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SEMI-CONFORMABLE ALTERATION AND VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS

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SUMMARY - Broad zones of semi-conformable alteration in ancient volcanic terranes define the presence of extensive, submarine hydrothermal systems. The configuration and composition of these zones allows the mineral explorationist to determine the presence of shallow, low temperature hydrothermal systems in which very little base metal mineralization is generated, or of stacked, semi-conformable alteration zones defining a deep, penetrating hydrothermal system in which base metal-rich fluids were generated, ponded and debouched to form massive sulphide deposits on the seafloor.

1. INTRODUCTION

One of the major aspects of ongoing research on volcanogenic massive sulphide deposits (VMS) is the recognition of the extent, morphology and alteration mineral assemblages defining hydrothermal systems responsible for collection and deposition of metals on the seafloor. This is particularly important to the mineral industry in that the above parameters will dictate base metal exploration strategy; once the systematics of the hydrothermal system are known the sulphide-rich upflow zones and seafloor discharge points can be more efficiently targeted.

It is generally accepted that VMS deposits are at least in part products of hydrothermal fluid discharge from a convection system driven by a source of anomalously high heat flow. The presence of broad, semi-conformable alteration zones in volcanic terranes containing VMS deposits is evidence that large segments of the ocean floor are affected by circulatory hydrothermal fluid flow. The question arises as to what extent regional sub-seafloor metasomatism is responsible for metal leaching, sequestering and ultimately the generation of VMS deposits.

Two different scales of semi-conformable alteration are observed in ancient volcanic terranes containing VMS deposits: a) tectonic domains 1000's of km^2 in area, and b) tectonic depressions 100's of km^2 in area.

2. TECTONIC DOMAIN-SCALE ALTERATION

2.1 Bergslagen District

In the western half of the Early Proterozoic Bergslagen domain, more than a dozen past and present producing massive sulphide deposits are hosted within the upper part of a mixed volcanic-sedimentary pile, which is underlain by a thick sequence of felsic volcanics and overlain by turbiditic sediments (Oen et al., 1982, Vivallo and Rickard, 1984). Three of these deposits contain over 12 million tonnes of Zn-Pb-Cu-Ag sulphide and one exceeds 35 million tonnes. The region containing the massive sulphide deposits encompasses an area approximately 350 by 150km, and is believed to represent an epicontinental rift system in which large volumes of felsic pyroclastic material were deposited during opening of a wide, shallow intra-continental sea (Oen et al., 1982, Lagerblad, 1988). The mixed volcanic-sedimentary pile represents intermittent felsic volcanism with reworking of previous formations and deposition of carbonate- and silicate-rich chemical sediments, the latter rich in iron and manganese. The massive sulphide deposits are spatially associated with the chemical sediments, and are commonly hosted by the carbonates near the contact with the overlying wacke-mudstone formation.

Both the mixed volcanic-sedimentary group and the underlying felsic volcanic group are overprinted by a number of semiconformable alteration zones (Lagerblad and Gorbatchev, 1985). Extending over the entire area of the epicontinental rift is a zone of quartz-microcline alteration known locally as leptite. In places this potassium-enriched zone is overlain by stratiform, Mg-enriched chloritic rocks. Less extensive zone of sodium enrichment are sporadically observed below the microcline-quartz alteration (Tragardh, 1988). Directly below many of the massive sulphide deposits these semi-conformable alteration zones are cross-cut by discordant chlorite-rich zones of Mg and Fe enrichment believed to represent hydrothermal upflow zones. (Vivallo and Rickard, 1984; Tragardh, 1988).

The alkali-enriched volcaniclastic rocks were first thought to represent primary rock compositions until extensive geochemical surveys by Lagerblad and Gorbatchev (1985) and Bromley-Challenor (1988) demonstrated that both the potassium and sodium enriched strata lay outside the normal compositional range for felsic volcanic rocks (Figure 1). The persistent change down through the mixed volcanic-sediment and felsic volcanic packages from Mg-K through K to Na enrichment appears to represent a large scale subseafloor metasomatic zonation.

