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VOLCANIC ROCK GEOCHEMISTRY AS A GUIDE FOR MASSIVE SULPHIDE EXPLORATION IN CENTRAL NEWFOUNDLAND

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ABSTRACT

Preliminary results from whole rock geochemical studies in the Wild Bight, Lushs Bight, Pacquet Harbour and Victoria Lake groups and the Betts Cove (ophiolite) Complex, central Newfoundland, suggest that volcanogenic massive sulphide (VMS) deposits in these sequences are hosted by volcanic rocks of island-arc geochemical signatures. There is a widespread specific association of VMS deposits with strongly incompatible element-depleted volcanic rocks, interpreted as the products of hydrous remelting of refractory mantle sources. The ore-bearing sequences of island-arc derivation are generally stratigraphically overlain by, or structurally juxtaposed with, volcanic rocks of non-arc signatures.

The geochemical and stratigraphic evidence suggests that massive sulphide deposition took place during arc-rifting events. The rocks with island-arc signatures represent the rifting stage (and in some cases, part of the pre-rifting history of the arc). Rocks with non-arc signatures represent volcanic activity in the newly-established back-arc basins.

The specific association of massive sulphides with strongly depleted volcanic rocks suggests a genetic link. It is postulated that in the rifting environment, these very hot magmas rise quickly to shallow depths with much of their heat of fusion intact. This anomalous heat would fuel more vigorous and larger hydrothermal cells, resulting in the leaching of increased quantities of metals in the subsurface. The deep fractures associated with the rifting would focus the fluids on the rising side of the cells, allowing more efficient delivery of metals fluids to the ore depositional environment. The presence of these strongly depleted volcanic rocks in ancient island arcs is probably a significant indicator of the presence of massive sulphides, and may prove to be a useful tool in regional exploration.

INTRODUCTION

Recent improvements in trace-element analytical techniques have provided geochemists and petrologists with a greater range of geochemical and isotopic data for studying ancient igneous rocks. Using Instrumental Neutron Activation Analysis (INAA), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and improvements in X-Ray Fluorescence (XRF) techniques, rapid, precise determination of the High Field Strength Elements (HFSE) (Ta, Nb, Zr, Hf, Y), Low Field Strength Elements (LFSE) (Rb, Sr, Ba, Cs,U, Th) and the Rare Earth Elements (REE) are now possible at very low concentrations. Utilizing this capability, detailed geochemical studies of volcanic rocks have been initiated in the massive suphide districts of central Newfoundland. The aims of these studies are, a) to determine the nature of the paleotectonic environments that are represented by these volcanic rocks, and b) to investigate the relationships between volcanic rock geochemistry and the presence or absence of volcanogenic massive sulphide (VMS) deposits.

The approach applied here, is based on the hypothesis that volcanogenic sulphide mineralization in central Newfoundland may have taken place in response to a particular set of paleotectonic conditions, as is the case in well studied modern examples such as in the Kuroko District, Japan, or in Fiji (Sillitoe, 1982; Cathles *et al.*, 1983). If the favourable paleotectonic environment can be identified and characterized by the types of volcanic rocks that erupted while it was extant (again, based on comparisons with modern environments), then perhaps those characteristics could be used to focus and direct exploration in complex oceanic volcanic terranes.

In 1984, a pilot study of the relationships between volcanic rock geochemistry and volcanogenic sulphide deposits was begun in the Wild Bight Group, central Newfoundland (Figure 1), to determine whether volcanic rocks associated with volcanogenic sulphides showed any characteristic geochemical signatures that could be used as a guide for exploration (Swinden, 1984, 1985). The initial

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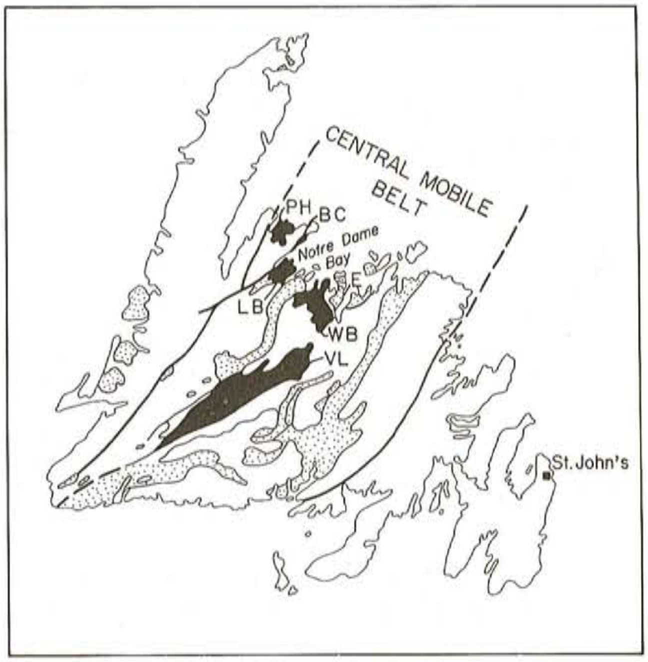

Figure 1. *Pre-Silurian vestiges of Iapetus Ocean in central Newfoundland (stippled). Sequences studied in this report are shown in black. WB–Wild Bight Group; LB–Lushs Bight Group; BC–Betts Cove Complex and Snooks Arm Group; PH–Pacquet Harbour Group; VL–Victoria Lake Group.*

success of this study (Swinden, 1985, 1987) led to the broadening of the scope of the project, to include other massive sulphide-bearing volcanic sequences in central Newfoundland. The objective of this comprehensive program is to identify and characterize consistencies in paleotectonic environments and geochemical signatures of the ore-associated rocks, for use as a tool in predictive metallogeny regionally across the Central Mobile Belt. Some of the preliminary results of this study are presented here.

Data from five sequences in north–central Newfoundland, the Wild Bight and Lushs Bight groups in Notre Dame Bay, the Betts Cove (ophiolite) Complex and the Pacquet Harbour Group on the Baie Verte Peninsula, and the Victoria Lake Group in south–central Newfoundland (Figure 1), suggest that massive sulphide mineralization occurred in these sequences during island-arc rifting. Host rocks in all sequences have a distinct geochemical signature of island-arc volcanism and are generally overlain by volcanic rocks generated from non-arc mantle sources. Within the rifted arc sequences, there is a close spatial association between VMS deposits and volcanic rocks that are anomalously depleted in incompatible elements, and apparently represent second-stage melting of refractory mantle sources. It is possible that this consistent association is an important indicator of tectonic events that trigger VMS deposition in these environments, and hence may have considerable application as an exploration tool.

METHODS

In this study, reliance is placed on elements that are likely to have been immobile through greenschist and lower amphibolite facies metamorphism at low water/rock ratios. These include the major elements TiO_2 and P_2O_5, the HFSE (Zr, Nb, Y, Ta, Hf) and the REE. Most LFSE (e.g., U, Rb, Sr, Cs) are too mobile to be useful in altered rocks. However, Th, although by definition a LFSE, is generally considered to be immobile under low-grade metamorphism.

In the following geochemical discussion, reference is made to 'arc signatures' and 'non-arc signatures'. Following Wood *et al.* (1979), Sun (1980), and many others, we consider oceanic volcanic rocks that result from magmatism influenced by subduction, to generally exhibit a marked depletion in the highly incompatible HFSE (Nb and/or Ta), and a marked enrichment in the LFSE elements (in altered rocks represented by Th) with respect to La. This is an empirical signature that is widely recognized in modern arc environments as characterizing arc magmatism, and although its origins remain somewhat contentious, the signature is clearly a magmatic phenomenon inherited from the source regions of the melts. The inter-element relationships that characterize this signature are generally considered to reflect mass transport from subducted sediment and/or altered oceanic crust from the subducting slab into magma source regions, in the overlying mantle wedge. They are manifested graphically on primitive mantle-normalized extended REE plots as a negative anomaly in Nb and a positive anomaly in Th with respect to La and Ce (Figure 2). Such an extended REE pattern constitutes an 'arc signature' in our terminology. Non-arc mantle sources will produce magmas having similar normalized abundances of La and Nb and normalized Th abundances that are similar to or less than La and Nb. Such a smooth pattern between Th and Ce constitutes a 'non-arc signature'.

To illustrate these relationships, a simple diagram has been devised, in which the ratio Nb/Th is plotted against Y (e.g., Figures 5, 8, 11, 14, 17, 19). The Nb/Th ratio is a measure of the extent of Nb depletion and Th enrichment in the magma source (i.e., it separates arc signatures with a low Nb/Th ratio from from non-arc signatures with higher Nb/Th ratio). Y serves as an indicator of the relative incompatible element depletion in the magma; very low Y contents (i.e., less than about 16 ppm) indicate highly depleted rocks that may be second stage melts. The stippled field of overlap between fields, results from uncertainties in analytical techniques and the gradational nature of the geochemical boundaries between these different rock types.

RESULTS

The Wild Bight Group

The Wild Bight Group (Figure 3) comprises a more than 8-km-thick sequence of Llanvirnian–Landeilian (Early

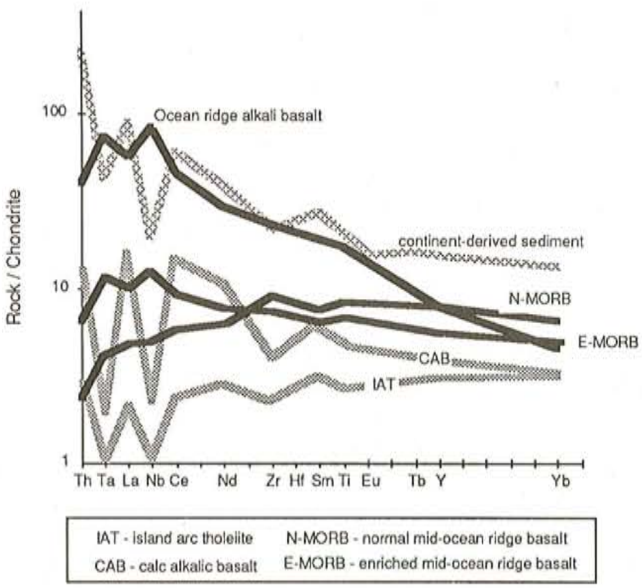

Figure 2. *Typical extended REE patterns for oceanic basalts of different types after Sun (1980), and a typical continent-derived oceanic sediment, after Hole et al. (1984). Island-arc rocks are stippled lines, non-arc rocks are black lines and sedimentary rocks are the hatched line. Note prominent negative Ta and Nb anomalies and high Th in the arc rocks and in the sediment.*

Ordovician) epiclastic, mafic and lesser felsic volcanic rocks and subvolcanic sills and dykes. Volcanic rocks, although comprising less than 25 percent of the stratigraphic record, occur at virtually all stratigraphic levels within the sequence in eleven separate volcanic accumulations. Mafic volcanic rocks comprise mainly pillow lava and lesser massive basalt flows, pillow breccia and fine grained hyaloclastite. Felsic volcanic rocks range from aphanitic rhyolite flows to crystal- and crystal-lithic tuff, and these form small, laterally restricted bodies within the dominantly mafic volcanic sequences.

The Wild Bight Group hosts four volcanogenic sulphide deposits (Figure 3). None have achieved production although one, the Point Leamington deposit, contains more than 13 mt of relatively low grade Cu–Zn-bearing massive sulphide (Walker and Collins, 1988). The Point Leamington and the Lockport deposits consist of massive sulphides capping extensive alteration stockworks. The former is hosted by felsic volcanic rocks, but has mafic pillow lavas approximately 200 m below in the footwall sequence; the latter is hosted by mafic volcanic rocks but is less than 300 m along strike from a small rhyolite body. The other two deposits, the Indian Cove and Long Pond prospects, comprise stockworks in felsic flow and pyroclastic rocks with no massive sulphide cap. The former has associated mafic volcanic rocks nearby in the stratigraphic sequence.

In a detailed petrological, geochemical and isotopic study of volcanic rocks in the Wild Bight Group, Swinden (1987) demonstrated a progressive change in the nature of the volcanic activity. The earliest volcanic rocks are dominantly LREE-enriched island-arc tholeiites (Figure 4). Later in the history of the Wild Bight Group, a new phase of volcanic activity began, which included continued eruption of island-arc tholeiites, but was characterised by the eruption of felsic volcanics of trondhjemitic composition and a suite of extremely incompatible element-depleted tholeiitic rocks ('strongly depleted arc', Figure 4). All of the volcanic rocks erupted to this point, carry a clear arc signature. Following eruption of these rocks, new mantle sources without the arc signature were apparently involved in the magmatism, and volcanic rocks at the top of the group carry a dominantly non-arc signature. This geochemical progression was interpreted (Swinden, 1987) to reflect a paleotectonic progression from an early stage of island-arc volcanism (the lowermost arc tholeiites), through an episode of arc-rifting (during which, the felsic volcanics and strongly depleted thoeliites were erupted), and culminating with the establishment of a back-arc basin (during which, the magmas with non-arc sources were erupted).

Volcanogenic sulphide deposits occur only in the central stratigraphic part of the Wild Bight Group and are, therefore, an integral part of the arc-rifting event. Furthermore, all are associated with strongly depleted tholeiites, the chemical characteristics of which are illustrated in Figure 4. These rocks contain very low concentrations of all incompatible elements (including less than 10 percent total REE) and are interpreted to have formed through complex, multi-stage hydrous remelting of the refractory mantle sources left after the removal of a first stage arc tholeiite melt (Swinden, 1987). All plot in Field 'C' of Figure 5. Wherever these rocks are found, volcanogenic sulphides are also found and conversely, no mineralization of this type is known to occur in the Wild Bight Group in their absence. Although it is true that volcanogenic sulphides are also closely associated with felsic volcanic rocks, the converse is not true. There are felsic volcanic bodies within the group that are apparently barren.

The Lushs Bight Group

The Lushs Bight Group (Figure 6) comprises a structurally complex sequence dominated by basaltic pillow lava having lesser pillow breccia and mafic tuffaceous rocks, and sheeted diabase dykes. Although generally considered to be part of a disrupted ophiolite (e.g., Dean, 1978; Kean, 1984, 1988), the Lushs Bight Group contains no cumulate plutonic elements of the ophiolite stratigraphy and ultramafic rocks occur only as very small fault-bounded fragments. The mafic volcanic rocks from different structural blocks in the Lushs Bight Group are generally homogeneous, both geologically and petrographically, and cannot be subdivided or correlated with confidence in the field. Felsic volcanic rocks occur locally in the western part of the group (Kean, 1988).

The Lushs Bight Group is overlain conformably by the Western Arm Group, a Lower Ordovician (MacLean, 1947) sequence of mafic pillow lava having lesser interbedded pyroclastic and epiclastic rocks. It has, historically, been interpreted as an island-arc sequence, built upon the Lushs Bight crust (Dean, 1978).

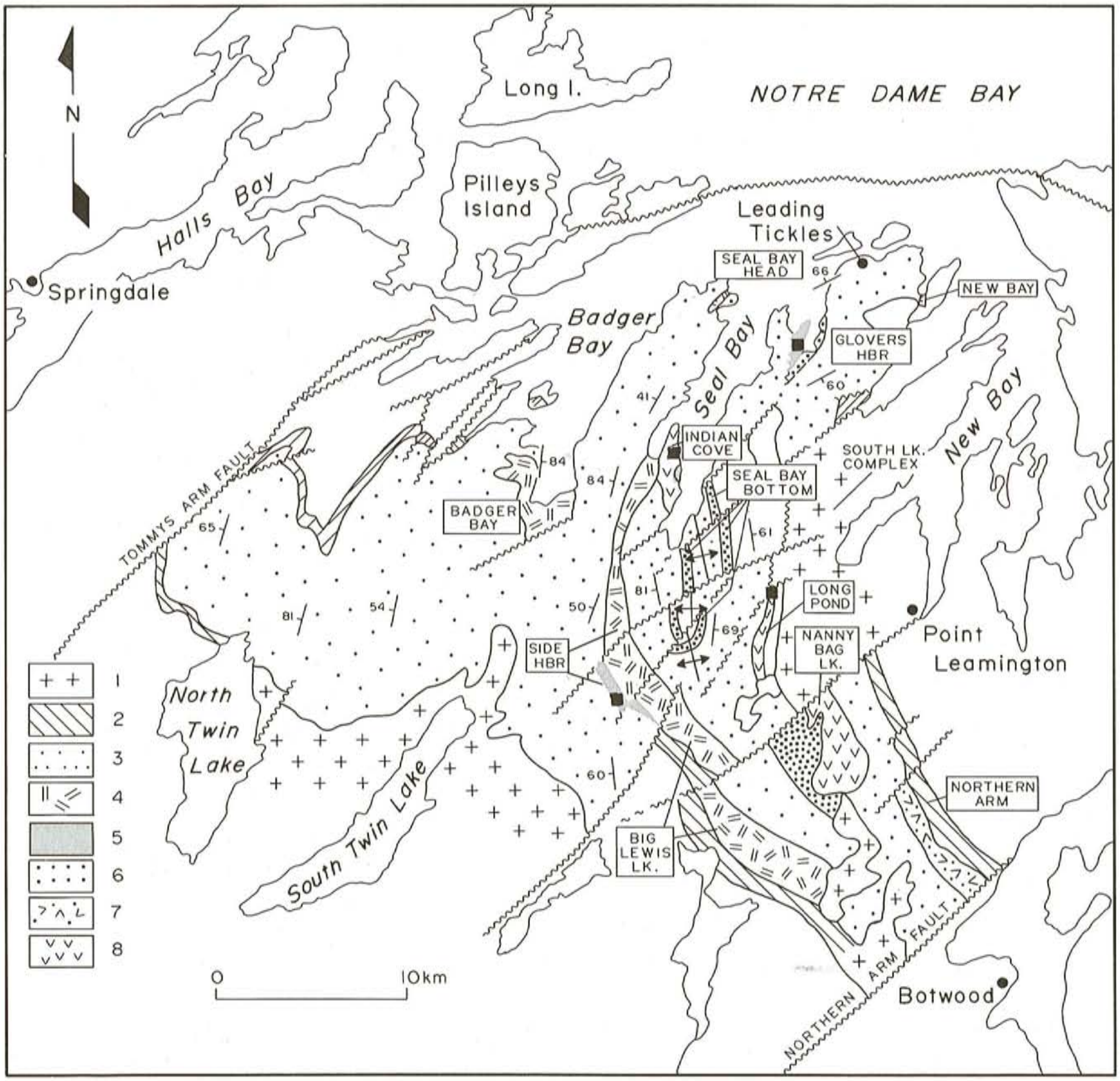

Figure 3. *Geological map of the Wild Bight Group after Swinden (1987) showing the geochemical affiliation of the volcanic rocks. 1—post-Ordovician plutonic rocks; 2—Caradocian shale (Shoal Arm Formation); 3—epiclastic rocks; 4—non-arc volcanic rock; 5—strongly depleted arc-tholeiites; 6—LREE-enriched and LREE-depleted arc-tholeiites; 7—mixed arc/non-arc sequences; 8—rhyolites. Black squares are volcanogenic sulphide deposits.*

The Lushs Bight Group contains more VMS occurrences per square kilometre than any other group of rocks in central Newfoundland (Dean, 1978). Three of these, the Whalesback, Little Bay and Little Deer, have seen production within the past 20 years (Whalesback and Little Bay are in the 2.5 to 4 mt range). Several other deposits produced lesser amounts during the 'copper boom' of the late 1800's. A complete summary of the major VMS occurrences is found in Kean and Evans (1988a) and Swinden *et al.* (1988). All of the deposits consist dominantly of pyrite, chalcopyrite and sphalerite and commonly occupy chloritic shear zones. Stratiform massive sulphides apparently occur at more than one stratigraphic level within the volcanic sequence, and stockwork-like alteration can, locally, be seen in the volcanic rocks and in the underlying sheeted dyke sequence (Kean, 1984; Kean and Evans,1988a).

The basal unit of the overlying Western Arm Group comprises siliceous, chocolate-brown argillite and interbedded ferruginous chert, argillite and green sandstone.

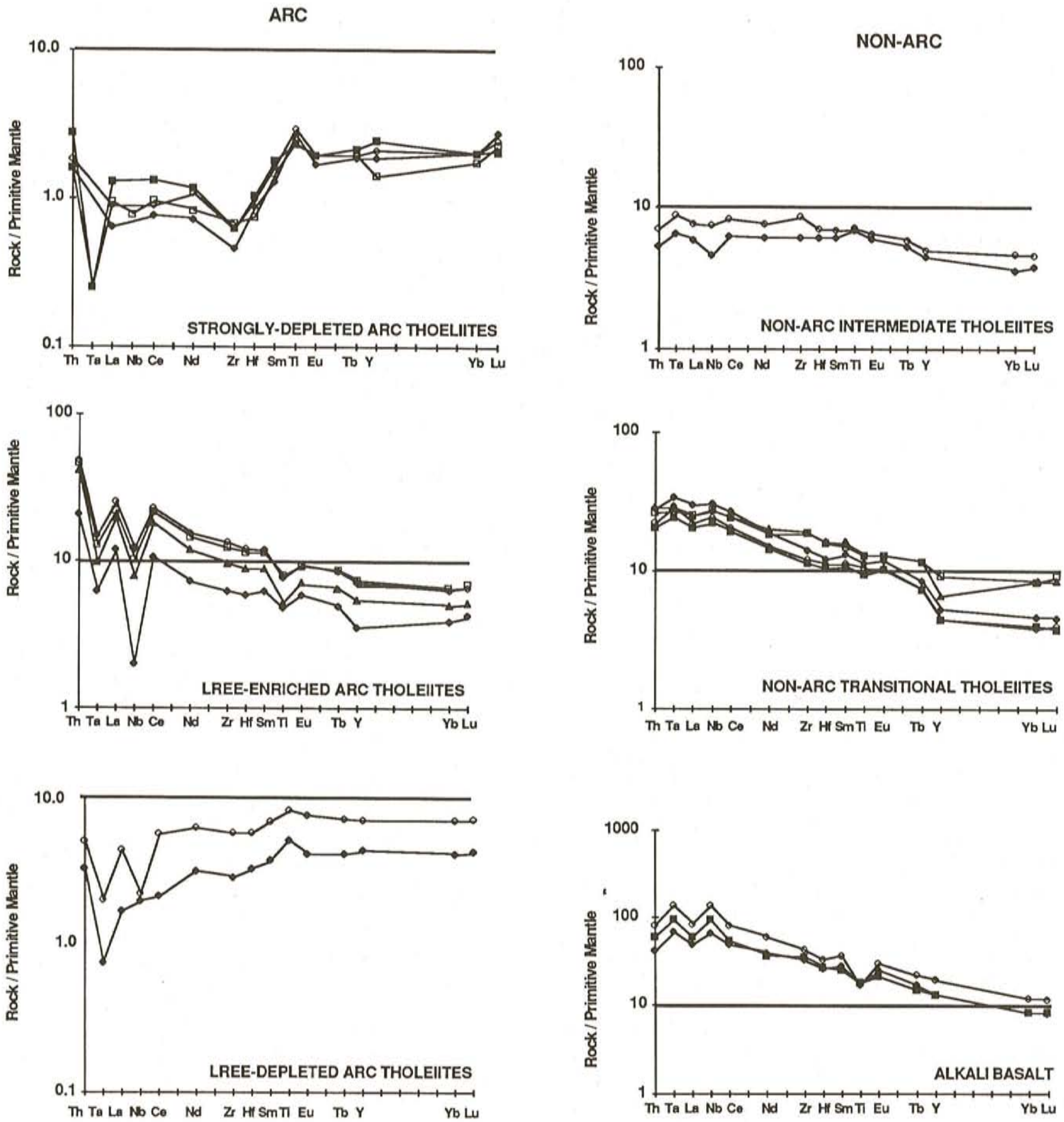

Figure 4. *Extended REE plots for volcanic rocks in the Wild Bight Group: Solid line on this and all subsequent extended REE plots is drawn at 10 x primitive mantle for ease of reference among plots. Primitive mantle normalizing values are: Th–0.088; La–0.63; Nb–0.65; Ce–1.59; Nd–1.21; Zr–9.8; Sm–0.399; Ti–1134; Eu–0.15; Gd–0.51; Y–3.9; Dy–0.75; Er–0.42; Yb–0.432; Lu–0.66.*

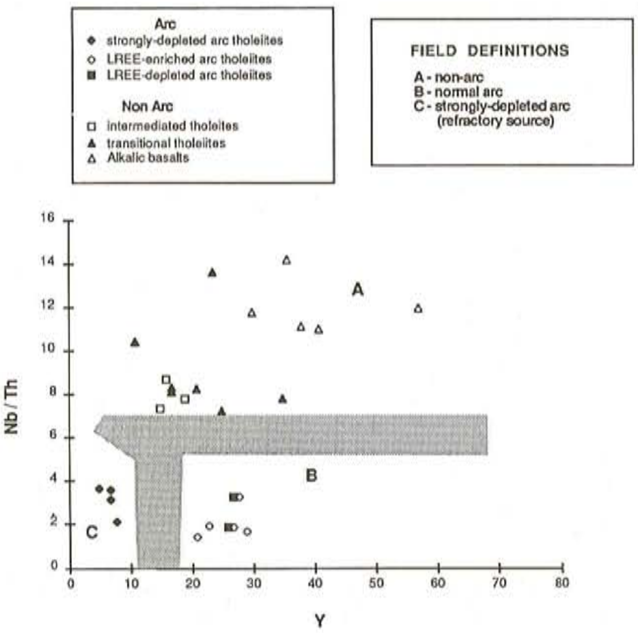

Figure 5. *Nb/Th versus Y for Wild Bight Group rocks: symbols are keyed to subdivisions illustrated in Figure 4. Stippled area is field of overlap.*

These sediments host narrow stratiform bands of massive pyrite, pyrrhotite, magnetite and rare chalcopyrite (Kean, 1984; