume des conferences; seminaire d'information 1993 (The exceptional mineral potential of Quebec, a reality yet to be discovered; information seminar 1993) Conference Abstracts. DV – Direction generale de l'Exploration Geologique et Minerale. p. 49-50.

Richards, J.P., 2003, Tectono-magmatic precursors for porphyry Cu-(Mo-Au) deposit formation: Economic Geology, v. 98, p. 1515-1534.

Sangster, D., 1980, Quantitative characteristics of volcanogenic massive sulphide deposits I. Metal content and size distribution of massive sulphide deposits in volcanic centers: Canadian Institute of Mining and Metallurgy Bulletin, v. 73, p. 74-81.

Santaguida, F., Gibson, H.L., Watkinson, D.H., and Hannington, M.D., 1998, Semi-conformable epidote-quartz hydrothermal alteration in the Central Noranda Volcanic Complex: Relationship to volcanic activity and VMS mineralization: Canadian Minerals Research Organization Project 94E07, Annual Report, The Use of Regional-Scale Alteration and Subvolcanic Intrusions in the Exploration for Volcanic-Associated Massive Sulphide Deposits, p. 139-180.

Sebert, C., and Barrett, T.J., 1996, Stratigraphy, alteration, and mineralization at the Tulsequah chief massive sulfide deposit, northwestern British Columbia; Exploration and Mining Geology 5, 4, p. 281-308.

Sharpe, R., and Gemmell, J.B., 2002, The Archean Cu-Zn magnetite-rich Gossan Hill volcanic-hosted massive sulfide deposit, Western Australia; genesis of a multistage hydrothermal system: Economic Geology, v. 97, p. 517-539.

Sherlock, R.L., Roth, T., Spooner, E.T.C., and Bray, C.J., 1999, The origin of the Eskay Creek precious metal-rich volcanogenic massive sulfide deposit: fluid inclusion and stable isotope data: Economic Geology, v. 94, p. 803-824.

Sillitoe, R.H., Hannington, M.D., and Thompson, J.F.H., 1996, High sulfidation deposits in the volcanogenic massive sulfide environment: Economic Geology, v. 91, p. 204-212.

Sinclair, W.D., Chorlton, L.B., Laramée, R.M., and Eckstrand, O.R., 1999, World Minerals Geoscience Database Project: Digital databases of generalized world geology and mineral deposits for mineral exploration and research; http://gdr.nrcan.gc.ca/minres/index_e.php.

Singer, D.A., 1995, World-class base and precious metal deposits - a quantitative analysis: Economic Geology, v. 90, p. 88-104.

Spooner, E.T.C., and Fyfe, W.S., 1973, Subseafloor metamorphism, heat and mass transfer: Contributions to Mineralogy and Petrology, v. 42, p. 287-304.

Spry, P.G., Peter, J.M., and Slack, J.F., 2000, Meta-exhalites as exploration guides to ore, *in* Spry, P.G., Marshall, B., and Vokes, F.M., eds., Metamorphosed and Metamorphogenic Ore Deposits: Reviews in Economic Geology, v. 11, p. 163-201.

Stern, R.A., Syme, E.C., Bailes, A.H., and Lucas, S.B., 1995, Paleoproterozoic (1.90-1.86 Ga) arc volcanism in the Flin Flon Belt, Trans-Hudson Orogen, Canada: Contributions to Mineralogy and Petrology, v. 119, p. 117-141.

Stinton, J.M., and Detrick, R.S., 1992, Mid-ocean ridge magma chambers: Journal of Geophysical Research, v. 97, p. 197-216.

Swinden, H.S., Kean, B.F., and Dunning, G.R., 1988, Geological and paleotectonic settings of volcanogenic massive sulfide mineralization in Central Newfoundland, *in* Swinden, H.S., and Kean, B.F., eds., The Volcanogenic Sulphide Districts of Newfoundland: A Guidebook and Reference Manual for Volcanogenic Sulphide Deposits in the Early Paleozoic Oceanic Volcanic Terranes of Central Newfoundland: Geological Association of Canada, Mineral Deposits Division, p. 2-27.

Syme, E.C., and Bailes, A.H., 1993, Stratigraphy and tectonic setting of Early Proterozoic volcanogenic massive sulphide deposits, Flin Flon, Manitoba: Economic Geology, v. 88, p. 566-589.

Taylor, B.E., and South B.C., 1985, Regional stable isotope systematics of hydrothermal alteration and massive sulfide deposition in the West Shasta District, California: Economic Geology, v. 80, p. 2149-2163.

Thompson, A. J., Hauff, B., and Robitaille, P.L., 1999, Alteration mapping in exploration: Application of short-wave infrared (SWIR) spectroscopy: Society of Economic Geology Newsletter, v. 39.

van Staal, C.R., Wilson, R.A., Rogers, N., Fyffe, L.R., Langton, J.P., McCutcheon, S.R., McNicoll, V., and Ravenhurst, C.E., 2003, Geology and tectonic history of the Bathurst Supergroup, Bathurst Mining Camp, and its relationships to coeval rocks in southwestern New Brunswick and adjacent Maine - a synthesis, *in* Goodfellow, W.D., McCutcheon, S.R., and Peter, J.M., eds., Massive Sulfide Deposits of the Bathurst Mining Camp, New Brunswick and Northern Maine: Economic Geology Monograph 11, p. 37-60.

Walker, P.N., and Barbour, D.M., 1981,Geology of the Buchans ore horizon breccias, *in* Swanson, E.A., Strong, D.F., and Thurlow, J.G., eds., The Buchans Ore Body; Fifty Years of Geology and Mining: Geological Association of Canada, Special Paper 22, p. 161-185.

Whalen, J.B., McNicoll, V.J., Galley, A.G., and Longstaffe, F.J., 2004, Tectonic and metallogenic importance of an Archean composite high- and low-Al tonalite suite, western Superior Province, Canada: Precambrian Research, v. 132, p. 275-301.

Wyman, D.A., Bleeker, W., and Kerrich, R., 1999, A 2.7 Ga komatiite, low Ti tholeiite, arc tholeiite transition, and inferred proto-arc geodynamic setting of the Kidd Creek deposit: Evidence from precise trace element data, *in* Hannington, M.D., and Barrie, C.T., eds., The Giant Kidd Creek Volcanogenic Massive Sulfide Deposit, Western Abitibi Subprovince, Canada: Economic Geology Monograph 10, p. 511-528.

Yang, K., and Scott, S.D., 2003, Geochemical relationships of felsic magmas to ore metals in massive sulfide deposits of the Bathurst mining camp, Iberian Pyrite Belt, Hokuroko district and the Abitibi Belt, *in* Goodfellow, W.D., McCutcheon, S.R., and Peter, J.M., eds., Massive Sulfide Deposits of the Bathurst Mining Camp, New Brunswick and Northern Maine: Economic Geology, Monograph 11, p. 457-478.

Ziegler, P.L., 1992, Plate tectonics, plate moving mechanisms and rifting: Tectonophysics, v. 215, p. 9-34.