VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS

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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 it's Pb, 40% of its Ag and 3% of its Au. Because of their polymetallic content, VMS deposits continue to be one of the best 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., 1996). 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 wallrock. These stratabound bodies are typically underlain by discordant to semi-concordant stockwork veins and disseminated sulphides. The stockwork vein systems, or "pipes", are

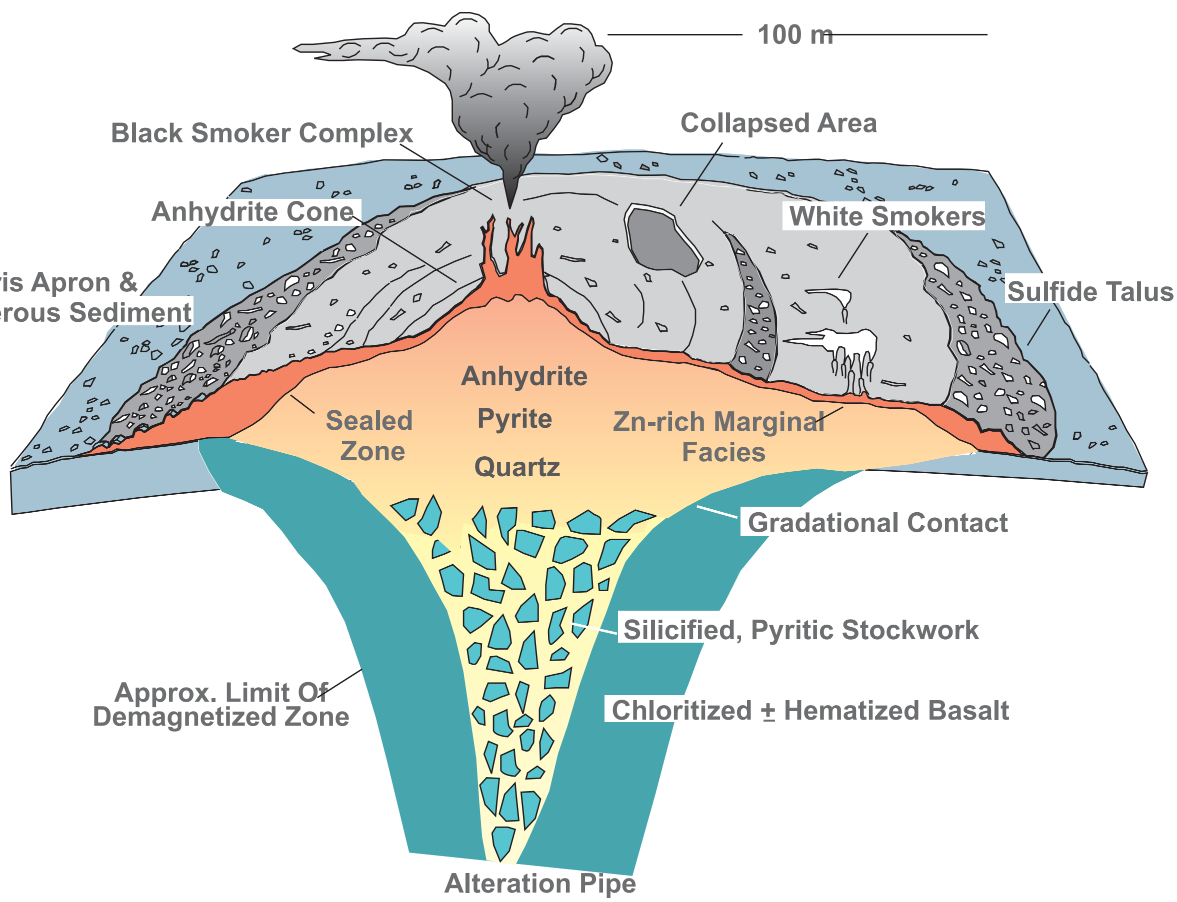

FIG. 1. Schematic of the modern TAG sulphide deposit on the Mid-Atlantic Ridge represents a classic cross-section of a VMS deposit, with a concordant semi-massive to massive sulphide lens underlain by a discordant stockwork vein system and associated alteration halo, or "pipe". From Hannington et al (1996).

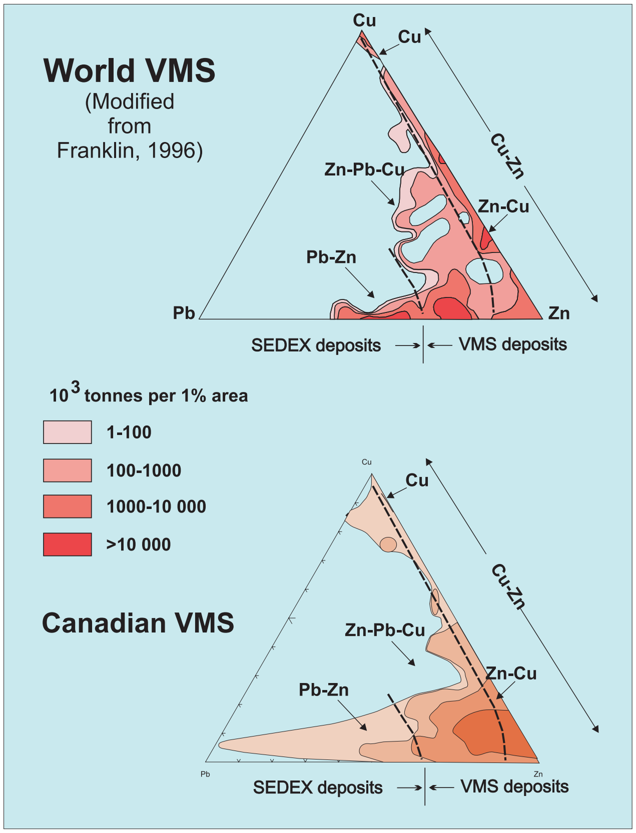

FIG. 2. Base metal classification of worldwide and Canadian VMS deposits as defined first by Franklin et al. (1981) and modified by Large (1992) to include the Zn-Pb-Cu class. The preponderance of Cu-Zn and Zn-Cu VMS deposits in Canada is due to the abundance of Precambrian primitive oceanic arc settings.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

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) 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 simple bimodal definition of "normal" vs. "Au-rich" VMS deposits (Fig. 3). This originally was meant 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 concentrations of Au in ppm is greater than the combined base metals (Zn+Cu+Pb in wt. %: Fig. 3). A third classification that is gaining popularity in Canada is a five-fold grouping suggested by Barrie and Hannington (1999) to indicate dominant host-rock lithology. Host-rock lithologies include strata up to 3000m below the deposit and up to 5000m along strike. The five groups are mafic-dominated, bimodal mafic, bimodal-felsic, siliciclastic-mafic, and bimodal-siliciclastic (Fig. 4). The order of this grouping reflects not only a progressive change from a less effusive to a more volcaniclastic-dominated environment, but also one in which felsic volcanic rocks become generally more prominent. These lithological groupings generally correlate with different tectonic settings. The groups associated with mafic volcanic and volcaniclastic strata are more common in oceanic arcs and spreading centers, whereas the two groups dominated by felsic strata are more common in arc-continent margin and continental arc regimes.

Geographical Distribution

There are close to 800 known VMS deposits worldwide with geological reserves 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 Bransfield Strait on the Antarctic Peninsula (Peterson et al., 2004). Cu and Au have been produced from Tertiary-age deposits hosted in ophiolites around the eastern Mediterranean for over 5000 years. Up to 2002, VMS deposits are estimated to have supplied over 5 billion t of sulphide ore (Franklin and

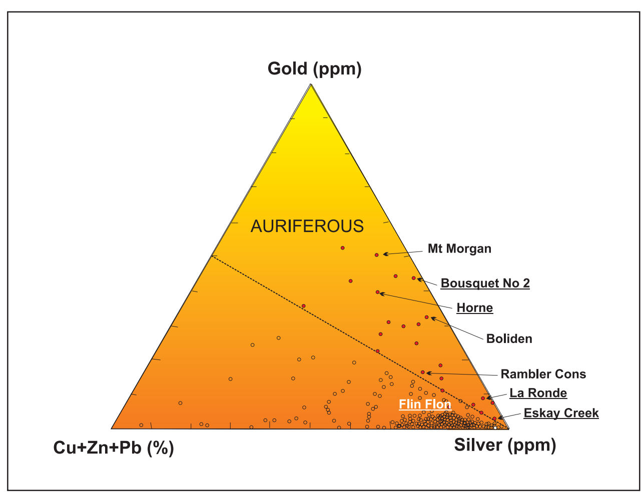

FIG. 3. Classification of VMS deposits based on their relative proportions of Cu+Zn+Pb versus precious metals (Au, Ag). Some of Canada's better known auriferous deposits (underlined) are compared to international examples. Despite having produced 170 t of Au, the Flin Flon deposit is not considered an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

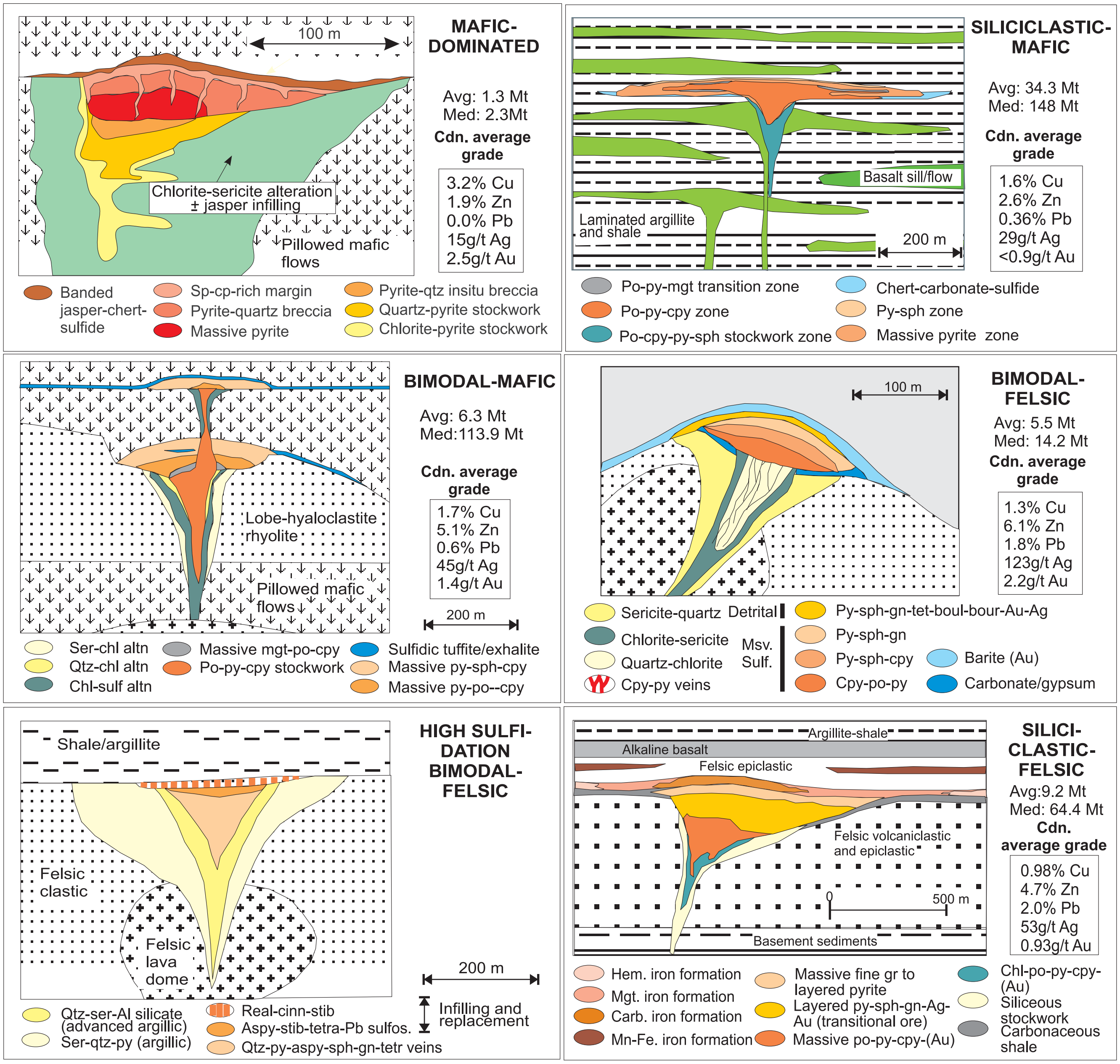

FIG. 4. Graphic representation of the lithological classification for VMS deposits by Barrie and Hannington (1999), with "high sulfidation" type an added subtype to the bimodal-felsic group. Average and median sizes for each type for all Canadian deposits, along with average grade.

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 it's Ag and 2.2% of it's Au (Singer, 1995).

Over 350 deposits and major VMS occurrences containing geological reserves >200,000 t are known in Canada, of which only 13 are presently producing mines (Figure 6, Table 2). Four of these will close in the next two years. VMS deposits are known to occur in every province and territory except Alberta and P.E.I. The largest number of deposits is in Quebec (33%), 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).

Grade and Tonnage

The 800 VMS deposits worldwide range in size from 200,000 t to giant deposits. Among the largest is Neves Corvo in Spain's Iberian Pyrite Belt (IPB), with reserves in excess of 270 Mt t, with 8.5 million t of contained metals having a value in 1999 of over 16 billion dollars (US) (Barrie and Hannington, 1999) (Fig. 8, 9a; Table 3). The entire Iberian Pyrite Belt contains 88 deposits, with 7 over 100 Mt, containing an aggregate 1.575 billion tones of ore containing 62.6 Mt Zn+Cu+Pb (Carvalho et al, 1999). The next largest districts are the Urals and Rudny-Altai of Russia and Kazakhstan with over 70 Mt of contained metals each (Fig. 5). Canada contains 4 giant VMS deposits (Windy Craggy,

Table 1. Major World VMS Deposits and Districts

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

* numbers refer to Figure 5; tonnage is approximate

Brunswick No. 12, 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 300 Mt of ore containing 30 Mt of combined Zn, Cu and Pb (Fig. 6, 10a). The 128 Mt Brunswick No. 12 deposit alone contained 16.4 Mt of metal (Table 1). This is followed by the 149.3 Mt Kidd Creek deposit containing 12.6 Mt of metal. The largest known Canadian VMS deposit is the 297 Mt Windy Craggy, but it only contains 4.1 Mt of metals. 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 55 Mt LaRonde VMS deposit contains 258 t of gold, and because of its high Au/base metal ratio (Au ppm/Zn+Cu+Pb% = 1.9) it is classified by Agnico-Eagle Inc. 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 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 known 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 deposits 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. 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 within the footwall stratigraphy can also influence hydrothermal fluid composition, as is believed to be the case with the Se-rich Wolverine and KZK deposits in the Finlayson Lake camp (Bradshaw et al., 2003). Possible contributions from devolatilizing subvolcanic intrusions may also account for anomalous concentrations of Se, Sn, In, Bi, Te, and possibly Au and Sb (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 still preserved in the geological record formed mainly in oceanic and continental nascent-arc, rifted arc and back-arc settings (Allen et al. 2002; Franklin et al. 1998) (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 remnants of obducted ocean-floor. Examples of these may 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, 2003).

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

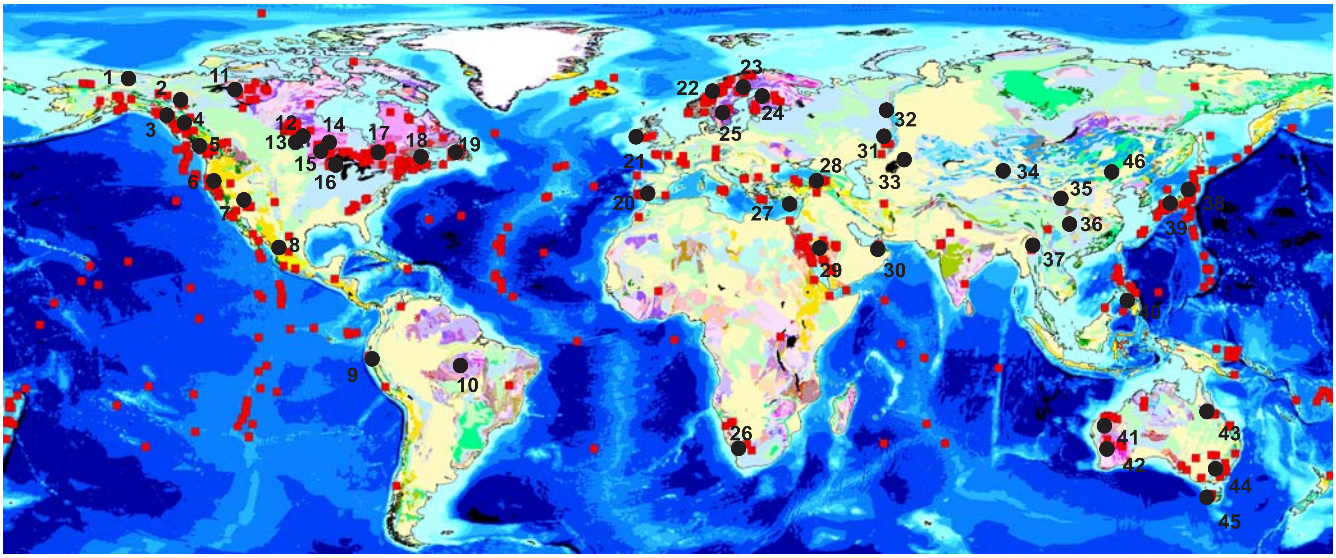

FIG. 5. Distribution of ancient and modern VMS deposits, with major districts highlighted with respect to known aggregate geological reserves. From GSC World Minerals Project.

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). The Ni-rich Potterdoal VMS deposit within the same Kidd-Munro komatiitic assemblage, is another rare example of a komatiite-associated VMS deposit (Epp and Crocket, 1999).

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 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 of this include the Sturgeon Lake camp in the Archean Wabigoon terrane of Ontario (Morton et al., 1990; Whalen et al., 2004) and the

Table 2. Canadian VMS deposits presently in production

Deposit	Location	Mt	Cu wt.%	Zn wt.%	Pb wt.%	Ag g/t	Au g/t	Age
Kidd Creek	Abitibi, Ontario	149.3	2.89	6.36	0.22	92	0.05	Archean
Brunswick No. 12	Bathurst, N.B.	137.3	0.33	9.56	3.56	100	0.2	Ordovician
Selbaie	Abitibi, Quebec	47.3	0.98	1.98		20	0.9	Archean
LaRonde	Abitibi, Quebec	55	0.33	2.11		50	4.66	Archean
Buttle Lake	Wrangellia, B.C.	26.3	1.9	5.93	0.55	55	2.15	Devonian
Louvicourt	Abitibi, Quebec	15.1	3.67	1.55		29	0.9	Archean
Triple 7	Trans-Hudson Orogen, Manitoba	14.5	2.64	4.98		31	2.12	Paleoproterozoic
Bouchard-Hebert	Abitibi, Quebec	10.2	2.11	4.79		15	1.4	Archean
Callinan	Trans-Hudson Orogen, Manitoba	8.4	1.29	4.02		26	2.05	Paleoproterozoic
Duck Pond*	Central Volcanic Belt, Nfld.	3.9	3.59	6.82	1.1	71	0	Ordovician
Bell Allard	Abitibi, Quebec	3.2	1.5	13.77		43	0.8	Archean
Chisel North	Trans-Hudson Orogen, Manitoba	2.8	0.15	9.36	0.4	22	0.4	Paleoproterozoic
Eskay Creek	Stikine, B.C.	4	0.33	5.4	2.2	998	26.4	Jurassic
Konuto	Trans-Hudson Orogen, Manitoba	1.9	4.13	1.41		9	2.07	Paleoproterozoic

* In pre-production for 2006; [1]Includes production and estimated reserves where applicable. From Hannington et al., 1999.

Table 3. Examples of Large-Tonnage VMS Deposits of the World (Canadian deposits in red).

Deposit	Location	Mt	Cu wt.%	Zn wt.%	Pb wt.%	Ag g/t	Au g/t	Age
***Giant Deposits* (>100 Mt)**								
Windy Craggy	British Columbia	297.4	1.38			4	0.2	Triassic
Neves Corvo	Portugal	270	1.6	1.4	0.3	30		Carboniferous
Aljustrel	Portugal	250	0.8	3	1	38	0.8	Carboniferous
Rio Tinto (massive)	Spain	250	1	2	1	30	0.22	Carboniferous
La Zarza	Spain	164	0.7	1.5	0.5	24	1	Carboniferous
Horne (No. 5 Zone)	Quebec	150	0.1	0.7			0.3	Archean
Kidd Creek	Ontario	149.3	2.89	6.36	0.26	92	0.05	Archean
Brunswick No. 12	New Brunswick	137.3	0.33	9.56	3.56	100	0.2	Ordovician
Tharsis	Spain	110	0.5	2.7	0.6	22	0.7	Carboniferous
Mt. Lyell	Tasmania	106.8	1.19	0.04	0.01	7	0.41	Cambrian
***Very Large Deposits* (50-100 Mt)**								
Ruttan	Manitoba	82.8	1.37	1.63	0.08	13	0.5	Paleoproterozoic
Aznacollar	Spain	74	0.49	2.14	1.04	44	0.5	Carboniferous
Los Frailes	Spain	70	0.34	3.92	2.25	63		Carboniferous
Masa Valerde	Spain	70	0.5	1.3	0.6	38	0.8	Carboniferous
Caribou	New Brunswick	70	0.5	4.3	1.6			Ordovician
Flin Flon	Manitoba	62.5	2.17	4.13		42	2.64	Paleoproterozoic
Crandon	Wisconsin	61	1.1	5.6	0.5	37	1	Paleoproterozoic
Geco	Ontario	58.4	1.86	3.45	0.15	50		Archean
Sotiel	Spain	59	0.6	4.9	1.9			Carboniferous
LaRonde	Quebec	55	0.33	2.11		50	4.66	Archean
Matsumine-Shakanai	Japan	54.2	2.19	2.63	0.76	64	0.62	Miocene
Horne Mine	Quebec	54	2.2			13	6.1	Archean
***Large Deposits* (25-50 Mt)**								
Mt. Morgan	Queensland	50	0.7	0.1	0.05	6	4.7	Devonian
Lousal	Portugal	50	0.7	1.4	0.8			Carboniferous
Britannia	British Columbia	48.8	1.9	0.65		7	0.69	Jurassic
Migollas	Spain	47.6	0.83	2.23	1.3			Carboniferous
Preiska	South Africa	47.2	0.98	1.98		20	0	Proterozoic
Selbaie (all orebodies)	Quebec	44	1.05	1.98		39	0.6	Archean
Norita	Quebec	37.6	2.17	4.13		41	2.6	Archean
Avoca	Ireland	37	0.7					Ordovician
Aguas Tenidas	Spain	35						Carboniferous
Bawdwin	Burma	34.1	0.48	13	9.09	232	0.06	Ordovician
Arctic (Brooks Range)	Alaska	32.9	4	5.5	0.8	51	0.02	Devonian
Pyhasalmi	Finland	31.1	0.75	2.43	0.06	17	0.2	Proterozoic
United Verde	USA	30	4.8	0.2		50	1.37	Proterozoic
Madenkoy	Turkey	30	3.9	4.3				Cretaceous
Besshi	Japan	29.9	2.6	0.3		21	0.7	Jurassic
Outokumpu	Finland	28	3.8	1	0.01	9	0.08	Proterozoic
Hitachi	Japan	27.2	1.4	0.6		5	0.5	Cretaceous
Buttle Lake	British Columbia	26.3	1.9	5.93	0.55	55	2.15	Devonian
Murgul	Turkey	26.2	2.03			0		Jurassic
Scuddles	W. Australia	26.1	1.2	6.9	0.5	59	0.9	Archean
Cayeli	Turkey	26	4.7	7.3				Cretaceous
Mattagami Lake	Quebec	25.6	0.42	5.1		22	0.3	Archean
Granduc	British Columbia	25.1	1.79	0.1	0.02	11	0.17	Jurassic
Lokken	Norway	25	2.1	1.9	0.1	19	0.29	Ordovician

[1]Includes production and estimated reserves where applicable. From Hannington et al., 1999.

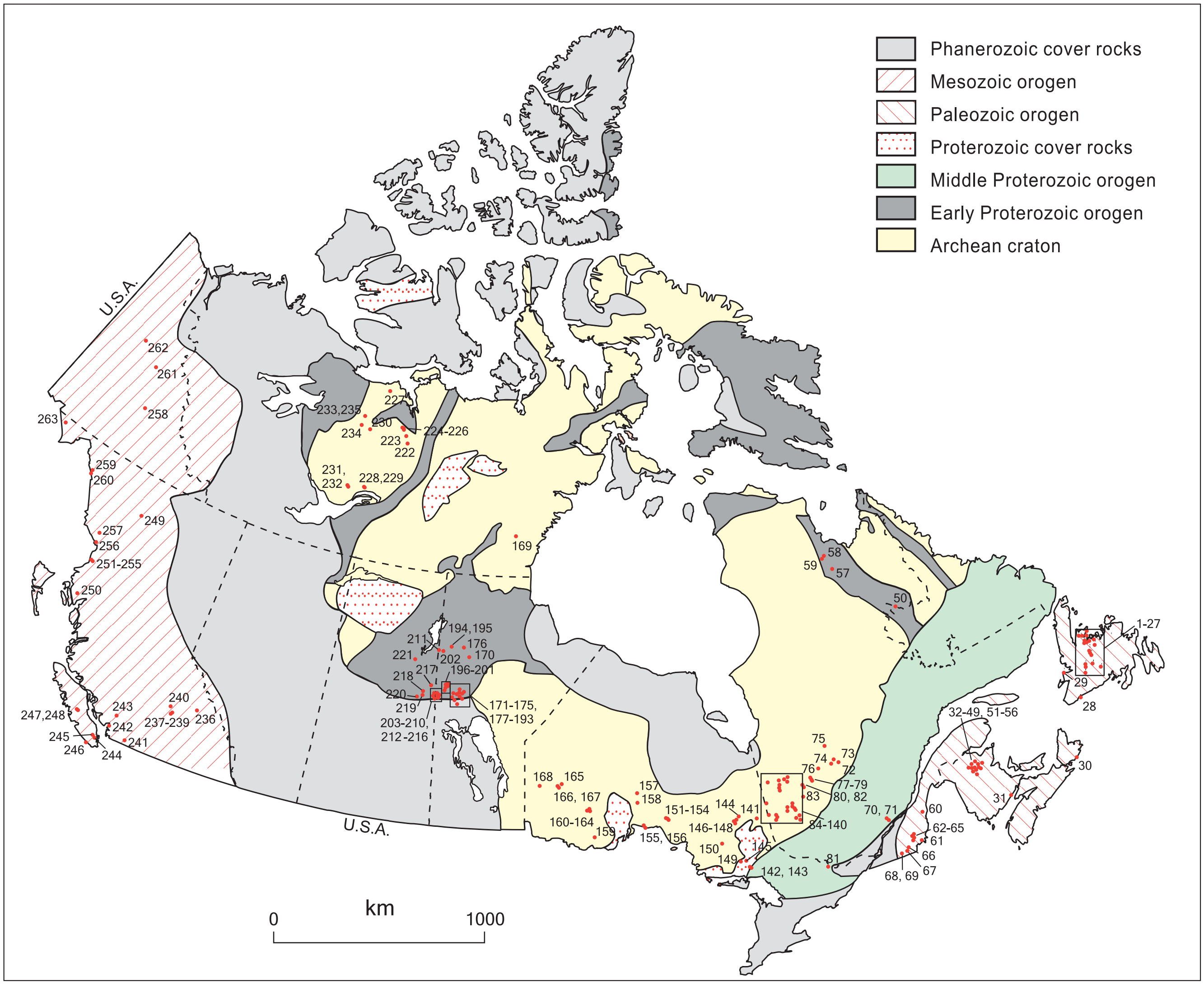

FIG. 6. Distribution of VMS deposits in Canada by geologic province. Numbers correspond to deposits listed in the national VMS database (Appendix 1).

Devonian Buttle Lake VMS camp in the Wrangellia Terrane of BC (Barrett and Sherlock, 1996). Outside Canada, the Paleoproterozoic Skellefte mining district in Sweden (Weihed, 1996) and the Cambrian Mount Read VMS district

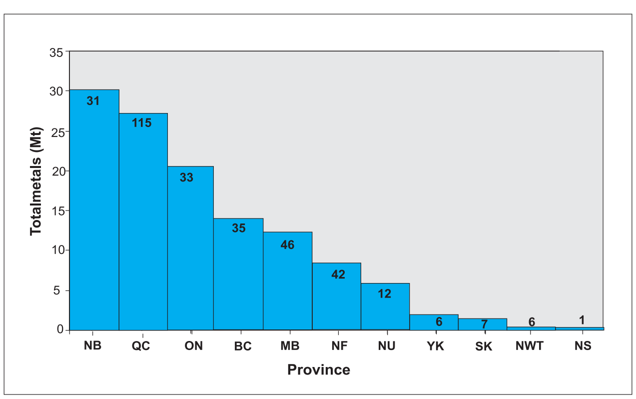

FIG. 7. Histogram of the total tonnage of base metals from known VMS deposits per province, and the number of deposits the aggregate tonnage was calculated from. Total metals represent original geological reserves.

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 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; Bedard 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).

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). 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., 1996), the Cambro-Ordovician Mount Windsor district of Queensland

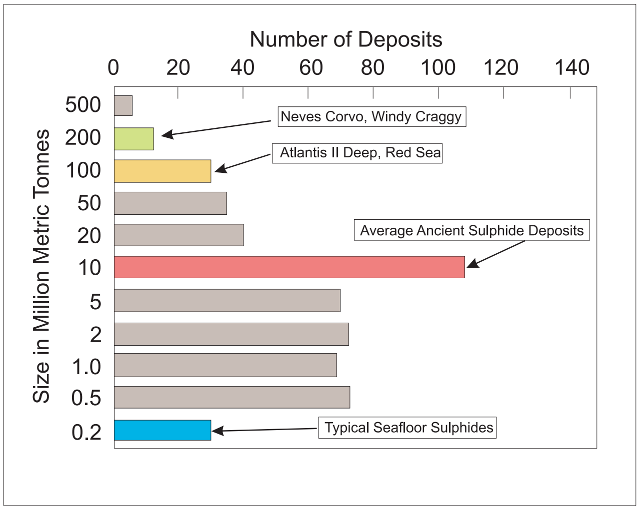

FIG. 8. Worldwide size distribution for VMS deposits, with deposits over 50 Mt considered "giant", and those over 150 Mt considered "supergiant". Atlantis Deep is considered the largest modern example of a seafloor massive sulphide deposit, with Neves Corvo and Windy Craggy ancient examples of supergiant deposits. Modified from Hannington et al (1995).

(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).

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

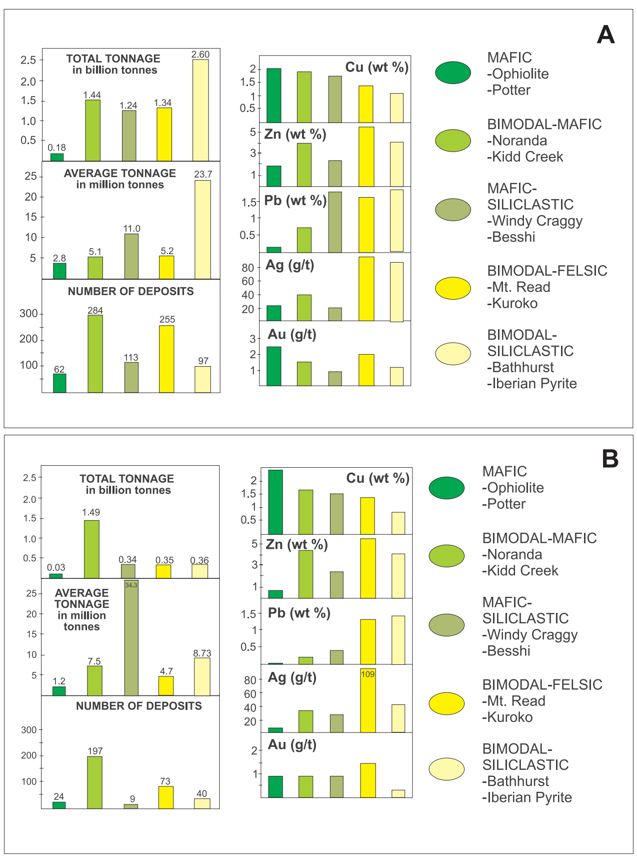

FIG. 9 statistics for VMS deposits grouped by lithologic class (Barrie and Hannington, 1999): a) worldwide deposits; b) Canadian deposits grouped by lithologic class.

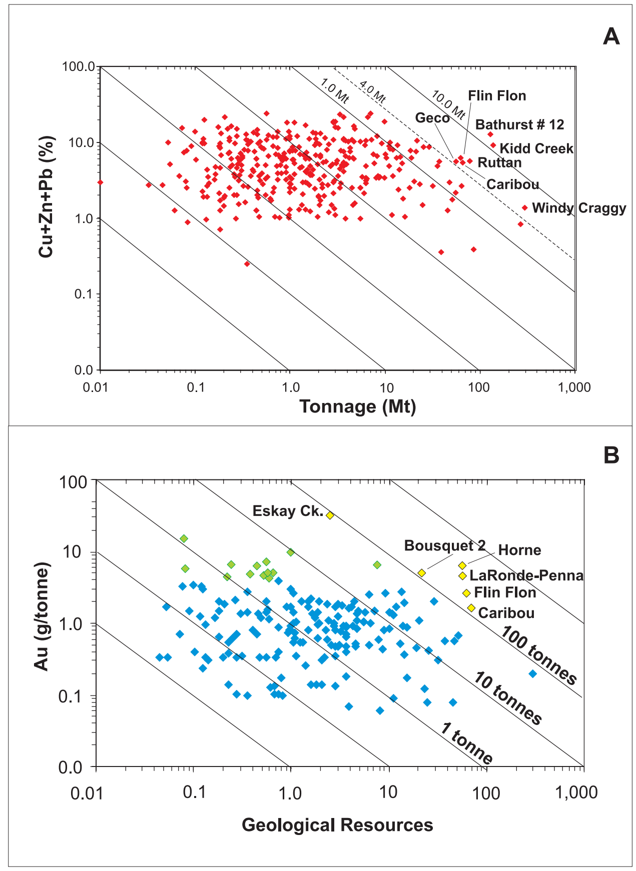

FIG. 10. Distribution of Canadian VMS deposits with respect to aggregate base metal grade versus tonnes (a) and contained Au versus long tonnes (b); most auriferous Au deposits contain > 4 g/t Au (green diamonds). Those containing over 1000 tonnes of Au (yellow diamonds) include both auriferous VMS deposits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

formation of multiple mineral deposit types, including epithermal and VMS deposits. A good example of this is the Lower Jurassic Hazelton Group in the Todogoone and Sustut regions of BC, the former containing 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 BC 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

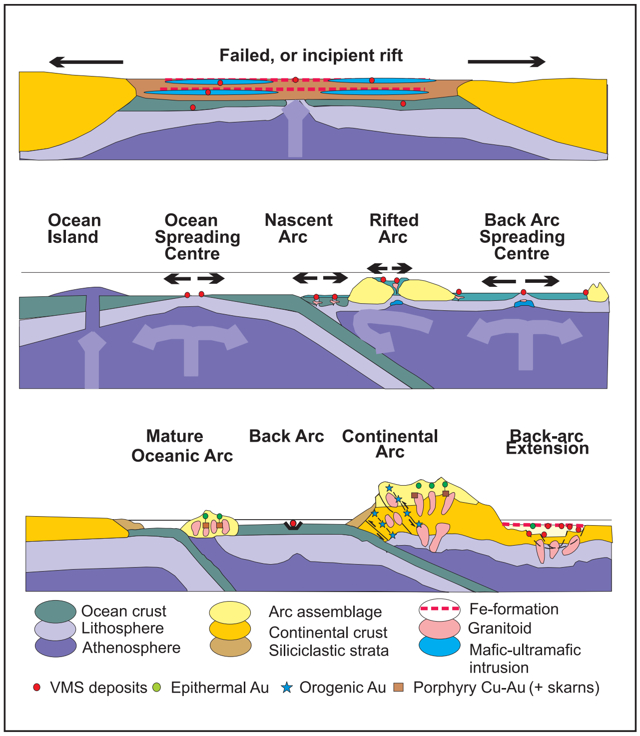

FIG. 11. There are three principal tectonic environments in which VMS deposits form, each representing a stage in the formation of the earth's crust. TOP: Early earth evolution was dominated by mantle plume activity during which numerous incipient rift events formed basins characterized by early ocean 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, post accretion arc rifting (Windy Craggy). MIDDLE: The formation of true 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. BOTTOM: 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.

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 BC coast (Goodfellow et al., 1999).

District-scale Environments

Most, but not all significant 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 a regional thinning of the basement, depressurization of the underlying mantle, and generation of mafic magmas (Fig. 13). In ocean spreading-ridge settings these magmas rise to within a few thousand meters 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 1000 to 1400°C mafic magmas 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 instead remain in the underlying basement rocks. These different scenarios result in various 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 sub-seafloor 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, neutral 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 mimic 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 (Fig. 15; Fig. 16a, b, c). Above this are Na-Ca-rich greenschist-facies assemblages characterized by albite, quartz, chlorite, actinolite and epidote. Closer to the seafloor are

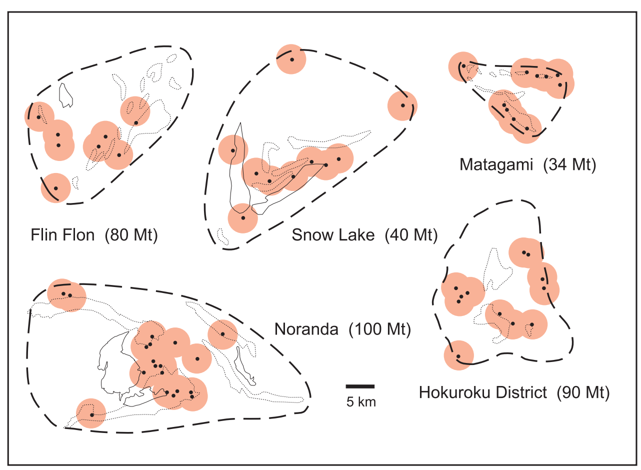

FIG. 12. A same-scale comparison of selected VMS districts. A 5 km diameter circle around each deposit shows the hypothetical area of influence of proximal-scale alteration about each deposit, all encircled by a dashed line defining the proposed extent of a regional-scale alteration system for each camp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

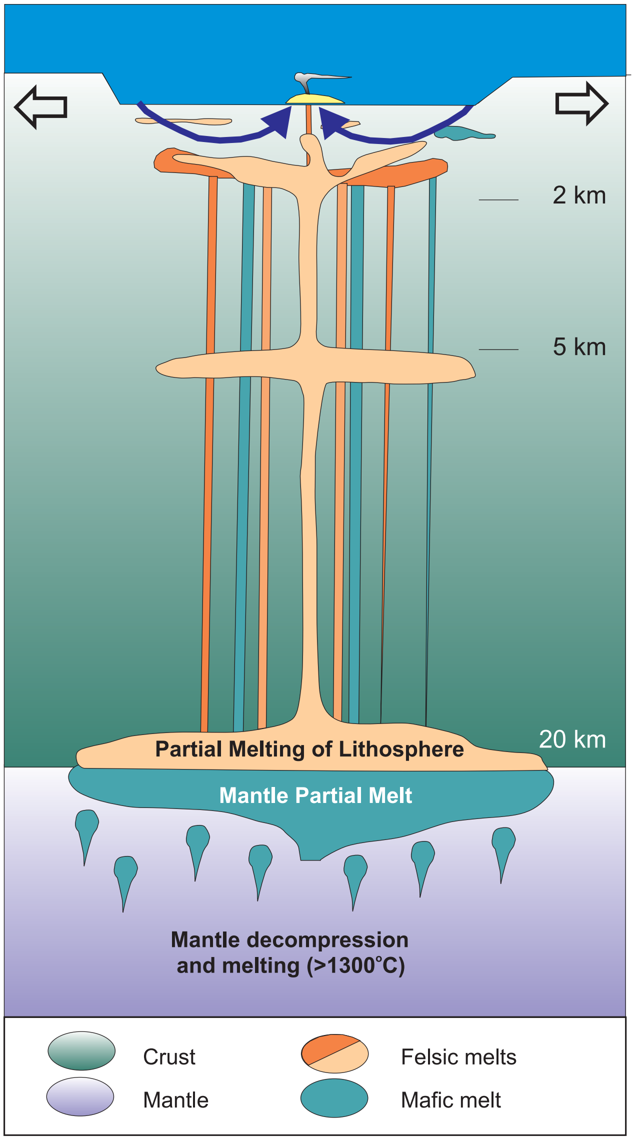

FIG. 13. VMS environments are characterized by tectonic extension at various scales. Extension results in crustal thinning, mantle depressurization and the generation of basaltic melts. Depending on crustal thickness and density, these mafic melts may pond at the base of the crust, resulting in partial melting and generation of granitoid melts. These anhydrous, high temperature melts may quickly rise to a sub-seafloor environment (<3 km below seafloor), where their heat may initiate and sustain convective hydrothermal cells which form VMS deposits.

zeolite-clay and related sub-greenschist mineral assemblages characterized by K-Mg-rich smectites, mixed layer chlorites and K-feldspar. Recognition of these chemical and mineralogical changes in the ancient rock record can be further enhanced by mapping shifts in bulk rock oxygen and hydrogen isotope compositions of the different zones (Green et al., 1983; Taylor and South, 1985; Aggerwal 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 intrusion (Eastoe et al., 1987; Gibson and Watkinson, 1990; Brauhart et al., 1998; Galley, 2003). Faults that act as conduits for volcanic feeder systems tend to be the focal point for ascent of high-temperature, metal-laden hydrothermal fluids which form VMS deposits. These fault systems may remain active through several cycles of volcanic and hydrothermal activity. The result is several periods of VMS formation at different stratigraphic levels with a 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 sub-seafloor environment tends to support high temperature (>350°C) hydrothermal systems, which in turn can form Cu, Cu-Zn and Zn-Cu- (Pb) VMS deposits with variable Au and Ag contents. Areally extensive, 1-5m thick Fe-rich "exhalites" may mark the most prospective VMS horizons (Spry et al., 2000; Peter, 2003) (Fig. 16f, g). These exhalite deposits form from a combination of fine volcaniclastic material, chert and carbonate.

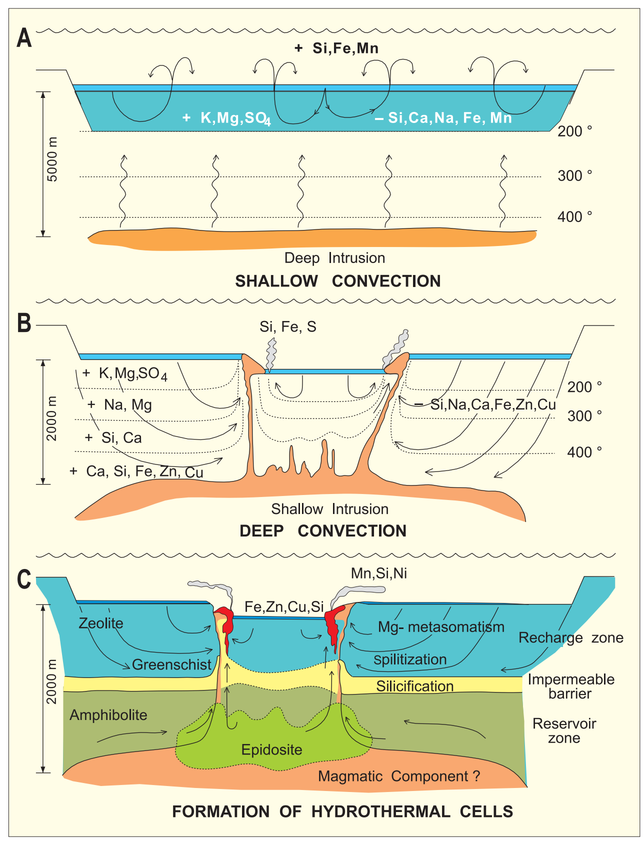

FIG. 14. The development and maturation of a generic sub-seafloor hydrothermal system involves three stages: 1) Relatively deep emplacement of a subvolcanic intrusion below a rift/caldera and establishment of a shallow circulating, low temperature seawater convection system. This results in shallow sub-seafloor alteration and associated formation of chemical sedimentation. 2) Higher level intrusion of subvolcanic magmas and resultant generation of a deep-seated sub-seafloor seawater convection system in which net gains and losses of elements are dictated by sub-horizontal isotherms. 3) Development of a mature, large-scale hydrothermal system in which subhorizontal isotherms control the formation of semi-conformable hydrothermal alteration assemblages. The high temperature reaction zone next to the cooling intrusion is periodically breached due to seismic activity or dike emplacement allowing focused upflow of metal-rich fluids to the seafloor and formation of VMS deposits. From Galley (1993).

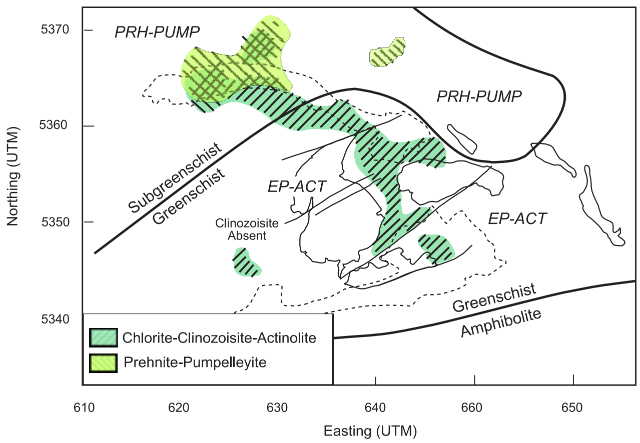

FIG. 15. Comparison of regional greenschist facies hydrothermal alteration in the Noranda Volcanic Complex with previously mapped metamorphic isograds (solid lines: from Dimroth et al. 1983; Powell et al., 1993). The distribution of greenschist facies hydrothermal alteration (shaded) suggests that interpreted 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).

They form during the immature and/or waning stages of regional hydrothermal activity when shallowly circulating seawater strips Fe, Si and some base metals at <250°C and precipitates them on the seafloor through extensive, but diffuse, hydrothermal venting. Formation of exhalites on a basalt-dominated substrate is commonly accompanied by silicification and/or chloritization of the underlying 200-500 m of strata (Fig. 16d, e). Examples of this are observed in the Noranda, Matagami Lake, and Snow Lake VMS camps (Kalogeropoulos and Scott, 1983; Liaghat and MacLean, 1992; Bailes and Galley, 1999). In felsic volcaniclastic-dominated terranes the generation of Fe-formation is 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 IPB (Munha and Kerrich, 1980).

Mafic, felsic, and bimodal siliciclastic volcanic assemblages tend to host volumetrically smaller mafic and/or felsic sill-dike complexes, and generally contain Zn-Cu-Co and Zn-Pb-Cu-Ag VMS deposits, respectively. In deposit settings proximal to discrete extrusive complexes more Cu-rich deposits, such as Neves Corvo in the IPB, may also form. The district-scale semiconformable hydrothermal systems consist of low-temperature mineral assemblages, with Mg-K smectite and K-feldspar alteration and the formation of extensive low-temperature Fe-Si-Mn deposits (i.e., a type of iron formation). Other types of iron formation are interpreted to be products of plume fallout from high-temperature hydrothermal venting in a reduced, stratified water column, or collection of hypersaline brines within fault-controlled depressions on the seafloor (Peter, 2003). Individual units of iron formation can extend for tens of km, as in the Bathurst VMS camp in New Brunswick (Peter and Goodfellow, 1996a), the Paleoproterozoic Bergslagen district (Allen et al., 1996), the Devono-Mississippian IPB in Spain and Portugal (Carvalho et al., 1999) and the Mississippian

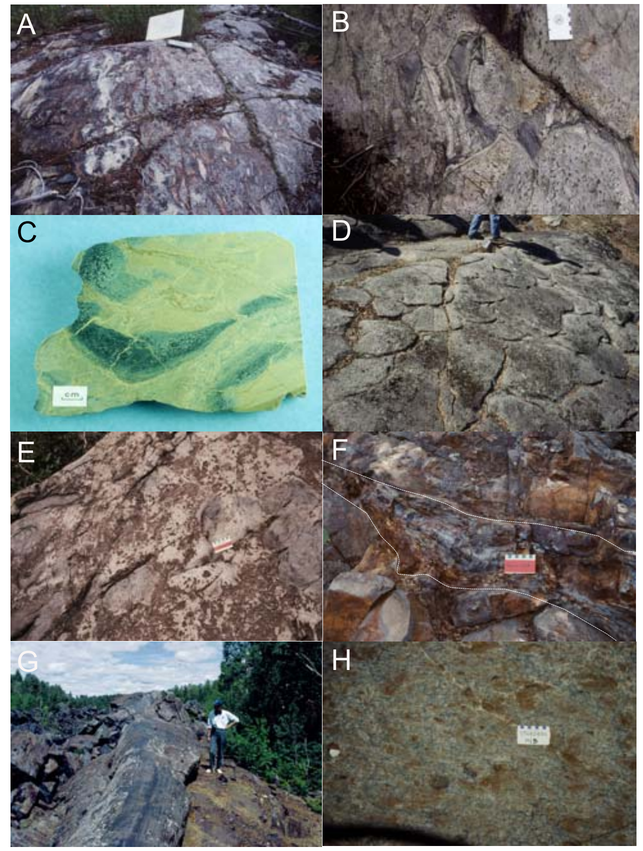

Fig. 16 A) High temperature hydrothermal alteration of mafic volcaniclastic turbidite overlain by a strongly silicified mafic debris flow 1200m below the Chisel-Lost-Ghost VMS horizon, Snow Lake. This represents a regional-scale reaction zone overlain by high temperature zone of silica dumping ; B) Strongly silicified pillows with pipe vesicles infilled with actinolite, epidote and magnetite, and interpillow hyaloclastite completing replaced by the same assemblage. This alteration facies directly overlies the subvolcanic Mooshla intrusion, Bousquet VMS camp; C) An example of epidosite typical of the root zones of VMS hydrothermal upflow zones in which high fluid/rock ratios has resulted in leaching of lithophile, chalcophile and LFSE from the strata (J. Lydon); D) Strongly Mg-altered pillows metamorphosed to c.g. anthophyllite-cordierite in the footwall strata to the Winston Lake Zn-Cu deposit, Terrace Bay ON; E) Silicified basaltic andesite of the Upper Amulet fm., Noranda, as an example of pervasive silica dumping that occurs in mafic flows directly underlying tuffaceous exhalite units in many Precambrian VMS camps; F) Mine Contact Tuff exhalite horizon (between white lines) that over-lies the silicified andesites of the Waite fm., Noranda; G) Banded magnetite-chert Fe-formation over-lying the Austin Brook massive sulphide deposit, Bathurst camp (J. Peter); H) Chloritoid-rich zone below the Matabi deposit, Sturgeon Lake, where Fe-rich hydrothermal fluids crossed a previously-formed carbonate-rich regional alteration zone.

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, 1996b).

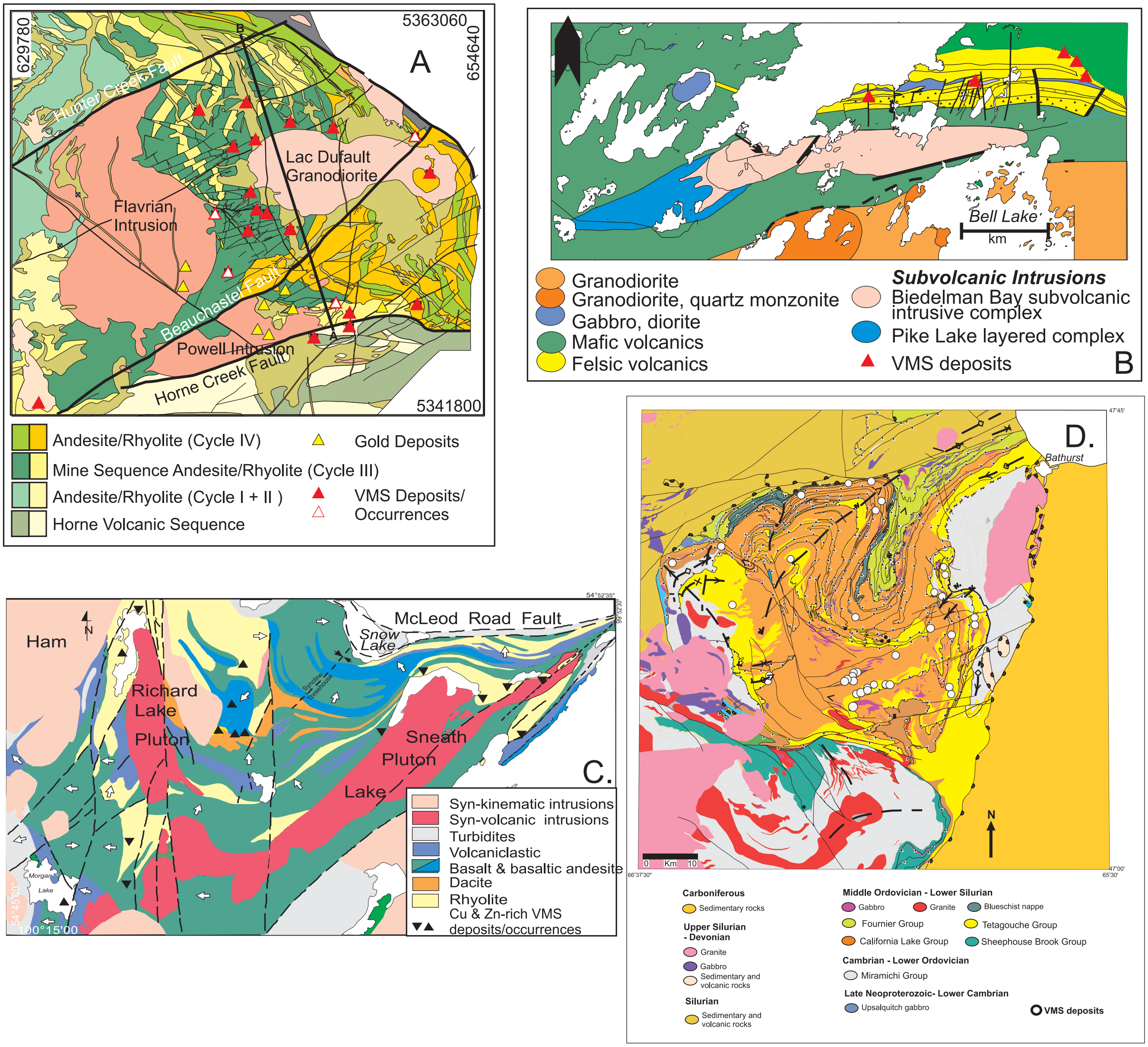

FIG. 17. Examples of clusters of VMS deposits defining a mining camp. These include: A) the Archean Noranda camp, with 14 bimodal-mafic type deposits underlain by the Flavrian-Powell subvolcanic intrusion (Santaguida, 1994); B) the Paleoproterozoic Flin Flin district with 17 VMS deposits hosted within a series of block-bounded terranes representing different stages of oceanic arc development. For this reason the district contains a wide variety of VMS types (Syme and Bailes, 1993; Galley and Jonasson, 2003); C) the Paleoproterozoic Snow Lake camp with two subvolcanic intrusions (Sneath Lake and Richard Lake) involved in two separate hydrothermal events that formed 8 bimodal-mafic deposits (modified from Bailes and Galley, 1999); and D) the Ordovician Bathurst camp with 35 deposits dominated by the bimodal-siliciclastic deposit type (modified from van Staal, 2003).

Deposit-scale Environments

VMS deposits consist of a massive to semi massive stratabound sulphide lens, and most are underlain by a sulphide-silicate stockwork vein system (Figs.1 and 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, the 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 meters wide and hundreds of meters in strike length. The 148 Mt Kidd Creek deposit begins at the present erosion surface and extends for over 2000 m downplunge (original strike length), with the 5 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., Figs. 1 and 18). Observations of modern seafloor hydrothermal vent complexes in effusive, flow-dominated terranes indicate that the deposits begin to form as a series of sulphide-silicate-sulfate chimneys (Fig. 18a). These become structurally unstable with continued growth and collapse, and coalesce to form a breccia mound (Fig. 18b,c). Continued circulation of hydrothermal fluids within this breccia mound results in sealing from seawater by a sil-

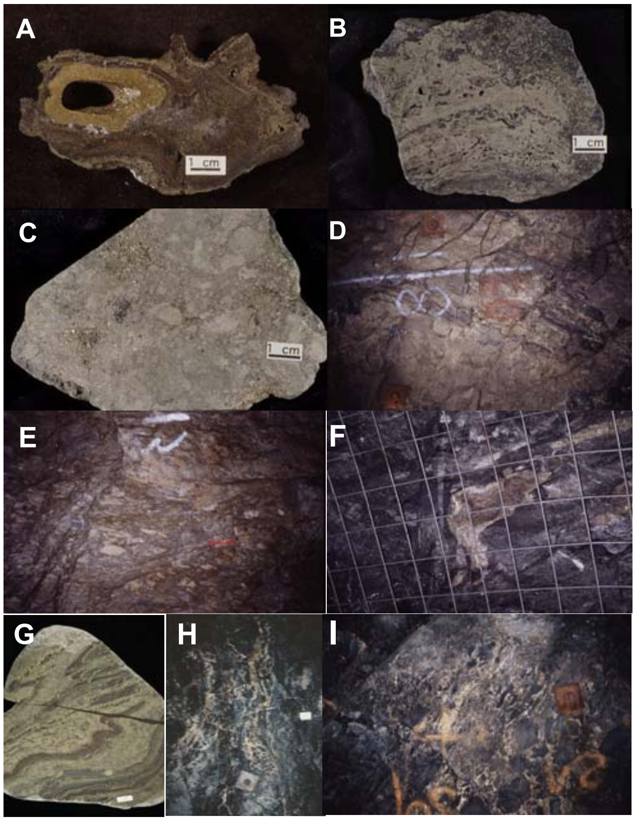

Fig. 18. A) Example of a zoned sulphide chimney from the Endeavour Ridge vent field (I.R. Jonasson); B) Typical textures from a massive sulphide mound, Main vent field, Juan de Fuca Ridge. Banding from incremental chimney growth, with ovoids representing worm casts. Fragment cemented by later sulphide growth during mound collapse and subsequent invasion by hydrothermal fluid (A.G. Galley); C) Sandy sulphide ore from Cretaceous Aarja deposit, Semail ophiolite, Oman. Typical texture due to repeated mound collapse due to anhydrite dissolution and re-cementing with later sulphide (I.R. Jonasson); D) Partial replacement of finely bedded tuff by massive pyrrhotite-chalcopyrite at the Ansil deposit, Noranda (A.G. Galley); E) Rhyolite clasts cemented by pyrite-sphalerite rich sulphide groundmass, Louvicourt deposit, Val d'Or (A.G. Galley); F) Pyrite-sphalerite clast as part of a proximal debris flow, Louvicourt, Val d'Or (A.G. Galley); G) Cranston tuff unit with lit-par-lit replacement and in-filling by first pyrite-sphalerite, followed by pyrrhotite-chalcopyrite, Ansil deposit, Noranda (A.G. Galley); H) Well-developed pyrrhotite-chalcopyrite vein stockwork zone with intense chlorite alteration of the rhyolite wallrocks, Ansil deposit, Noranda (A.G. Galley). In-filling of rhyolite hyaloclastite in immediate footwall to the Ansil massive sulphide lens, Noranda (A.G. Galley).

ica, clay, and/or sulfate cap. Progressive deposition of metal sulphides within the mound results in the formation of a complexly textured, semi massive 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 (Fig. 19). This process is referred to as zone refining (Eldridge et al., 1983) and results in a chalcopyrite-rich core and a sphalerite galena-rich outer zone (Fig. 19). 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. Massive pyritic cores and thin, base- and precious-metal enriched outer margins are a characteristic of VMS deposits that have had a protracted thermal history (e.g., Hannington et al., 1998; Petersen et al., 2000).

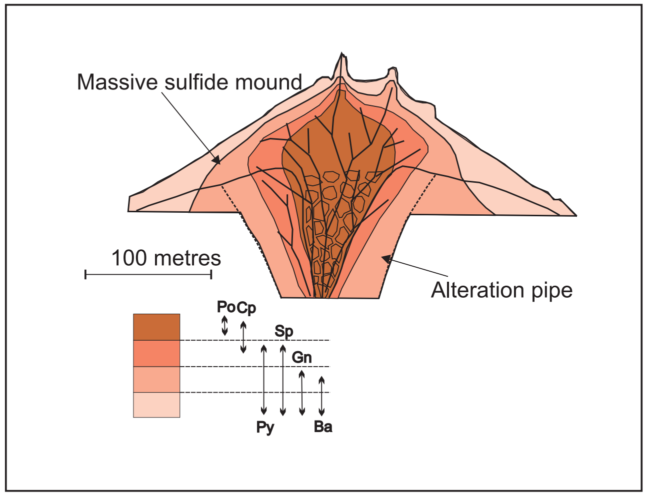

FIG. 19.The mineral zonation commonly observed within VMS deposits is largely a function of hydrothermal fluid temperature and composition. Temperature zonation results in the zoning of sulphide minerals within both the discordant stockwork zone and the conformable sulphide mound. From Lydon (1984).

Although many VMS deposits have a clastic component, this is usually subordinate to the massive sulphide facies. In many cases, such as the HW orebody at Buttle Lake (Barrett and Sherlock, 1996a), British Columbia, Kidd Creek, Ontario (Hannnington et al., 1999b), Louvicourt, Quebec, and Triple 7, Manitoba these subordinate clastic facies contain a mixture of sulphide and host rock fragments. 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 (Barret 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 sub-seafloor replacement. This occurs when hydrothermal fluids infill primary pore space in either extrusive, autoclastic, volcaniclastic or epiclastic successions below an impermeable cap (Fig. 18d, e). 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 (Fig. 18g). Hydrothermal fluid seepage up the rift margins resulted in unit-by-unit replacement of the laminated volcaniclastic layers by pyrite, sphalerite and silica. Some exceptionally large massive sulphide deposits have formed within volcanic depressions infilled with autoclastic and het-

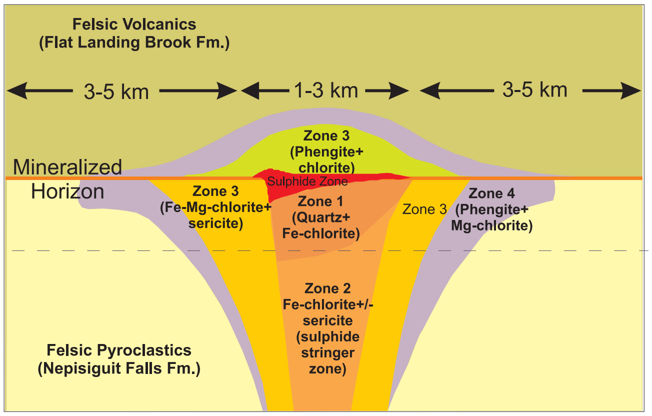

FIG. 20. A composite section through a VMS alteration system in the Bathurst mining camp as an example of a VMS proximal alteration zone metamorphosed to greenschist grade mineral assemblages. From Goodfellow et al. (2003).

erolithologic 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).

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. These stockwork vein systems occur at the center 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 meters. Proximal hanging-wall alteration can manifest itself as a semi-conformable halo up to tens of meters thick (Brunswick No 12, Bathurst) or may continue above the deposit for tens to hundreds of meters 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. 20), but with deposits such as Chisel Lake, Snow Lake 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 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 BC. 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,± 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 (e.g., <1,500 m water depth), boiling may have occurred either in the upflow zone or in the immediate sub-seafloor. Depending on the extent of boiling, this can result in vertically extensive pyritic stockwork 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 sub-surface boiling of hydrothermal fluids, which resulted in the formation of low temperature (<200°C) Sb-Hg-As-Pb sulfosalt-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-chalocpyrite-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 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. 21). 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).

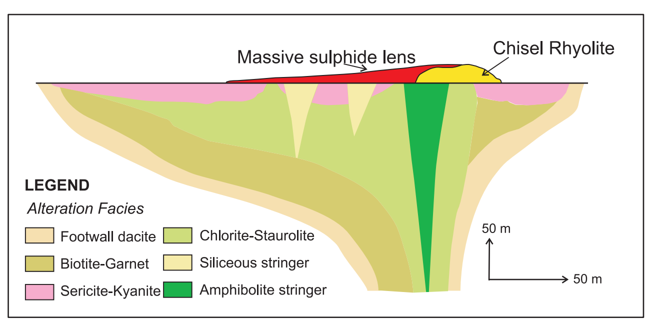

FIG. 21. A stylized cross section through the proximal alteration zone at the Chisel deposit, Snow Lake mining camp, illustrating the changes in mineral assemblages that occur when the terrane undergoes lower to middle amphibolite grade regional metamorphism. From Galley et al. (1993).

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), 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 with minimal heat loss into sub-seafloor settings where hydrothermal convection can be initiated. For this reason, most prospective VMS environments are characterized by high-level sill-dike swarms, discrete felsic extrusive centers 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, caldera). Stacked alteration zones can have an aggregate thickness of 2000-3000 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 (Lydon, 1996; Large et al., 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 sub-seafloor 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 kilometers to tens of kilometers (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, 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 and Goodfellow, 2003a,b). Vertical and horizontal facies variations 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.

1) 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 centers and rifted continental margins are also prospective.

2) VMS formation occurs during periods of major ocean-closing and terrane accretion. This includes 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).

3) In effusive flow-dominated settings in oceanic arc and continental margin arcs, VMS can be associated with 15-25 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, $(La/Yb)_N<7$, $(Gd/Yb)_N<2$ and Y/Zr< 7 define high-temperature (>900°C) felsic volcanic environments favourable for VMS formation. The presence of synvolcanic dike swarms and exhalite horizons are indicative of areas of high paleo-heat flow.

4) In continental back arc, bimodal siliciclastic-dominated settings aeromagnetic surveys can be used to identify areally extensive Fe-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 centers. Volumetrically minor sill-dike complexes also may identify

higher temperature hydrothermal centers.

5) 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.

6) 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-spar). 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 sub-seafloor 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 1:20K scale and complimentary 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-sulfidation 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 enrvironments 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 BC 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; i.e. 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. Where are the continental back-arc environments in the Superior, Slave and Grenville provinces? Have we explored enough in the +2.8 Ga 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. 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 BC, such as the Triassic Slide Mountain and Cache Creek terrane, should be reevaluated 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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