2.2 Iberian Pyrite Belt

The Carboniferous Iberian Pyrite Belt is a 250km long volcanic-sedimentary domain straddling the Spanish-Portugese border (Strauss and Madel, 1974,). Eight large polymetallic massive sulphide deposits, including several over 100 million tonnes, viz., Tharsas and La Zarza and over 250 million tonnes, viz., Aljustrel and Neves Corvo occur near, or along the contact between the mixed felsic volcanic-volcaniclastic-epiclastic sequence and an overlying mudstone-wacke group (Schermerhorn, 1970, Carvalho, 1986, Richards and Sides, 1991). Extensive formations of manganese-iron rich chemical sediments also occur within this stratigraphic section, some spatially associated with the VMS deposits.

The footwall stratigraphy to the massive sulphide bearing stratigraphic interval is characterized by belt-scale zones of sodium enrichment and less extensive potassium and magnesium enrichment (Munha e l al., 1980, Barriga, 1990). Because of the extent and apparent pervasiveness of the sodium enrichment, early workers believed the rock compositions to be either primary, or a prodct of regional metamorphism and labelled the rocks as spilites or keratophyres (Schermerhom, 1975); a consistent mineralogical zonation upwards from albite-rich basal strata to adularia-chlorite rich rocks was attributed by some to a regional metamorphic gradient (Strauss and Madel, 1974). Detailed petrographic studies have since revealed that the alkali enrichment was not pervasive, but rather controlled by the primary permeability of the host volcanics (Munha et al., 1980). Elevated whole rock oxygen isotope values for the alkali-enriched rocks indicates that they were altered through low temperature interaction with seawater (Munha et al., 1980; Fouillac and Javoy, 1988) (Figure 2).

3. TECTONIC DEPRESSION-SCALE ALTERATION ZONES

3.1 Ocean-floor rift-related alteration

Semi-conformable alteration zones are commonly associated with discrete volcanic structures, such as cauldrons and back arc to oceanic axial rift zones and shield volcanoes which commonly host VMS deposits. These structures usually have surface areas measured in

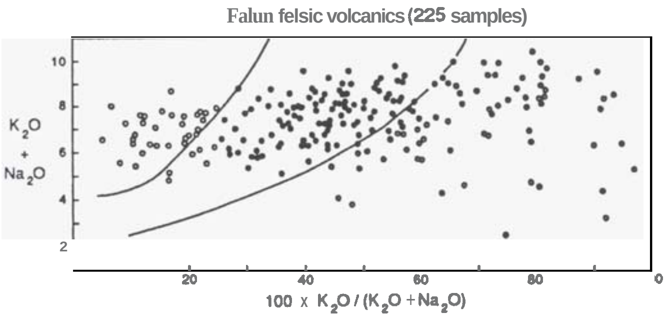

Figure 1: Harker diagram showing alkali metasomatism of felsic volcanics in part of Bergslagen District, with infilled circles representing normal felsic compositions, K-enriched rocks lying to the right and Na-enriched to the left of this field (Bromely-Challenor, 1988)

the 100s of km^2. Some of the definitive research on sub-seafloor metasomatism was carried out on the ophiolite suites in East Liguria, Italy (Spooner and Fyfe, 1973), the Trodoos Complex, Cyprus (Spooner, 1977, Heaton and Sheppard, 1977) and the Samail Complex, Oman (Gregory and Taylor, 1981, Haymon et al., 1990). Stacked, semi-conformable alteration zones are spatially associated with mafic to felsic feeder dyke swarms and plagiogranite stocks that reach to high levels within the overlying mafic to bimodal volcanic sequences, within the confines of the rift zone. These axial rifts consist of eruptive fissure systems that include very elongate, low relief shield volcanoes. The VMS deposits located within these environments are generally chalcopyrite-pyrite rich and less than 5 million tonnes. Exceptions include the Lasail deposit in Oman (12 million tonnes). Rift-related VMS deposits are commonly associated with discontinous, thin horizons of silica-manganese-iron rich chemical sediments (Constantinou and Govett, 1972).

