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The Geology and Geochemistry of Exhalative Ore Deposits in Tertiary Basic Fore-Arc Volcanic Terrains, Olympic Peninsula, Washington

by P.C. Nisbet, *Northwest Kaolin Ltd.*, and A.V. Ambrose, *Northwest Minerals Inc.*

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ABSTRACT

An examination of the volcanics of the Crescent Formation on the Olympic Peninsula was undertaken for this study, in order to determine variations between exhalative deposits of ophiolitic and fore-arc origins. Information gathered during the investigation suggests that deposits related to early fore-arc formation are most closely related to deposits of deep ocean origins. With time, arc volcanics trend from basic to intermediate composition and their related ore deposits from black smoker type mineralization toward Beshi type massive sulfides. Massive sulfide terrains examined in the Crescent volcanics appear to be midway between these two end members, with elements of both types. Detailed geology and geochemistry of the deposits leads to the conclusion that similar ore bodies might be found in recent fore-arc chains and may constitute a greater potential resource for ocean mining than their ophiolitic counterparts.

INTRODUCTION

Since the time of Hutton and the concept of uniformitarianism, it has been the job of the geologist to relate ancient events to corresponding recent geological process. Though the use of this technique is an excellent tool for explaining the strata accumulated on continents in past eras, our lack of data on recent oceanic events limits its utility. Using information taken from continentally accreted ophiolites, discovery has recently been made of actively forming exhalative deposits in oceanic spreading centers. This reverse uniformitarianism (The key to the

present, may be found in the past.) may serve as a general tool for mineral exploration in oceanic environments.

Using this concept, a basic fore-arc volcanic terrain of Eocene age was chosen for detailed study, with hopes of initiating exploration for recent ore deposits of like origin. Geologic mapping and geochemical sampling were conducted to determine the physiochemical parameters of these exhalative systems and their relation to deposits formed in deep ocean and more developed arc settings. The data gathered was used to construct an exploration model with postulated grades and tonnages for recent exhalatives. Given the correctness of the model, it may be possible to locate minable resources in arc terrains such as the Aleutian Islands.

GENERAL GEOLOGY

The Crescent Formation is a pile of basic fore-arc volcanics accumulated on the continental margin during the Eocene. Lower Crescent extrusives are composed of interbedded pillow basalts, basaltic andesites, quartz keratophyres and related tuffs, tuff breccias and mixed organic/chemical sediments. Locally, small stocks of gabbroic intrusives occur near eruptive centers, associated with diabasic dike and sill complexes. With time, the eruptives trend toward more intermediate composition and the upper member is composed of mixed basaltic andesite and andesite, many flows of which are subaerially erupted.

Unlike similar terrains, i.e. Japan, the Crescent contains few centers of andesite and rhyolite composition. Cowan (1982) inferred that the arc may have been uprooted during large scale

References and illustrations at end of paper.

tectonic activity on the San Juan and Leech River Faults during the Oligocene. If the system was cut off from supplies of fresh magma, more differentiated melts would not have formed. Thus the Crescent Formation offers an excellent opportunity to study early fore-arc formation processes without inhibiting volumes of later more felsic rocks.

EXHALATIVE DEPOSIT GEOLOGY

Within the lower member of the Crescent Formation there are numerous occurrences of deposits of hydrothermal exhalative origin. In the earliest portions of the formation these are represented by the Black and White Mine copper-manganese deposit, the Hama Hama manganese deposits and the Maple Creek barite prospect. As the volcanic pile thickened, more extensive hydrothermal systems were generated, including the massive sulfide deposit at Slab Camp Creek. Examination of these occurrences suggests a depositional progression from early black smoker venting, similar to that found in recent spreading centers, toward later deposits more closely related to Beshi type massive sulfides.

The Maple Creek barite prospect contains many features described by the USGS (oral communications) from the southern end of the San Juan black smoker field. Thin crusts of sulfide, partly replaced by barite and silica, are found along contacts of an earlier flow and overlying tuffaceous sediments. The main body of the barite deposit contains replaced chimney structures laying parallel to bedding, with concentric rings containing oxidized and replaced copper minerals. Siliceous casts similar to tube worms described from Juan de Fuca have been found, which, when seen in thin section, contain some remnant bituminous material. Replacement in this deposit may be related to white smoker activity, mentioned from several spreading center vent areas.

The Black and White Mine represents a slightly less replaced black smoker occurrence, which has been deeply oxidized, presumably post-venting. Vent rocks show extensive chloritic replacement of host basalt with minor sericite and kaolin directly above the vent. Bodies of ore containing native copper, chalcocite, cuprite, malachite and azurite are found with manganese jasperoids in the vent area. Close inspection of the ore revealed algal matte structures, replaced by silicates and copper minerals and several tube worms and bivalve casts. Ore grades encountered were 5-7% Cu, 1-2% Zn, 0.15% Ni and 0.45 opt Ag, values not dissimilar from those found in smoker deposits of recent origins.

Some hydrothermal vents formed very near extrusive centers. Along the Hama Hama River, thin manganese mantos of these vents are found altered and replaced by later pillow basalts. Such locations were not conducive to the preservation of sulfide bodies, but minor quantities of native copper can be found with manganese silicates in interstitial spaces between pillows.

Work by Nisbet (1983) on the Manganese silicate deposit at Slab Camp Creek indicated that this

occurrence appeared to be a distal facies expression of a hydrothermal exhalative system. The manganese ore body at Slab Creek (See Figure 1.) occurs in a small third order paleo-basin. The deposit rests on pillow basalts and is surrounded by a layer of red ferrogenous limey argillite. At the edge of the basin a thin zone of iron and manganese oxides gives way to a thicker zone of silicates and jaspilites. The basin bottom contains a unit of pyritic marl. There is a marked similarity between this deposit and deposits related to massive sulfide bearing horizons in other volcanic formations. By tracing the organic/chemical sediments back toward their point of origin, a hydrothermal venting center at Deer Park was located, which contained a small massive sulfide body.

The best example of massive sulfide development in the middle to late lower Crescent Formation occurs at the Angeles Star Mine (See Figure 2). This massive sulfide body rests above an altered smectite-chlorite breccia zone in spilitic basalt which contains minor quartz veining and scattered pyrite-arsenopyrite. The ore body may be broken into three parts, a lower microbrecciated quartz-kaolin zone below massive pyrite-sphalerite-chalcopryite, capped by a siliceous barite zone. Extending outward from the massive sulfide is an altered chalcopryite bearing tuff, capped by manganese and iron bearing manto sediments. The manto sediments are composed of varying amounts of fine grained chlorite, talc, iron and manganese oxides and carbonates and organic matter. The geology is very similar to other massive sulfide bodies. Ore materials contain 7.5% Zn, 0.25% Cu and 0.05 opt Au.

Close inspection of the barite cap of the Angeles Star revealed structures similar to those found at the Maple Creek barite prospect. Faint outlines of what might be collapsed chimney structures and some casts of aquatic fauna have been found. From this data, a postulated progression for the system may be drawn. Earliest hydrothermal venting creates black smokers, as at the Black and White Mine, which may be followed by white smoker activity and emplacement of a cap rock. If hydrothermal activity continues past the development of the cap, massive sulfides will be deposited beneath it. In the oldest portions of the arc, the relatively young volcanic pile lacked strong hydrothermal convection, and only later, when the pile was thicker, did white smoker and then massive sulfide deposits form.

From geological observations it is possible to conclude that exhalatives in early fore-arc terrains are most closely related to ophiolitic black smokers. With thicker accumulation of volcanics, massive sulfide bodies will begin to form. This progression leads eventually to the development of mineralization accompanying intermediate and felsic extrusive activity and the formation of Beshi and Kuroko type massive sulfides. Since these types of massive sulfides can contain tens of millions of tons of very high grade ore, their recent counterparts would constitute major oceanic resources.

GEOCHEMISTRY

Chemical analysis of rocks for major and trace

elements is now a standard tool for the continent bound exploration geologist, however, ocean mineral exploration has not yet begun to employ it. The primary reason for implementing a geochemical exploration program is to discover concealed ore bodies and thus far in ocean resource evaluation, only surface concentrations of minerals have been sought. Massive sulfide ore deposits, even recent ones, by their nature imply burial and concealment. Black smokers may be ore deposits while active, but prolonged seawater contact oxidizes and depletes their metals values post-venting. If ocean mining is to progress, the next generation of targets must be the concealed massive sulfides. Geochemistry may then be a powerful tool for the ocean prospector.

Since the depth of burial of an ocean prospect is key to it's most recent or even active systems. Geochemical exploration for massive sulfides is geared toward finding sedimentary horizons associated with exhalative events and following them back toward their source, the vent or site of massive sulfide deposition. In ocean exploration only those sediments of relatively recent origins need be examined, to locate their shallow source, the ore body.

In the Crescent Formation, 400 samples of exhalative related rock were gathered and analyzed. A general profile of the distribution of elements from vent to distal facies is given in Figures 3-6.

Samples taken from both the distal facies and proximal facies were analyzed with the following results. The main body of the massive sulfide contained high zinc, low copper and high gold values, with an average ore running 7.5 percent zinc, 0.25 percent copper and 0.05 opt gold. The sulfide bearing tuff unit contained higher copper and lower zinc values, with a slightly more erratic gold concentration, averaging 2.0 percent copper, 3.0 percent zinc and 0.02 opt gold. The baritic jasperoidal cap was relatively metals poor, averaging 0.2 percent zinc, 0.05 percent copper and 0.01 opt gold.

In the distal deposits, the base metals concentrations were low but anomalous, containing a few hundred to a thousand ppm of copper and zinc. Gold was concentrated in the jasperoids and marls with an average concentration of 300 ppb and minor pyritic zones in the jasperoid carrying 1 to 2 ppm.

A more complete trace elemental analysis, element by element, was compiled to determine element distribution in the system, vent to distal basin. Arsenic's highest concentration was in the basalts directly below massive sulfide. Values decreased in the massive sulfide and the surrounding sediments, but were anomalously high in the distal jasperoids. Barium values are slightly anomalous in the vent and reach their highest values in the over lying cap. Distal distribution is relatively low. Lead is low but anomalous in the massive sulfide and in the pyritic zones of the distal jasperoid. Values of 300 ppm are seldom encountered even in the massive sulfide. Manganese distribution shows increased content in a manto surrounding the massive sulfide with decreasing concentration

toward the distal facies. The jasperoids of the distal facies contain extremely high manganese values in the range of 10's of percent. Mercury is fairly low in the system, but slightly anomalous in the baritic cap. Sodium is most abundant in the albitized basalt below massive sulfide. Silver values average slightly less the 0.3 opt in massive sulfide, below detection limits in the surrounding sediments and 0.25 opt in the distal basin. Tellurium is found primarily in the zone below massive sulfide.

Thallium shows a relative increase in the vent, a fairly high concentration in the mineralized tuffs and decreasing values in the manto. The distal deposits are relatively depleted of thallium with respect to concentrations in surrounding sediments. Potassium is generally highest in the central core of the massive sulfide, with values decreasing rather rapidly to background in the surrounding manto. The altered tuff beds of the footwall show only minor enrichment in potassium, seldom more than 1.5 times background, a signal very easily lost in the noise. Aluminum, normally considered a rather non-mobile element, is relatively depleted in the lower vent zone, shows increased values in the clay rich horizons directly below massive sulfides, then drops to extremely low values in the sulfide and cap horizons. In the manto in close proximity to the massive sulfide, aluminum values begin to increase till a peak is reached at approximately 1000 meters from the ore body. After a slightly decrease from highest values, a stable plateau is reached in values. Silica shows a pattern very similar to aluminum's, varying only in location of the peak value. Silica peaks in the cap rocks directly above massive sulfides, but reaches stable concentration levels in the same area as aluminum. Magnesium values are depleted throughout the hydrothermally altered zone and in the massive sulfide and cap. In manto materials, magnesium values increase to a peak in the same general area as aluminum values, then show a similar tapering off to a plateau. Total iron concentration is highest in the massive sulfide, naturally. Silicate bound iron concentration, however, shows a pattern similar to magnesium's. Lithium, being a magnesium substitutor in this system, also shows a pattern similar to iron and magnesium.

Using this elemental distribution pattern, it is possible to select some elements which may prove useful in exploring for massive sulfides by analyzing ocean sediments. Thallium, with it's very broadly based peak centering on the ore body, would be very useful in the proximal facies. Lithium, silicate iron, magnesium and manganese all have very wide halos, in the manto sediments, which may be used to guide exploration toward the proximal facies. In the very near vicinity of the ore body, mercury, barium, precious and base metals may prove useful.

THE TARGET

Where black smoker bodies are thin accumulations of sulfides of a foot or so thick spread over extensive distances, massive sulfide are compact and thick. A typical massive sulfide will contain from 5-50 million tons of ore ranging from 10-100 feet thick. The composite value of the metals contained runs from 80-200 dollars per ton

and the total value of the deposits from 400 million to 4 billion dollars.

In recent and active exhalative terrains, massive sulfides should rest below an overburden of a few tens of feet of unconsolidated sediments and ten to twenty feet of capping materials. Since water also constitutes an overburden, it must be noted that where black smokers are found in deep ocean settings, massive sulfides form at depths of 300-800 feet. The cost of mining an undersea massive sulfide should be comparable to that for vacuuming up a smoker deposit, but the total grade and precious metals contents of the massive sulfide are higher.

Massive sulfides are found in arc terrains, inside the boundaries of national governments. Black smoker deposits are found in international water and their exploitation is governed by international treaty. Clauses of the United Nations Treaty of the Sea impose prohibitive royalties on mining black smokers. National governments are usually easier to deal with than international bodies.

All together, massive sulfides are a better target for exploration and exploitation than black smoker fields.

CONCLUSIONS

Based on the work done for this study, the following can be deduced:

1. During early arc formation, hydrothermal venting follows a pattern similar to that found in ophiolitic black smokers. As the arc develops, exhalatives progress from black smoker phases to white smoker phases and eventually to massive sulfide formation.
2. It is possible to use the geochemical signatures found in sedimentary horizons associated with massive sulfides to find the venting center and ore body. By sampling recent oceanic sediments and analyzing for anomalous concentrations of thallium, manganese, magnesium, silicate iron, lithium, barium, mercury and base and precious metals, these horizons can be found and traced to their source.
3. Massive sulfide bodies are better targets for exploration than deep ocean smoker deposits. Ocean depth, location, deposit geometry, ore grade and tenor are far better in oceanic massive sulfides. Judged by their size and the great number mined on the continents, they constitute a major ocean resource for mineral development.

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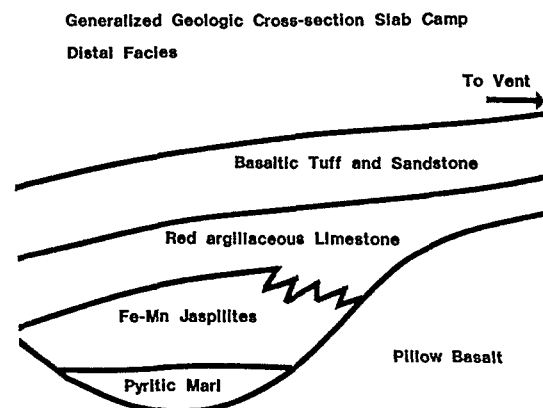


Fig. 1—Geology cross-section Slab Camp Creek manganese deposit.

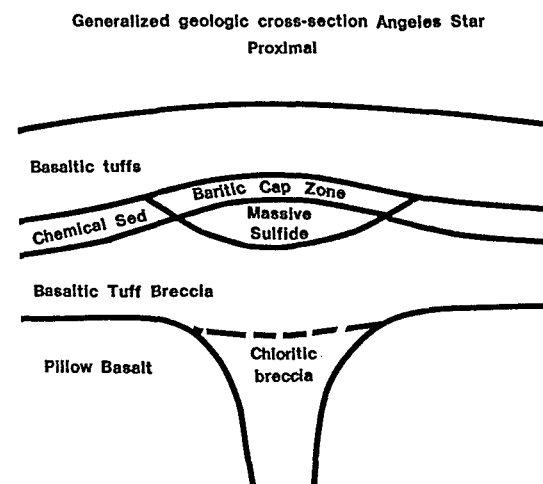


Fig. 2—Generalized geology cross section, Angeles Star mine massive sulfide.

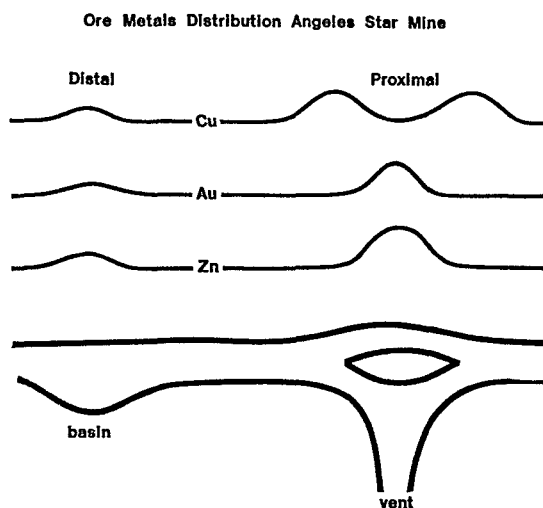


Fig. 3—Ore metal distribution, Angeles Star exhalative system.

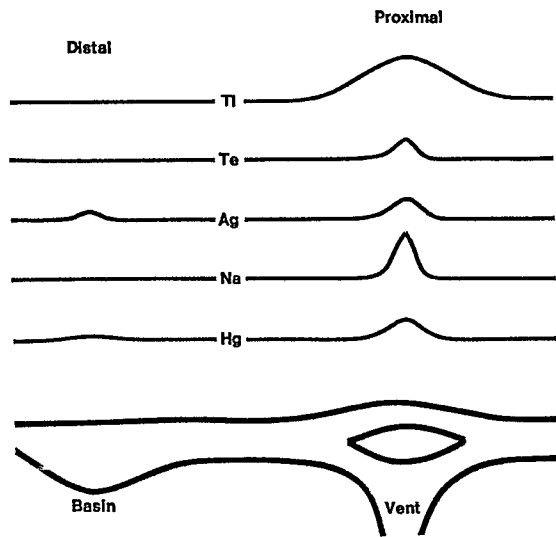


Fig. 4—Thallium, tellurium, silver, sodium, and mercury distribution.

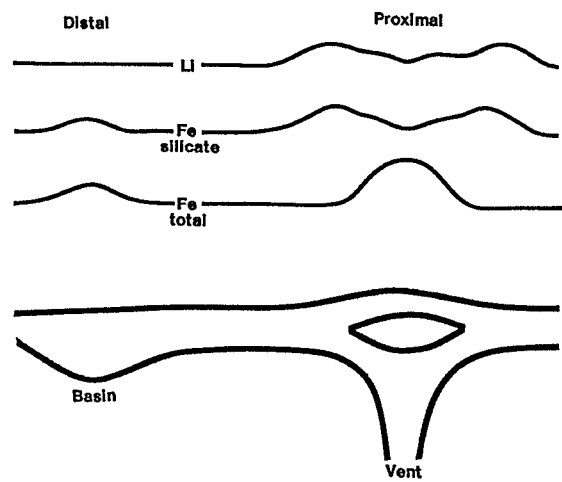


Fig. 5—Lithium and iron distribution for Angeles Star system.

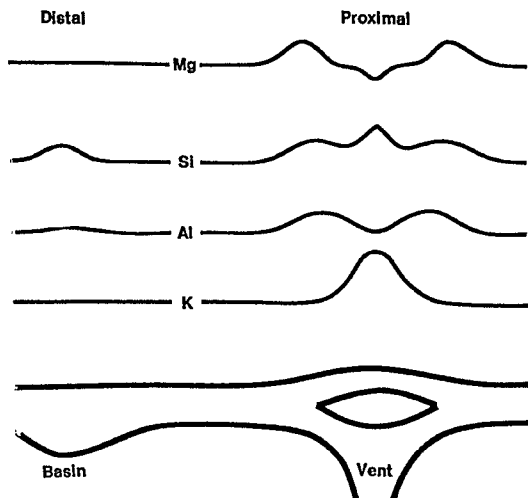


Fig. 6—Magnesium, silica, aluminum, and potassium distribution.

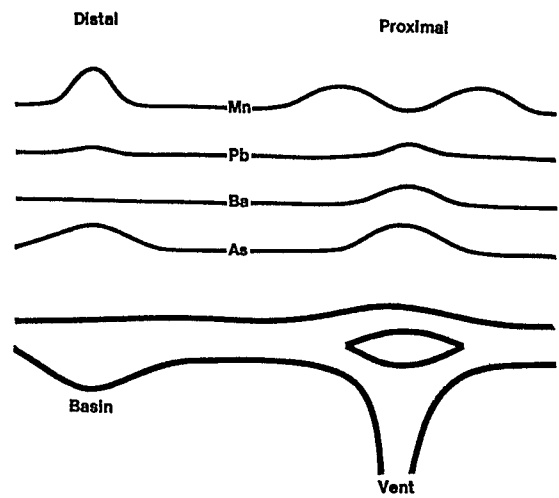


Fig. 7—Manganese, lead, barium, and arsenic distribution.