Paper 49

The VMS Model: Advances and Application to Exploration Targeting

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ABSTRACT

Volcanic Massive Sulphide (VMS) deposits are significant sources of Cu, Zn and, to a lesser extent, Pb, Ag, Au, Cd, Se, Sn, Bi and minor amounts of other metals. VMS deposits are one of the most thoroughly researched deposit class and one of the few with an active, modern analog. They form on, and immediately below the seafloor, by the discharge of a high temperature, evolved, seawater-dominated hydrothermal fluid during contemporaneous volcanism and/ or plutonism. The volcanic-hydrothermal model for VMS deposits has continuously evolved and the combined geological, geophysical and geochemical exploration methods that result from this evolution have added to the attractiveness of this deposit type as an economic target. However, many questions concerning VMS genesis remain, such as the source of metals and gold, and prediction of the metal potential of a given belt. As exploration goes deeper success will require a more sophisticated and predictive model that integrates geophysics, geochemistry and geology in 3D GIS formats to improve identification of the key elements of the VMS model that will lead to more subsurface discoveries.

INTRODUCTION

The acronym VMS refers collectively to volcanogenic (Franklin et al., 2005), volcanic-associated (Franklin, 1995), and volcanic-hosted (Large et al., 2001b) massive sulphide deposits. VMS deposits are major sources of Cu and Zn and, to a lesser extent, Pb, Ag, Au, Cd, Se, Sn, Bi and minor amounts of other metals, such as indium (Franklin et al., 2005). The metal contents and tonnage of VMS deposits are log normally distributed but, as indicated by geometric means that range from 2.7 to 7.1 Mt (depending on VMS deposit type; Franklin et al., 2005; Sangster, 1977), they are relatively small exploration targets. As a deposit type they contain some giant deposits that are anomalous either because of their size (e.g., Rio Tinto, Leistel et al., 1998), their size and base-metal content (e.g., Kidd Creek, Hannington et al., 1999a; Neves Corvo, Relvas et al., 2002), or their size and precious metal (Au, Ag) content (e.g., Horne, Kerr and Gibson, 1993; LaRonde, Dube et al, 2007; Boliden, Allen et al., 1996b, Bergman-Weihed et al., 1996). It is their high value multi-metal character and concentrated value per tonne mined, which continue to make VMS deposits an economically viable exploration target. The ability to target this deposit type by a combination of geological, geophysical and geochemical methods adds to its attractiveness. However, the small size of most VMS deposits, metallurgical challenges such as grain size

and deleterious metal content, and potential environmental impacts due to refining processes can detract from their economic value as priority exploration targets.

In this paper we examine our current knowledge of VMS deposit genesis, highlight aspects of the model that have exploration significance, and discuss shortcomings of the model, from both a scientific and exploration perspective. Geophysical techniques and details of the petrochemical aspects of the VMS model are not discussed, but are contained in the companion papers by Boivin (2007) and Piercey (2007) in this volume.

THE VMS MODEL

VMS deposits are syngenetic, stratabound and in part stratiform accumulations of massive to semi-massive sulphide. The deposits consist of two parts: a concordant massive sulphide lens (>60% sulphide minerals), and discordant vein-type sulphide mineralization, commonly called the stringer or stockwork zone, located within an envelope of altered footwall volcanic and or sedimentary rocks (Figure 1). In some cases, the hanging-wall sedimentary or volcanic rocks are also altered. In some deposits the stratiform massive sulphide lens comprises the entire economic deposit, whereas in other deposits appreciable quantities of ore are also mined from the stockwork zone.

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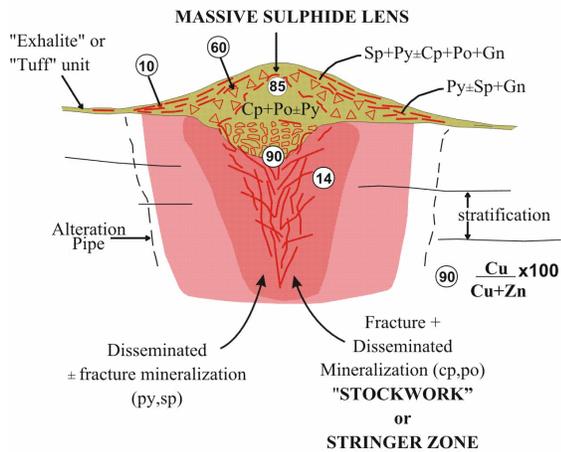
Figure 1: Idealized VMS deposit showing a strataform lens of massive sulphide overlying a discordant stringer sulphide zone within an envelope of altered rock (alteration pipe). Basemetal zonation indicated by numbers in circles with the highest numbers being Cu-rich and the lower numbers more Zn-rich (Py = pyrite, Cp = chalcopyrite, Po = pyrrhotite, Sp = sphalerite, and Gn = galena; modified from Gibson, 2005).

Since the discovery of active hydrothermal vent systems on the present-day ocean floor, research has significantly aided understanding of many aspects of VMS deposits such that they are one of the most thoroughly researched deposit classes (see reviews in Franklin et al., 2005; Hannington et al., 2005 and references therein). Based on this extensive research, it is now well accepted that VMS deposits form syngenetically as a product of seafloor hydrothermal systems that formed in spatial, temporal and genetic association with contemporaneous volcanism and/or plutonism. VMS deposits form on, and

immediately below the seafloor, by the discharge of a high temperature, evolved, seawater-dominated hydrothermal fluid (Franklin et al., 1981; Lydon, 1984; 1988, Large et al., 2001a; Franklin et al., 2005, and references therein) as shown in the model presented in Figure 2. The model illustrates the six main elements that are considered essential to the formation of VMS hydrothermal systems, and these elements are described below (modified from Franklin et al., 2005). Geological, geochemical and geophysical criteria developed for the recognition of these elements form an integral part of many exploration programs.

1. A heat source that is sometimes manifested by large, sill-like, synvolcanic hyabyssal intrusions to initiate, drive and sustain a long-lived, high temperature hydrothermal system (Cathles 1981; Cathles et al., 1997).
2. A high-temperature reaction zone that forms through the interaction of evolved seawater with volcanic and sedimentary strata. During this interaction, metals are "leached" from the rocks.
3. Deep penetrating, synvolcanic faults that focus recharge and discharge of metal-bearing hydrothermal fluid.
4. Footwall and hanging wall alteration zones that are products of the interaction of near surface strata with mixtures of high-temperature ascending hydrothermal fluid and ambient seawater.
5. The massive sulphide deposit that formed at or near the seafloor and whose metal content was refined by successive hydrothermal events.
6. Distal products, primarily exhalites, that represent a hydrothermal contribution to background sedimentation.
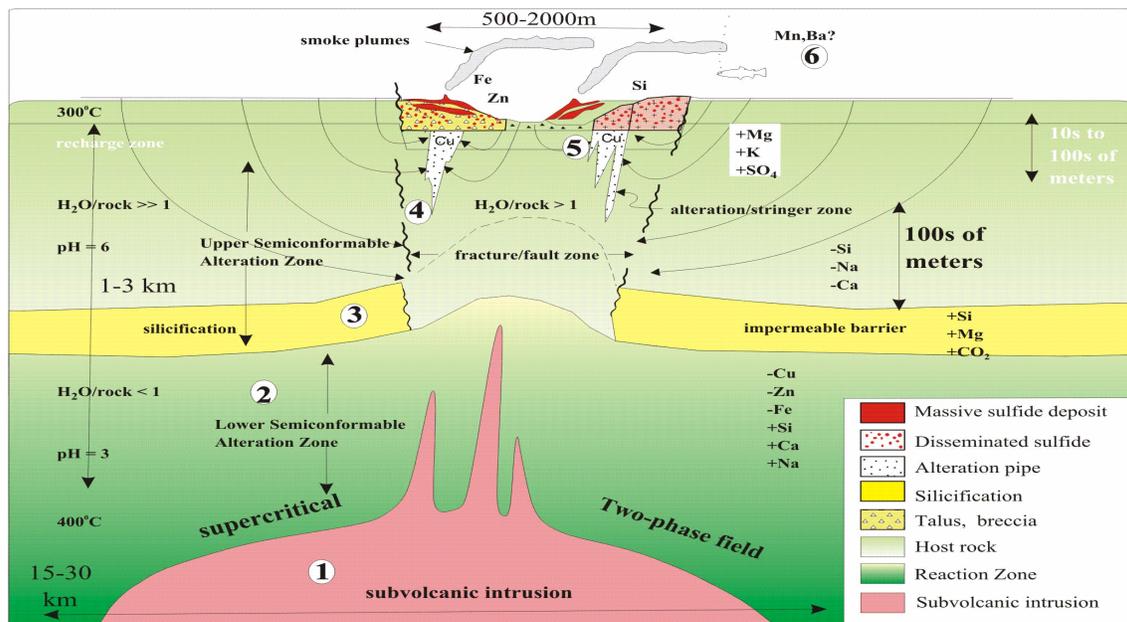
Figure 2: A schematic illustrating the relationship between subvolcanic intrusions, subsea-floor alteration, synvolcanic faulting and the generation of VMS deposits (modified after Galley, 1993 and Franklin et al., 2005). Refer to text for description of the six elements.

DISCUSSION AND ASSESSMENT OF THE MODEL

Our assessment of the geological and geochemical attributes of the VMS model and their applicability and significance to exploration will start with large-scale features and progress to features that characterize the immediate deposit environment. First we address features indicative of a favorable geodynamic environment; these are commonly the most difficult to relate directly to VMS deposit genesis, but, because of their scale, are generally the most important for area selection and greenfields exploration. Secondly, we address features at the scale of the volcano-sedimentary environment that have relevance to both greenfields and brownfields exploration. Lastly, we discuss features of the immediate deposit environment, which are most relevant to property-scale, or brownfields exploration.

It is important to recognize that the essential elements of the VMS model, which are illustrated in Figure 2, operate to a variable degree in all submarine volcano-sedimentary hydrothermal systems regardless of whether they contain VMS deposits or not. Therefore, two important questions to consider within the context of the hydrothermal model are: 1) what elements in the model influence the efficiency and longevity required of an ore-forming submarine hydrothermal system, and 2) are there elements missing from the current model whose inclusion in a particular basin or all basins would result in VMS formation (e.g., a magmatic contribution of metals)?

GEODYNAMIC ENVIRONMENT

There is growing consensus that VMS deposits preferentially form during episodic rifting of oceanic and continental volcanic arcs, fore arcs, and in back-arc extensional environments (Figure 3; van Staal et al., 1995; Vearncombe and Kerrich, 1999; Carvalho et al., 1999; Piercey et al., 2001; Allen et al., 2002; Rogers and vanStaal, 2003; Rogers et al., 2003; Hart et al., 2004; Hannington et al., 2005; Franklin et al., 2005,). Although a large number of factors influence the formation and preservation of VMS deposits, crustal thinning and rifting are essential to the formation of a productive VMS hydrothermal system (Figures 2 and 3). Extension and thinning of the crust during rifting depressurizes the lithospheric mantle. The resultant mantle melting and rift-related faulting focuses magmatic activity at various levels in the thinned crust (Figure 3). Mafic magmas pond near the base of the thinned crust and, if rifting is long-lived, partial melting of the crust generates rhyolitic melts. This combination of mafic mantle and felsic crustal melts result in the typical bimodal volcanism of many rift and VMS environments (Hart et al., 2004).

Thus, extension provides the localized, high level heat source required to generate and sustain a high-temperature hydrothermal system and it is the deep, cross-stratal structural permeability afforded by faults developed and reactivated during rifting that permit efficient hydrothermal circulation and discharge; all are fundamental elements of a productive VMS hydrothermal system. The role of extension and rifting in VMS formation is recognized in the 5-fold lithotectonic classification of VMS deposits proposed by Franklin et al., (2005), which classifies VMS districts (not deposits) and is based on the entire volcano-sedimentary assemblage within a district (Table 1). The inclusion of a much larger, district-scale, stratigraphic interval, rather than the immediate deposit host rocks, has the advantage of more confidently relating the VMS district and the VMS deposits to their geodynamic setting.
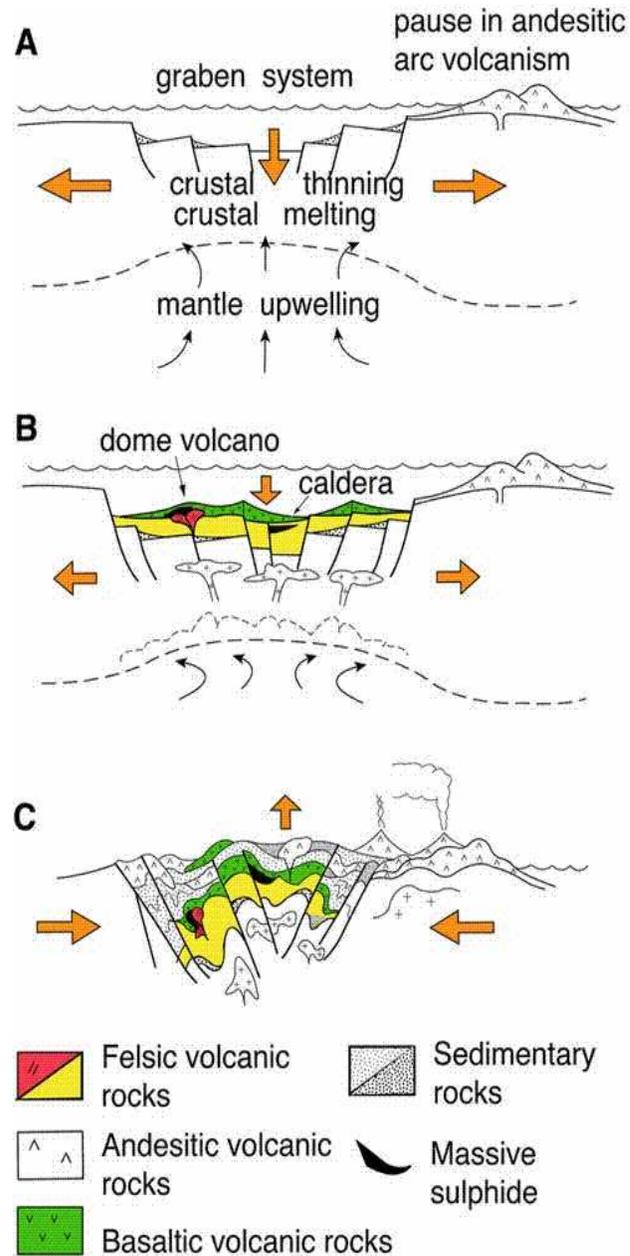
Figure 3: Rifting of a volcanic arc showing: A) crustal thinning, subsidence, and mantle upwelling; B) volcanism and the formation of VMS deposits; and C) return to a compressive arc environment and deformation of the rift succession (from Allen et al., 2002)

Table 1: VMS deposit types, facies, petrochemical assemblages, and tectonic setting (modified after Franklin, et al., 2005; Piercey, 2007; LOTI = Low Ti Basalt, MORB = Mid-Ocean Ridge Basalt, EMORB=Enriched MORB, BABB-Back Arc Basin Basalt, OIB- Ocean Island Basalt, HFSE-High Field Strength Elements)

Type	Typical Facies	Petrochemical Assemblages	Tectonic Setting (Inferred for Archean examples)	Examples
Mafic	Dominantly mafic flows and, 10% felsic flows/domes. Mafic sills and dikes common, minor argillite and chert. (Ophiolitic assemblages)	MORB- L O T I -boninite basalts	Mature intra-oceanic backarcs	South Urals, Russia Central Newfoundland, Canada Troodos, Cyprus Semail, Oman Pontides, Turkey and Albania
Pelitic-mafic	Mafic sills, subordinate flows with argillite, carbonaceous argillite subequal or dominant, minor chert and trace to absent felsic volcanic facies.	MORB, EMORB basalts, Alkaline basalt (OIB)	Sedimented mid-ocean ridges, transforms or backarcs	Outokumpu, Finland Labrador Trough, Windy Craggy, Canada Mid and South Urals, Russia Besshi district, Japan
Bimodal-mafic	Dominantly mafic flows with up to 25% felsic flows/domes and subordinate felsic/mafic volcaniclastic rocks and terrigenous sedimentary rocks (wackes, argillites)	MORB , LOTI, BABB boninite, icelandite (lesser calc-alkalic and island arc tholeiites) FIII (FIV) >/= FII rhyolites	Rifted oceanic arcs	Abitibi, East Slave, Flin Flon, Canada Mid and south Urals, Russia and Kazakhstan Tambo Grande, Peru Zacatecas, Mexico
Bimodal-felsic	Felsic flows/domes, volcaniclastic rocks dominant with 10-40% mafic flows and sills and <10 terrigenous sediments (wackes, argillites). Some portions of succession may be subaerial or shallow water.	MORB, OIB-Alkalic basalt FII (<FIII) rhyolites (HFSE-enriched)	Continental margin arcs and related backarcs	Western Slave, Finlayson Lake, and Dunnage Zone, Myra Falls, Eskay Creek, Canada Skellefte and Bergslagen, Sweden Mount Read Volcanics, Tasmania Pontides, Turkey Hokuroko, Japan
Siliciclastic-felsic	Siliciclastic rocks up to 75 %, felsic volcaniclastic rocks with subordinate flows/domes with <10% mafic flows and sills and minor Fe- and Mn-rich sedimentary rocks (ironformation). Some portions of succession may be subaerial or shallow water.	M O R B , O I B -Alkaline basalt FII (<FIII) rhyolites (HFSE-enriched)	Mature epicontinental backarc	Murchison, W.Australia Rudny Altai, Kazakhstan and Russia Iberian Pyrite Belt, Spain and Portugal Jibelt and Guemessa, Morocco Bathurst, Canada Campo Morado, Mexico

In greenfields exploration recognition of a rift environment is essential to area selection. The first feature an explorationist conducting a regional reconnaissance survey needs to observe is the basic stratigraphy of an area, and in this regard it is important to recognize that rifts are characterized by distinctive rock associations and alteration, including: 1) a pre-rift volcanic, volcano-sedimentary, or sedimentary succession, that could be part of an ocean island, continental margin or epicontinental sequence; 2) a syn-rift succession characterized by a bi-modal volcanic or volcano-sedimentary complex that is dominated by either basalts (or andesitic basalt) or rhyolitic volcanic rocks; 3) in some cases (bimodal felsic and siliciclastic–felsic deposits), a post-rift thermal subsidence succession characterized by well stratified marine sedimentary rocks with or without volcanic rocks or differentiated arc volcanic rocks indicative of a return to a compressive arc tectonic regime; 4) evidence from sedimentary structures volcanic facies and fossils of widespread submarine environments and rapid subsidence from terrestrial or shallow marine environment to deep marine environment (e.g., Sturgeon Lake VMS district, Morton et al., 1991; Hudak et al., 2003l; Skellefte, Allen et al., 1996b; Bergslagen, Allen et al., 1996a); 5) extensive synvolcanic dike swarms as evidence of rifting and subsidence (e.g., Noranda District, Gibson et al. 1999, Flin Flon District, Gibson et al., 2003); 6) widespread moderate to strong regional semiconformable alteration and local areas of strong hydrothermal alteration and metallic mineralization (base and/or precious metal vein showings, disseminated sulphide zones) within pre- and syn-rift successions; and 7) the presence of high-level, comagmatic, subvolcanic intrusions consisting of tonalite, trondhjemite, quartz diorite and gabbro and whose felsic phases are geochemically equivalent to associated felsic volcanic rocks (e.g., Flavrian Pluton, Noranda; Beidelman Bay pluton, Sturgeon Lake , Snow Lake; Goldie, 1976; Goldie et al., 1979; Galley, 2003; Bailes and Galley, 1999).

Furthermore, subvolcanic intrusions are hypothesized to be the source of heat that initiated and sustained a sub-seafloor convective hydrothermal system that in some cases also supplied metals to the ore-forming VMS hydrothermal system (e.g., Goldie, 1976; Campbell et al., 1981; Morton et al., 1991; Paradis et al., 1993). However, recent geochemical, and geochronological studies indicate that the most voluminous phases of the subvolcanic intrusions were emplaced later than the associated VMS deposits and their associated mafic and felsic volcanics (Galley, 2003). The occurrence of these multi-phase subvolcanic intrusions indicates the presence of long-lived thermal corridors in which repeated rift-related volcanism and intrusive activity provide suitable VMS environments (Galley et al., 2000; Galley, 2003; Hart et al., 2004; Franklin et al., 2005). These features can be readily observed during regional reconnaissance of a potential greenfields VMS exploration target.

Syn-rift volcanic rocks can also be recognized, defined and correlated by using lithogeochemistry to recognize petrochemical assemblages of mafic and felsic volcanic rocks that are distinctive of rifting and high temperature magmas (Table 1; Piercey, 2007). For example, the composition of mafic volcanic rocks, largely based on trace elements, enable recognition of favorable, relatively primitive volcanic arc and back arc environments versus more evolved and less prospective ocean floor and ocean island environments (Gelinas et al., 1984;Wyman et al., 1999; Crawford et al., 1992; Stolz, 1995; Stolz et al., 1997; Syme et al., 1996; Piercey et al., this volume). Petrochemical evidence for the presence of these primitive arc environments may include the presence of boninites (Wyman, 2000; Piercey et al, 2001) and low-Ti basalts and komatiites (Barrie and Pattison, 1999, Wyman et al., 1999). These rock types are the product of high volume melting of lithospheric mantle during stages of nascent arc development and later arc rifting. Another recently recognized and potentially significant association is the occurrence of icelandite and/or high-Ti andesites, in some VMS districts, particularly of the bimodal-mafic type. Embley et al. (1988) and Perfit et al. (1999) first described the relationship between high Fe and Ti andesite and massive sulphide at the Galapagos Ridge. Icelandites and/or high-Ti (Fe) andesites have also been recognized at Noranda (Gibson, 1990), the San Nicolas deposit in Mexico (Johnson et al., 2000), the Tambo Grande deposits in Peru (Tegart et al., 2000), the Mattabi deposit (Franklin et al 1975) and at Flin Flon (Wyman, 2000). Based on petrogenetic evidence, Embley et al. (1988) interpreted the andesites to be derived through contamination of basaltic melt by a partial melt generated from hydrated crust, indicating the presence of a high-level, crustal magma chamber (i.e., a heat source) during basalt eruption and VMS formation.

The composition of distinctive types of felsic volcanic rocks that host many VMS deposits are also used to identify prospectivity (Piercey et al., 2001; 2003). Felsic volcanic rocks associated with VMS deposits have specific compositions referred to as FII, and FIII by Lesher et al., 1986, Group II and III by Barrie et al., 1993, as transitional and tholeiitic by Barrett and Mclean (1994), and as FII, FIII, FIV by Hart et al. (2004). In each case these high silica rhyolite melts form at high temperatures (800-1000oC) from partial melting of the crust at shallow (<15km) levels within rift environments (Sigurdsson, 1977; Sillitoe, 1982; Beard and Lofgren, 1991; Barrie, 1995; Barrie and Pattison, 1999; Barrie et al., 1993;1999; Lentz, 1998; Prior et al., 1999a, 1999b; Hart et al., 2004). Moreover, even when a prospective volcanic arc succession has been identified, specific basalt and rhyolite compositions (e.g., mid-ocean ridge basalt, boninite and high Si rhyolite) may be used to define rifting events that bracket favorable ore intervals (horizons) kilometers from any VMS deposit. Thus, the petrochemistry of bimodal volcanic assemblages is used during regional greenfields exploration to target rift successions and settings permissive for VMS formation (Piercey and Gibson, 2005).

VMS –FAVOURABLE VOLCANO-SEDIMENTARY ENVIRONMENTS

A key characteristic of the VMS model is the diverse spectrum of volcano-sedimentary environments that are permissive for VMS formation (Large, 1992; Cas, 1992; Gibson et al., 1999; Large et al., 2001b; Franklin et al., 2005). These environments range from end members dominated by either flow, volcaniclastic, and or sedimentary lithofacies (Figures 4a to 4f). Although one of the end member lithofacies may be dominant within a lithostratigraphic type or within a VMS district (Table

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1), it is not the characteristics of a specific lithofacies that is of utmost importance to exploration. Rather, it is the characteristics that are common to the spectrum of volcano-sedimentary environments and, the relationship of these common key characteristics to fundamental processes within the VMS hydrothermal system, and the geological/geochemical criteria that allow recognition of these processes.
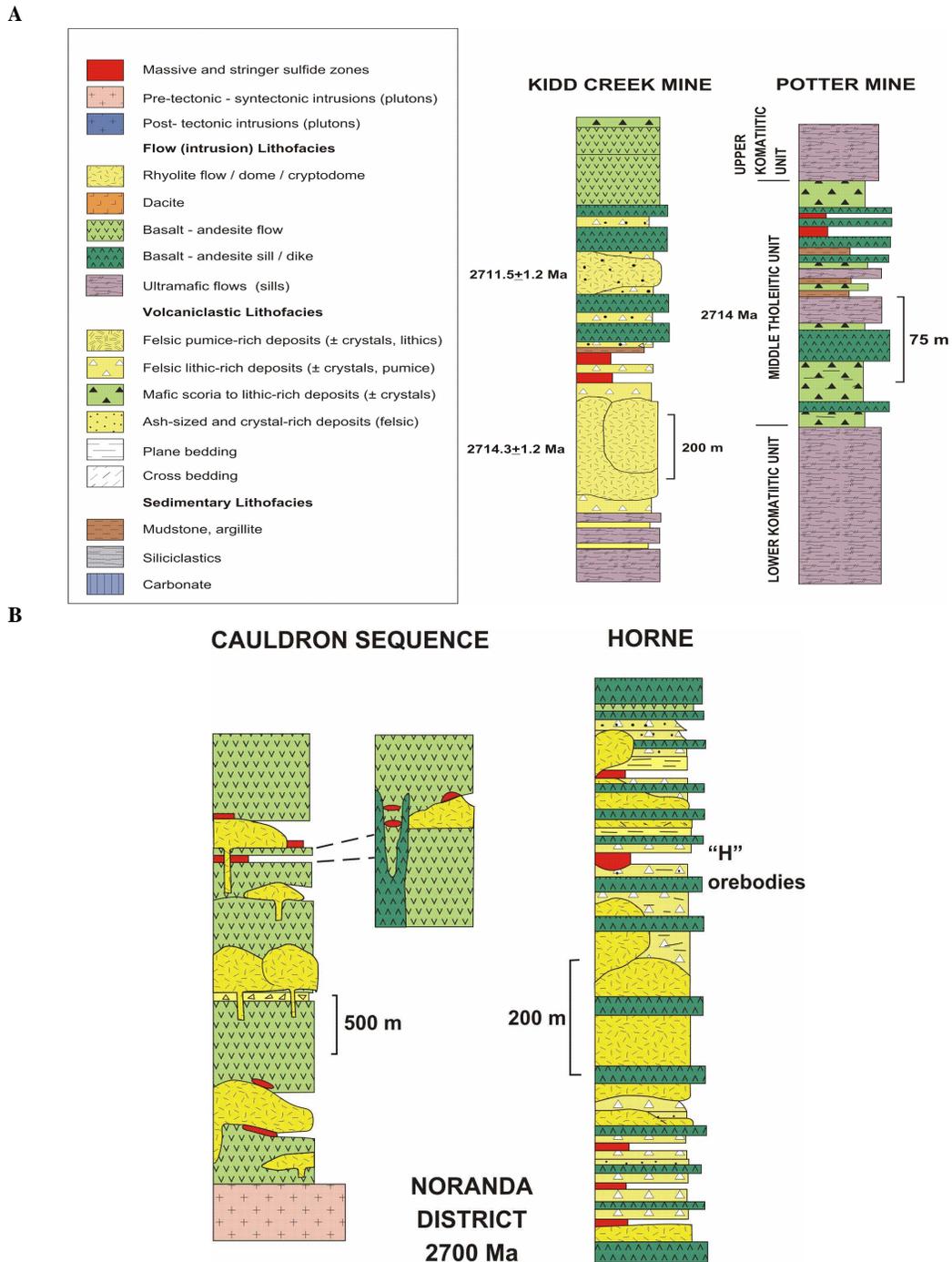
Figure 4: The spectrum of VMS environments (modified after Franklin et al., 2005): a) stratigraphic section of the bimodal-mafic Kidd Creek and Potter deposits; b) stratigraphic sections through the intra-Noranda cauldron flow dominated succession and the felsic volcaniclastic succession that hosts the Horne deposit. The intracauldron VMS deposits although occurring at several stratigraphic levels are clustered at two intervals marked by the C and Main Contacts exhalites (see Figure 6)
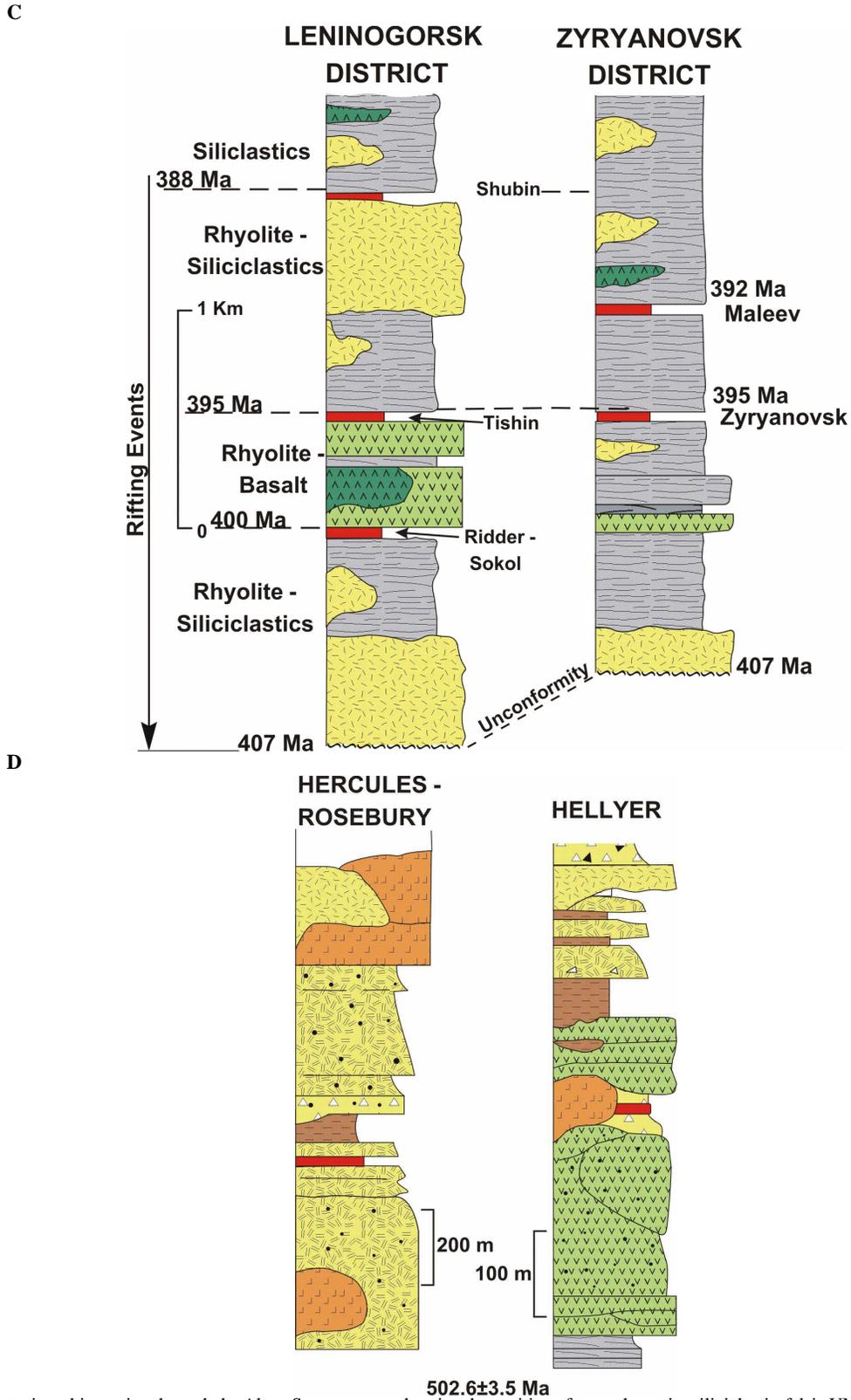
Figure 4: c) stratigraphic section through the Altay-Sayan orogen showing the position of some the major siliciclastic-felsic VMS deposits; d) stratigraphic sections through the bimodal-felsic Roseberry and Hellyer VMS deposits showing volcaniclastic versus flow facies environments
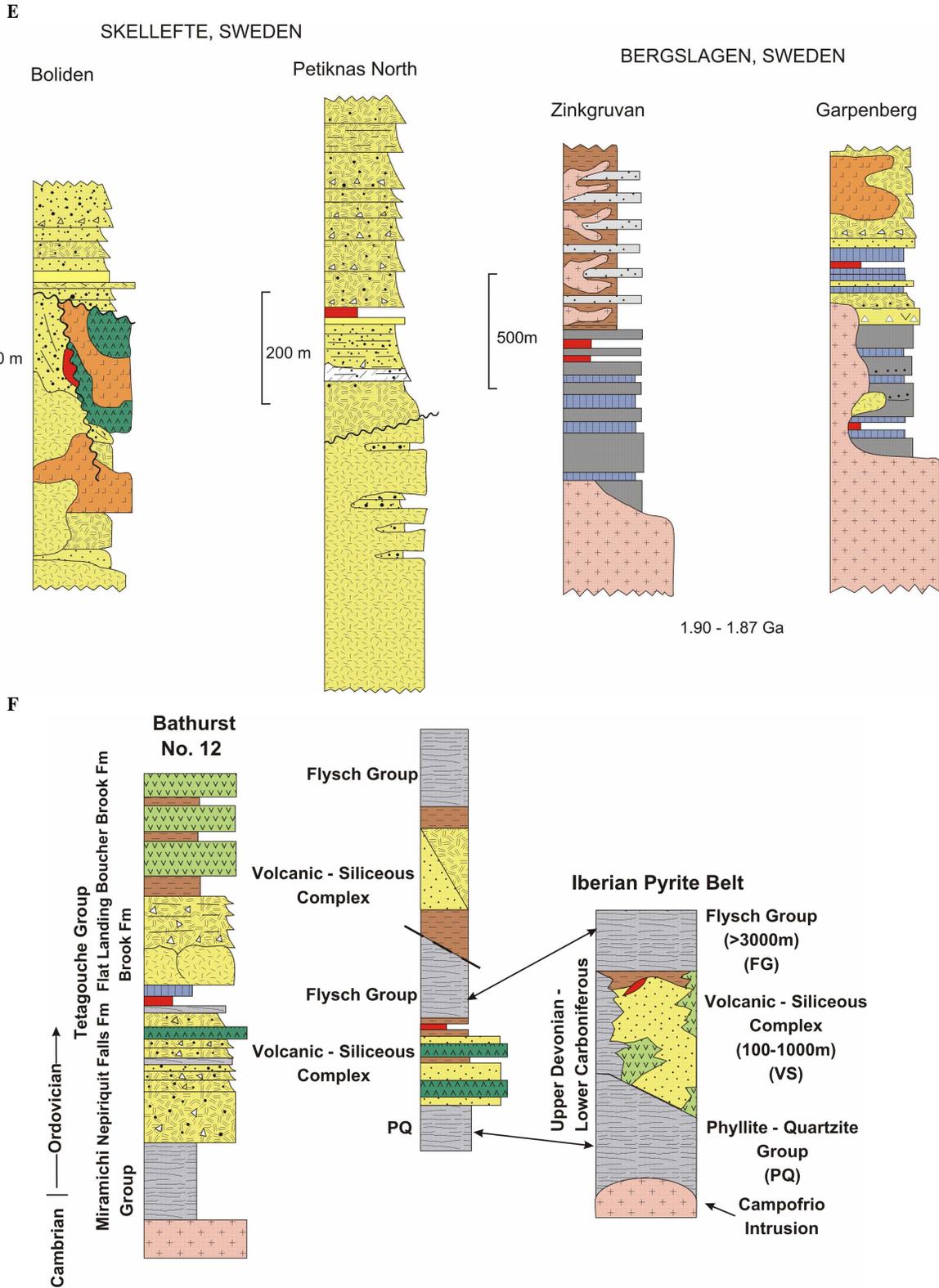
Figure 4: e) Stratigraphic sections through the VMS deposits in the Skellefte and Bergslagen districts contrasting the volcaniclastic facies that are the dominant host rocks; and f) stratigraphic section of the Bathurst District and Iberian Pyrite Belt illustrating the volcaniclastic and sedimentary lithofacies that characterize these siliciclastic-felsic successions
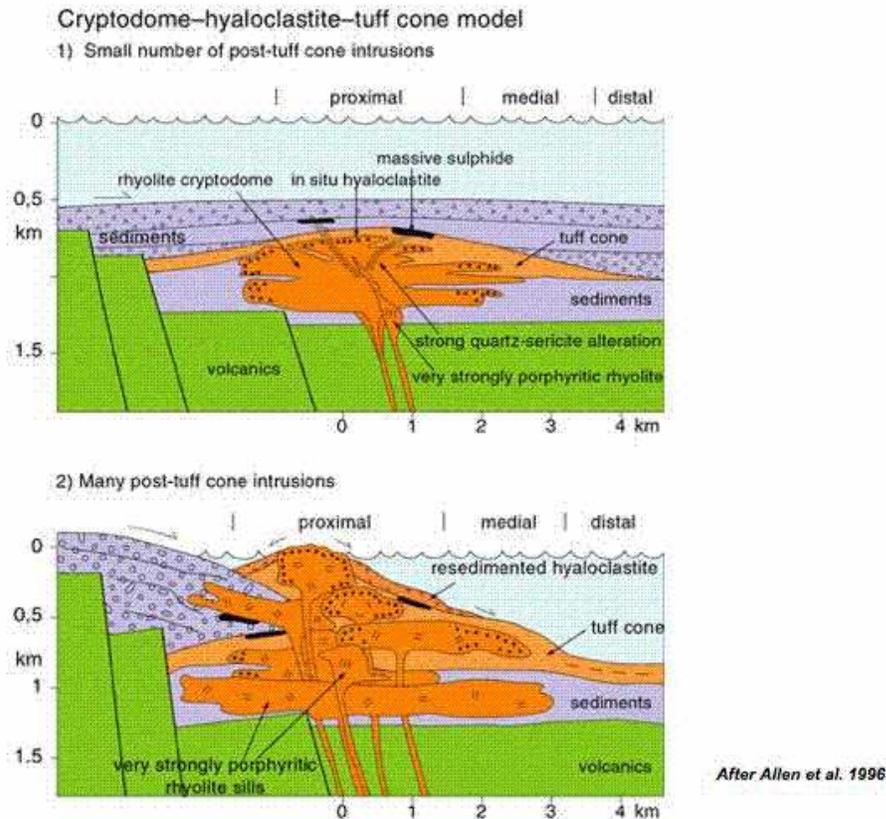
Figure 5: Location of massive sulphide lenses within a proximal volcanic centre marked by cryptodome-hyaloclastite-tuff cone volcanoes, Skellefte District, Sweden (from Allen, 1996b).

For example, exploration-relevant characteristics that are common to all the prospective volcano-sedimentary environments include:

1. Within all volcano-sedimentary environments VMS deposits occur within the proximal or vent area of volcanic centres. These proximal areas are recognized and defined by the presence of felsic flows, domes, and or cryptodomes and/or swarms of mafic and felsic synvolcanic dikes and/or sills (Figure 5); recognition of proximal volcanic facies in a mafic flow environment are more difficult but the occurrence of numerous mafic dikes and sills is a good indicator of vent proximity (Gibson et al., 1999). This spatial and temporal association between proximal volcanic centres and VMS deposits reflects their underlying structural control where faults (fissures) that are conduits for magma ascent are typically conduits for ascending hydrothermal fluid (Figure 2).

2. At the deposit scale VMS deposits generally occur within fault-bounded basins, depressions or grabens defined by abrupt changes in facies such as the occurrence of a thick ponded flow and/or volcaniclastic facies (McPhie and Allen, 2003; Busby et al., 2003). On a scale of 10's of kilometers, small,

deposit-scale basins are part of larger extensional basins or volcano-tectonic depressions (cauldrons) that may include calderas (Figure 6). Large volcano-tectonic subsidence structures are a seafloor manifestation of submarine rift environments and their recognition would be most important at the greenfields or regional exploration stage, but they are very difficult to recognize even in well-studied VMS districts. The presence of subvolcanic intrusions is one way to recognize central volcanic complexes, and perhaps volcano-tectonic subsidence structures. For example, at Noranda (Figure 6) and Sturgeon Lake synvolcanic, subvolcanic intrusions are interpreted to be a product of resurgent magmatism that followed collapse, and the intrusions themselves define the structural limits of the subsidence structures (Morton et al., 1991; Gibson and Watkinson, 1990; Hudak et al., 2003; Stix et al., 2003). The focusing of high geothermal gradients within these subsidence structures results in the characteristic clustering of VMS deposits. The presence of 14 VMS deposits within the Noranda cauldron is an example of this cluster effect (Sangster, 1977; Gibson and Watkinson, 1990), which makes this deposit types an even more desirable exploration target.

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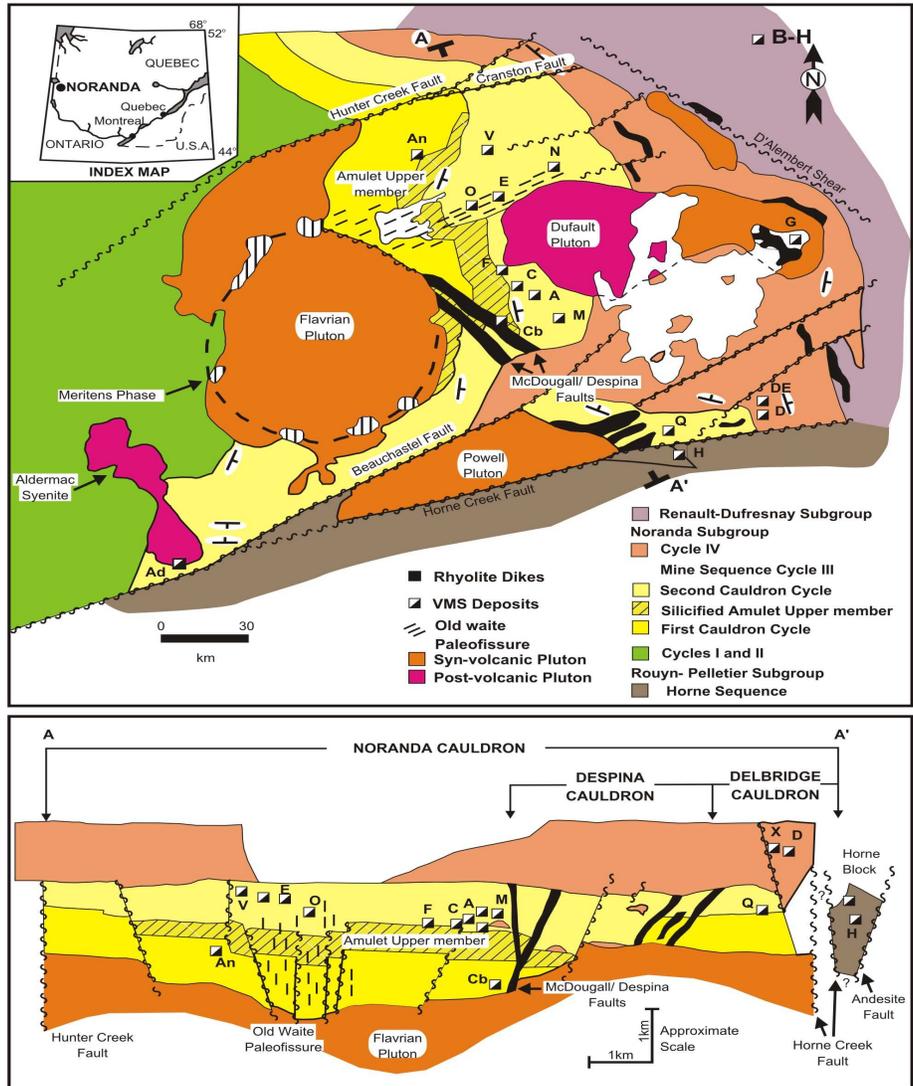
Figure 6: Geologic plan and cross section through the Noranda Volcanic Complex and Noranda cauldron showing the location of VMS deposits (refer to Figure 4b; modified after Gibson, 2005).
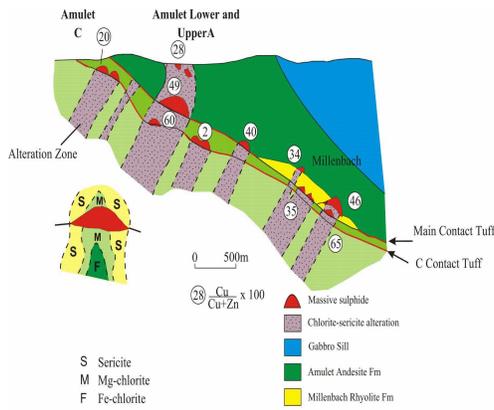
Figure 7: VMS deposits within the Noranda cauldron showing their location on two principal exhalative horizons referred to as the C and Main Contact tuff (modified from Gibson, 2005).

3. VMS deposits within a VMS district are distributed on one or two stratigraphic intervals (Figure 7). The favorable stratigraphic interval(s) marks a hiatus in volcanism that may be defined by a thin clastic-chemical sedimentary unit referred to as an exhalite, and/or an abrupt change in lithofacies or in lithofacies composition (petrochemical assemblages cited above). The presence of exhalative units are used to define prospective contacts, whereas the distribution and tenor of their contained metals and other trace and REE elements (e.g., Eu; Figure 8) have been used to define exploration targets along these contacts (Peter and Goodfellow, 1996; 2003)

4. Regional semiconfomable alteration zones are areas of altered rock with tens of kilometers of strike length that extend downwards from the paleosea-floor to the subvolcanic intrusion (Gibson et al., 1983; Gibson, 1990; Galley, 1993; Gibson et al., 1999; Brauhart et al., 1998; 2001; Hannington et al., 2003). They display vertical mineralogical and compositional zonations that, in successions that host mafic, pelitic-mafic and bimodal-mafic deposits, are divisible into an upper (e.g., diagenetic-zeolitic, carbonate, spilitic alteration) and lower (e.g., epidote-quartz alteration) semiconformable alteration zones as shown in Figure 2. In mafic volcanic facies epidote-quartz alteration is interpreted to represent, in part, the high temperature

reaction zone that may have provided the metals for ore-forming VMS fluids (Hannington et al. 2003; Franklin et al., 2005 and references therein). In highly metamorphosed terranes the alteration zonation is mineralogically enhanced through the development of distinctive, coarse-grained metamorphic assemblages (e.g. Bailes and Galley, 1999).

5. Semiconformable alteration mineral assemblages are mappable and their distribution and development, in part, is related to the primary permeability of the host lithofacies. For example, in successions dominated by flows the alteration assemblages preferentially develop in facies with a significant proportion of glass and in areas of higher permeability such as amygdule zones, and along flow contacts, flow breccias and synvolcanic faults (Gibson, 1990; Large et al., 2001b). In successions dominated by volcaniclastic and siliciclastic sedimentary facies the hydrothermal alteration assemblages are more pervasive and occur as a matrix cement and replacement of glass-rich clasts (Gifkins and Allen, 2001). However, alteration mineral assemblages indicative of a high temperature reaction zone (e.g., epidote quartz alteration in mafic flow and volcaniclastic lithofacies) are not recognized in environments dominated by a felsic volcaniclastic or pelitic lithofacies (Franklin et al., 2005).

A

B

Figure 8: a) Distribution of discordant footwall and hanging wall alteration zones; and b) geochemical and isotopic characteristics of footwall and hanging wall alteration zones with distance from massive sulphide (modified after Large et al., 2001a)

VMS DEPOSIT ENVIRONMENTS

Features of the VMS deposit and the immediate ore environment are well documented and understood. They are used in the direct detection (discovery) of new deposits because the significance of these features and the underlying processes responsible for their development are most easily related to the VMS model (refer to Large et al., 2001b, Franklin et al., 2005 and references therein). Some of these key features are briefly described below:

1. Distinctive mineralogical (Date et al., 1983), isotopic (Beaty and Taylor, 1982; Green et al., 1983; Cathles, 1993; Huston and Taylor, 1999) and whole-rock compositional changes (Riverin and Hodgson, 1980; Barrett and McLean, 1999; Barrett and Sherlock, 1996a, 1996b; Barrett et al., 1991; 1992; 1993; 1996; Gemmel and Fulton, 2001; Sharpe and Gemmel, 2001) are associated with footwall and hanging wall alteration. These alteration zones are formed by the interaction between ascending high temperature hydrothermal fluid, ambient seawater and mixtures of the two with footwall and hanging wall strata immediate to the VMS deposit (see references in Large et al., 2001a and b; Franklin et al., 2005). The mineralogical, geochemical and isotopic changes associated with hydrothermal alteration have been used extensively as vectors in exploration (Galley, 1993). A summary of the alteration zones and some of the significant geochemical and isotopic changes (vectors) that are associated with footwall and hanging wall alteration are illustrated in Figure 8.

2. Differences in the primary permeability and porosity of the footwall result in the variable morphology of both footwall and hanging wall alteration zones (Gibson, et al., 1999; Large et al., 2001b). For example, where the discharge conduit transects relatively impermeable strata (e.g., massive volcanic flow lithofacies) the alteration is vertically extensive but laterally restricted. Where the discharge conduit transects permeable strata (e.g., volcaniclastic lithofacies) the alteration zone is commonly broad, semiconformable and significantly larger than the VMS deposit presenting a large exploration target, but a challenge to vector within unless a mineralogical or chemical zonation can be detected.

3. It is now recognized that many VMS deposits form partly or entirely below the seafloor within unconsolidated sedimentary and volcaniclastic lithofacies through processes of infiltration, precipitation of sulphide minerals within pore spaces, and replacement (Kerr and Mason, 1990; Kerr and Gibson, 1993; Galley et al., 1995; Allen et al., 1996a; Hannington et al., 1999a; Doyle and Huston, 1999; Doyle and Allen, 2003 and references therein). Subsea-floor infiltration, precipitation and replacement may provide a more efficient mechanism to trap a higher proportion of metals as compared to sea-floor venting and this has implications for deposit size and therefore exploration (Doyle and Allen, 2003; Gibson,

1990). Subsea-floor replacement deposits may not be associated with an exhalative unit and detailed mapping is required to define and trace the ore-hosting lithofacies.

"Zone refining" is the process that results in the metal content and concentration essential to the formation of economic deposits. Zone refining develops because of the large thermal gradient, from hot at the base to cooler at the top, within a growing sulphide lens (Eldridge et al, 1983). High temperature fluids entering the base of the lens progressively deposit Cu within the base and interior of the lens and re-dissolve Zn, Pb, (+/-Au) and move them outward resulting in concentration of Zn, Pb and Au at the top of the lens. Zone refining may reflect a change in the temperature and composition of the hydrothermal fluid with time due to a change in fluid source or less interaction with cooler seawater due to self-sealing processes (Eldridge et al., 1983; Lydon, 1988; Large et al., 1989; Doyle and Huston, 1999; Gibson, et al., 1999). Zone refining is favored by a long-lived, high temperature hydrothermal system and i s characteristic of metal-rich deposits. However, in open-ended hydrothermal systems that are characterized by the "black smoker" vent systems documented in modern seafloor settings zone refining can result in almost complete stripping of base and precious metals, leaving behind a pyritic sulphide mound. A key indicator of a long-lived hydrothermal system is the continuation of footwall hydrothermal alteration assemblages into the hanging wall of a favorable stratigraphic interval or horizon.

TARGETING NEW AND UNDEVELOPED VMS DISTRICTS

Extensive studies of many VMS districts world-wide and an extensive inventory of mineralization on the modern sea floor enable some predictive criteria for targeting clusters of deposits, large deposits and polymetallic mineralization.

1. Deposits commonly occur in clusters that define VMS districts. VMS districts occur within large volcanic edifices, calderas and crustal structures. The Noranda and Bathurst districts are two well documented examples. Some "districts" like Kidd Creek contain only one main producer.

2. Large deposits, more than 50 or 100 million tones, are uncommon. Some large deposits are associated with a major long-lived crustal structure (i.e. Kidd Creek), or with thick successions of volcaniclastic rocks (i.e. Bathurst), or occur in more stable rifted continental margin settings (i.e. Iberian Pyrite Belt). The large deposits tend to be associated with large, diffuse low temperature alteration systems and felsic volcaniclastic and or siliciclastic lithofacies, including thin, but laterally extensive Fe and Fe-Mn formations (the notable exception is Kidd Creek).

3. Polymetallic and precious metal-rich deposits can be related to specific regional, local and compositional characteristics. Deposits associated with mafic dominated terranes tend to be Cu and Cu-Zn endowed. Large deposits such as Kidd Creek, Flin Flon and Horne have exceptional endowments of Cu, Au and/or

value-added metals (e.g., In and Sn at Kidd Creek). Continental margin or successor rifted arc-hosted deposits with felsic volcaniclastic-sedimentary host rocks have a higher Pb-Zn endowment (e.g. Zinkgruvan, Bergslagen) or Pb-Au-Ag concentrations (Roseberry, Tasmania; Petiknas, Sweden; Eskay Creek, Canada; Greens Creek, Alaska). The exception being Neves Corvo, which has a large Cu-Sn endowment, and coincidently is spatially associated with FIII rhyolite extrusives.

4. Strongly metamorphosed deposits commonly found in Archean or Proterozoic terranes tend to have coarser grained sulphides and consequently metal recovery is commonly better than for the finely crystalline sulphides in some of the less metamorphosed districts. Recrystallization can also complicate recoveries with metal intergrowth and substitution of deleterious metals, eg Se and Tl, but can also thermally and mechanically "purify" deposits of such metals as Hg, As and Sb.

SHORTCOMINGS OF THE VMS MODEL AND THE IMPACT ON EXPLORATION

Some questions to consider in developing a more accurate and therefore predictive VMS model include:

1. There is uncertainty as to the source of base and precious metals in VMS deposits (deRonde, 1995; Yang and Scott, 1996; 2002). Are the metals derived entirely from leaching of the deep footwall rocks by evolved seawater within high temperature reactions zones or is there a direct or indirect magmatic contribution to the VMS hydrothermal system? If the former process is favored more emphasis should be placed on understanding, recognizing and defining high temperature reaction zones. However, if the latter process is favored a more thorough understanding of the behavior of metals and sulphur during partial melting, magmatic fractionation, and the evolution of submarine volcanoes are required. Like many problems, the solution probably lies along the spectrum between the two end member metal sources depending on how evolved and volatile-rich the associated magmas are.

2. Why are some deposits Au-rich and others not? The Au-rich character of VMS deposits has been attributed to zone refining processes (Large et al., 1989), a magmatic contribution (de Ronde, 1995; Hannington, et al., 1999b; Hannington et al., 2005; Dube et al., 2007), boiling and phase separation of ascending hydrothermal fluids (Hannington et al., 1999b) and, in some cases, overprinting by later hydrothermal and tectonic events (Franklin et al., 2005) (Figure 3). If boiling is critical, then water depth also becomes critical as does the necessity to develop criteria to distinguish between strata deposited in shallower (above storm wave base) versus deeper water environments. Clearly, Au enrichment in VMS deposits is still poorly understood and it is of paramount importance to develop more robust exploration criteria in order to better target this economically attractive exploration deposit type.

3. Within the extensional tectonic regime, what specific regional tectonic and magmatic processes produce VMS-mineralized volcanoes versus unmineralized volcanoes, and how do we more consistently recognize the former? This is particularly important, as it is critical in exploration to confidently identify "productive" versus "unproductive" belts if a company is to devote the time and money to aggressively explore prior to any discovery!

4. Why are the best VMS deposits in a particular district (volcanic complex) most commonly distributed on just one or two stratigraphic horizons (or intervals)? And how do we confidently identify favourable ore horizons several kilometers (distal) from ore, within the first order basin?

5. Some VMS districts will only have one VMS deposit whereas others will have a cluster of deposits. Why is this so, and how do we identify those belts that have the potential to contain a cluster of economically viable VMS deposits?

GENERAL COMMENTS ON THE IMPACT OF VMS MODEL ON DESIGN OF GEOPHYSICS AND GEOCHEMICAL SURVEYS

Combined airborne electromagnetic and magnetic surveys and borehole TDEM surveys have been the primary tool in discovery of most VMS deposits. Ground gravity surveys have been successful in several camps for first detecting, then delineating the shape and size of undiscovered orebodies. Airborne gravity surveys are becoming more common as both a mapping and direct detection tool. High resolution and deeply penetrating surveys (eg. Megatem™, see Boivin, 2007) are presently used to identify deeper targets while other nontraditional geophysical techniques such as magnetotellurics and Titan 34 have shown early promise as deep search techniques. Table 2 summarizes applications for greenfields and brownfields exploration.

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Table 2: Exploration methods for VMS deposits

	Greenfields Exploration (Objective – selection of a favourable area)	**Brownfields Exploration** (Objective - discovery)
Geology	Compilation of existing geological data and maps. Reconnaissance mapping to identify rift successions, subvolcanic intrusions, and to identify areas of mineralization and alteration. Characterize known mineralization (1:10,000 – 1:20,000).	Detailed mapping to identify synvolcanic faults, intrusions, and proximal volcanic environments permissive for VMS formation (1:5000 to 1:2000). Map limits of alteration and mineralogical zonation. 3-D GIS compilation and interpretation of all data. Drilling to test targets (also must consider economic parameters, i.e., size, in designing drill programs and holes spacing.
Geochemistry	Sampling for petrochemistry (major, trace, rare earth elements) to identify rift related volcanic and intrusive rocks. Sampling (major and trace elements plus metals and oxygen isotopes) to characterize alteration and mineralization.	Sampling to aid in rock type identification, and to establish a chemostratigraphy that will aid stratigraphic correlation of favorable stratigraphic intervals and in the resolution of structural problems (majors, trace and rare earth elements). Systematic sampling of surface outcrops and core to define, characterize and vector within alteration (majors and trace elements, metals, and mineralogical (XRD) and mineral chemical data). Systematic soil, vegetation or water sampling where appropriate. Sampling to characterize mineralization (metals).
Geophysics	Compilation of previous geophysical surveys. Airborne geophysical surveys to support mapping and for direct detection (MAG, EM, radiometric, gravity?).	Ground and bore hole geophysical surveys (MAG, EM, IP, gravity..dependant on style of mineralization and deposit size – economic parameters).

The advent of 3D GIS visualization and whole earth modeling has resulted in the integration of high-resolution magnetics, gravity, EM, resistivity, volcanic lithofacies mapping, geochemistry and alteration indices in target generation. Such modeling at Noranda identified the West Ansil discovery in 2005 (Martin and Masson, 2005; Martin et al., 2007, this volume). However, there is a lack of physical-rock-property data for volcanic rocks, their altered equivalents and the spectrum of VMS ore types. The integration of geophysics with geology and geochemistry to develop a more predictive model, one that approaches reality, will require the addition of robust rock physical-rock-property data. In greenfields exploration integrated geophysics and GIS have the potential to map out dike systems, mafic lithofacies, faults, subvolcanic intrusions and alteration (silicification, disseminated sulphide, magnetite). Potential exists to map the framework of volcanic edifices and larger regional structures. Digital elevation mapping has become an important component in remote predictive mapping, whereas airborne and space-based hyperspectral surveys as VMS exploration tools are still in their infancy.

Rock geochemistry has traditionally been used to define, map and vector within VMS alteration zones, to differentiate volcanic rock types, and to develop a chemostratigraphy that aids stratigraphic correlation and tracing of favorable ore-hosting or bracketing units. In brownfields exploration lithogeochemical samples of outcrop and core are collected systematically (30 to 50m centres) in order to provide a 3-D database for effective geochemical targeting. Soil (vegetation) samples are collected to define targets in areas of thick cover. In greenfields exploration lithogeochemical sampling is directed at recognizing extensional arc and back arc environments and regional alteration; here the sampling is more widely spaced to cover the major units and alteration types.

Despite the promise and success of various geochemical, geophysical and GIS methods these should be considered ancillary to acquiring the regional geological context, and ensuring that staff can relate the characteristics defined by the VMS model to empirical observations made on the ground. Exploration geologists, geophysicists and geochemists should be encouraged and supported to upgrade their knowledge of field geology through the numerous field courses offered by universities and professional associations.

CONCLUSIONS

VMS deposits are, perhaps, one of the most thoroughly researched deposit types, and some fundamental questions remain regarding their genesis that impact on exploration. Although deposit scale studies remain essential, the answers to many of these questions hinge upon research that seeks to understand VMS deposits within the context of the tectonic-magmatic evolution of their host volcanic complexes. VMS deposits represent a spectrum of syngenetic deposit types that form within a broad range of submarine volcanic extensional environments. The integration of careful geological observations with geophysics and whole-rock geochemistry in 3D GIS formats for regional and detailed exploration programs can improve identification of the key elements of the VMS model that will lead to more subsurface discoveries.

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