The semi-conformable alteration zones include a Mg-enriched zeolite facies underlain by Na-enriched greenschist facies strata, dykes and sills. The stratigraphy below this, including gabbros near the petrologic Moho, are altered by interaction with more highly evolved fluids. The presence of this high temperature reaction zone is also marked by the presence of Ca-metasomatism in the form of epidote-chlorite enriched basalt, gabbro and plagiogranite within the sheeted dyke swarm underlain by Ca-Fe enriched actinolitic gabbro (Gregory and Taylor, 1981; Lydon and Jamieson, 1984; Haymon et al., 1990). These semi-conformable, high temperature zones are warped upwards below a paleo-rift zone by the intrusion of the dykes and plagiogranites to the floor of the rift. It is commonly above these zones of localised abnormally high heat flow that massive sulphide deposits develop.

The stacked, semi-conformable alteration zones mimic regional metamorphic gradients observed in older terranes, but their stable isotope chemistry indicates that the rocks within 3000m of the paleosurface were altered through interaction with low temperature, circulating seawater (Heaton and Sheppard, 1977; Gregory and Taylor, 1981) (Figure 2).

3.2 Cauldron-related alteration

Noranda Mining Camp- Semi-conformable alteration zones 10 to 20km long are observed associated with clusters of ancient VMS that define mining camps. In the Abitibi Belt of the Archaean Superior Province of the Canadian Shield the massive sulphide deposits of the Noranda camp are hosted within the Central Volcanic Complex of the Blake River Group (Gibson and Watkinson, 1990). This complex represents an infilled cauldron 20km in diameter that defines the top of a large shield volcano. The bimodal basaltic andesite-rhyolite sequence is divided into a number of cycles, each progressively infilling nested cauldrons. The core of the volcanic depression is marked by a fissure controlled, multi-phase dyke swarm that is the main feeder zone for the volcanic complex. The Central Volcanic Complex is floored by a large subvolcanic igneous complex (Flavrian Intrusion) composed of quartz diorite, tonalite and trondjemite (Goldie, 1976). The supracrustal rocks are regionally metamorphosed to greenschist facies.

Of the 14 massive sulphide deposits ranging from 0.37 to 16.37 million tonnes mined within the Central Volcanic Complex 4 are situated within or directly above the central dyke swarm (Gibson and Watkinson, 1990). The others are clustered about synvolcanic faults defining the margins of the nested cauldrons.

The volcanic strata within the Noranda cauldron are affected by several types of semi-conformable alteration (Gibson, 1990) (Figure 3). Almost all of the rocks within the structure are Na-enriched. Two zones of semi-conformable silicification extend for at least 15km along

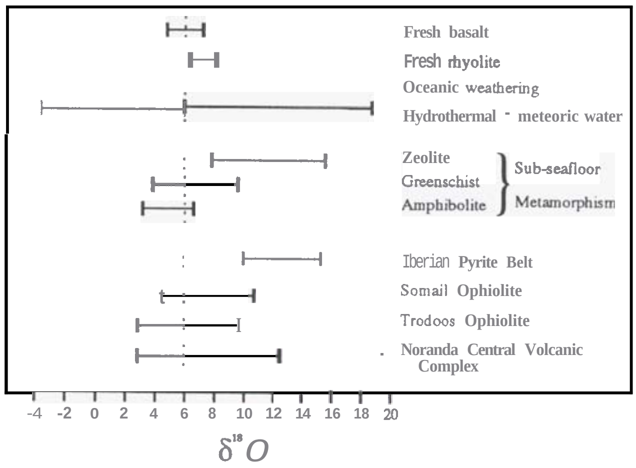

Figure 2: Ranges of ^{18}O values for hydrothermally altered rocks in submarine environments. Values for fresh basalt from Muehlenbachs and Clayton, (1972); fresh rhyolite from Taylor and South, (1985); hydrothermal-meteoric waters from Taylor (1974); sub-seafloor metamorphism from Spooner and Fyfe (1973); Iberian Pyrite Belt from Munha and Kerrich (1980) and Fouillac and Javoy (1988); Somail Ophiolite from Gregory and Taylor (1981), Trodoos Ophiolite from Spooner et al. (1977) and Noranda from Paradis et al. (in press).

stratigraphy overprinting Na-metasomatized rocks. These zones are restricted to andesite formations in the footwall to the two main sulphide horizons, within which alteration is concentrated along flow tops and other zones of high permeability. Directly overlying the silicified zones and along strike from the massive sulphide deposits an interlayered chert-tuff horizon (C contact tuff) extends as far along strike as the silicification, and is sulphide-rich close to the deposits.

A zone of Ca-enriched epidote-quartz alteration overprints the Na and Si enriched basaltic andesite of the first cauldron cycle. This alteration type becomes more intense about the main feeder dyke swarm, its upper contact warping upwards to follow the dykes up-section. With four VMS deposits spatially associated with the dyke swarm it is apparent that the upwarping of the semi-conformable alteration resulted in the creation of a hydrothermal upflow zone and the generation of massive sulphide. The variation from low to high temperature hydrothermal alteration within the semi-conformable alteration zones is well illustrated by the broad spectrum of ^{18}O values for the cauldron stratigraphy (Paradis et al., in press).

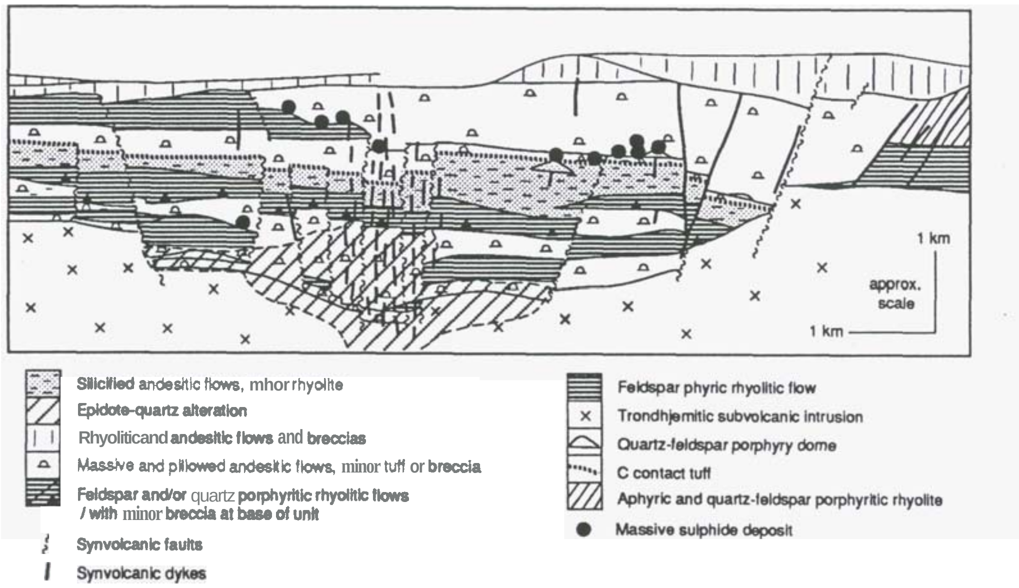

Figure 3: North-south section through Noranda cauldron showing relationship between semi-confromable alteration zones, C contact tuff, and VMS deposits (from Gibson, **1990).**

Snow Lake Mining Camp- The Snow Lake mining camp is within the Flin Flon Domain of the Early Proterozoic Trans-Hudson Orogen, central Manitoba, Canada. The Amisk Group volcanic sequence includes a thick mafic volcanic base overlain by at least four cycles of mafic to felsic volcanism (Bailes and Galley, 1991). The strata are regionally metamorphosed to biotite-almandine amphibolite grade. Six VMS deposits and numerous occurrences are hosted by two of the five cycles. Within the footwall stratigraphy of the massive sulphide horizons are extensive zones of semi-conformable alteration that extend for up to 15km (Bales, **1988)** (Figure 4). The stratigraphy containing both the semi-conformable alteration and the VMS deposits is floored by two large tonalitic, subvolcanic sill complexes (Sneath Lake and Richard Lake plutons).
Below the base metal horizon containing the Chisel-Lost-Ghost deposits there is an extensive zone of Mg-enriched and Na-Ca-Si depleted chlorite schist underlain by an extensively silicified formation. The silicified zone is in turn underlain by an intermittent zone of amphibole-chlorite enriched in Fe, Ca and heavy transition metals. The most intense alteration takes place about a subvolcanic felsic-mafic dyke swarm. The upper two semi-conformable zones are cross-cut by chlorite-aluminosilicate zones focussed about synvolcanic faults and forming discordant pipes below the Chisel deposit.
A semi-conformable zone of silicification not directly related to VMS deposits forms a zone 500m thick and over 12km long at the top of the basal mafic volcanic cycle. This zone displays an overall gain in Si and Na and losses in Mg, Fe, Mn and Zn (Skirrow, **1987).** Directly overlying the semi-conformable silicification is a mixed unit of sulphidic argillite, chert and felsic tuff (Foot-Mud horizon) that has the same strike length as the underlying alteration. The silicification is not associated with any other type of semi-conformable, or discordant alteration.

Sturgeon Lake Minina Camp- The Sturgeon Lake mining camp is within the English River Sub-province of the Archaean Superior Province, northwestern Ontario, Canada, and hosts four VMS deposits, including the 12 million tonne Mattabi deposit (Morton et **al., 1990).** The deposits are hosted within a 30km long caldera which contains a basal basalt pyroclastic-extrusive flow sequence overlain by a thick succession of felsic pyroclastic rocks. The caldera fill is intruded by the subvolcanic quartz diorite-tonalite Biedelman Bay intrusion. The sequence is metamorphosed to regional greenschist grade.

Felsic pyroclastic rocks are host to most of the massive sulphide mineralization and to extensive zones of semi-conformable alteration that are quite different in character from those described above due to the large amount of carbonate present. This includes a 24km long zone of strong Na-depletion associated with the VMS horizons in which there are extensive zones of iron carbonate-iron chlorite alteration and more local semi-conformable zones of iron carbonate-chloritoid-andalusite. Extensive zones of silicification are also present. These semi-conformable alteration zones are cross-cut along synvolcanic faults by zones of intense iron chlorite-iron carbonate-chloritoid and aluminosilicate alteration. Semi-conformable alteration zones are observed in both footwall and hangingwall stratigraphy to the known VMS deposits.

5. DISCUSSION

The recognition of broad, semi-conformable alteration zones in volcanic-dominated terranes is a first step for the mineral explorationist in defining areas of hydrothermal activity in which base metal deposits may be present. It is important for the explorationist to differentiate between semi-conformable alteration associated with low temperature, shallow hydrothermal systems and those generated by more extensive systems in which there is a good possibility of leaching and collecting significant quantities of base metals (Table 1). Widespread deposition of Fe-Mn-rich chemical sediments is commonly associated with the development of shallow alteration systems directly below the seafloor in which low temperatures and high sub-seafloor permeability result in the shallow, broad, diffuse convection of seawater. The characteristic high water-rock ratios in this type of system results in the significant transfer of iron and manganese to the hydrothermal fluid but is unsuitable for leaching base metals and sulphur (Hannington and Jonasson, **1992).** The diffuse exhalation of these fluids results in the formation of extensive Fe-Mn silicate, oxide and carbonate formations such as in the Bergslagen District and in the Iberian Pyrite Belt. In more reducing conditions, such as in the Archaean and Early Proterozoic, the manganese remains in solution and iron sulphide-silicate chemical sedimentation occurs such as at Noranda and Snow Lake. The spatial association of these broad, low temperature hydrothermal events with more discrete areas of base metal mineralization suggests that the latter is the first stage of a

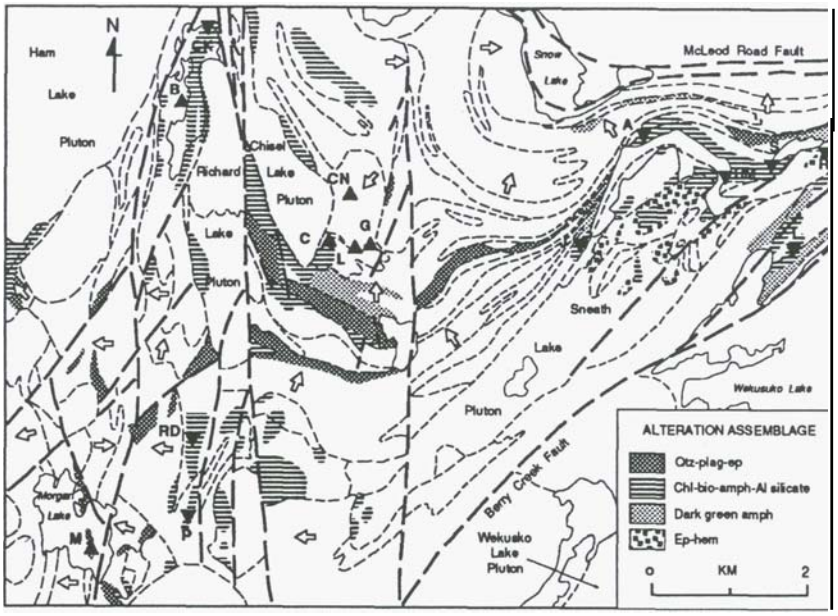

Figure 4: Distribution of semi-conformable alteration zones around the Snow Lake mining camp. Legend defines these zones by their metamorphic mineral assemblages. Black triangles represent known VMS deposits (adapted from Bailes, 1988).

hydrothermal system that may develop in places into one containing base metals.

The presence of stacked semi-conformable alteration zones is indicative of a deep penetrating hydrothermal system in which down-welling seawater evolves through a series of fluid-rock reactions at increasing temperatures and lowering water-rock ratios. These reactions change the redox and pH conditions of the fluid to the point where base metals and sulphur are leached from the strata and carried down with the fluid. Decreased permeablility due to secondary mineral formation (such as silicification) causes the system to stratify, resulting in the creation of a high temperature reservoir in which metal concentrations are further increased. The semi-conformable nature of the resultant reaction zones is due to both permeability control and by the fact that the isotherms controlling fluid-rock reactions are formed above sub-horizontal, high level subvolcanic sill complexes. The creation of feeder dyke swarms from the sill complex warps the isotherms upwards resulting in discordant, fluid upflow zones with roots in the high temperature semi-conformable zones. These upflow zones act as conduits for bringing the metal-rich fluids to the seafloor to generate massive sulphide deposits.

The stratiform nature of mature alteration systems and the progressive change in mineral assemblages from low to higher temperature commonly results in the assumption by geologists that they are a product of regional metamorphism. The confusion is perpetrated by workers who define hydrothermal zones through the use of metamorphic nomenclature (Figure 4). Subsequent regional metamorphism of these zones only compounds the nomenclature problems. Nonetheless, significant changes in the primary volcanic compositions within the metasomatic zones should allow the explorationist to see through any overprinting metamorphic effects and identify the nature and extent of hydrothermal alteration.

6. CONCLUSIONS

The recognition of semi-conformable alteration zones is key in defining areas in ancient volcanic terranes in which large-scale hydrothermal activity has taken place. The presence of an extensive, shallow, low temperature alteration zone close to the paleo-seafloor and overlain by equally extensive Fe-Mn- or Fe-rich chemical sediments defines a diffuse hydrothermal system which did not generate base metal mineralization. Volcanic stratigraphy containing well defined, subvolcanic sill complexes are commonly overlain by stacked, high to low temperature semi-conformable alteration zones defining hydrothermal systems extensive enough to leach base metals and generate VMS deposits.

7. ACKNOWLEDGEMENTS

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	HEAT SOURCE	ALTERATION	PRODUCT
STAGE 1 <150°C	Cooling volcanic stratigraphy	Shallow, low temp. semi-conformable altn zones	Diffuse hydrothermal discharge of Fe-Mn oxide and carbonate
STAGE 2 50-350°	High level sub-volcanic intrusion	Stacked, low to high temperature semi-conformable altn. zones	Focussed sulphate-silicate discharge along faults
STAGE 3 250-350°C	subvolcanic feeder dyke swarms along synvolcanic faults	Creation of fluid upflow zones that tap high temp. semi-conformable reservoir	Focussed high temp. sulphide-silicate discharge on aeafloor
STAGE 4 <150°C	cooling aubvolc. intrusions	Collapae of high temp. altn. aystem	Focussed low temp. discharge of Fe-Mn oxides and chert above sulphide mound

Table 1: Stages in the development of a submarine hydrothermal system

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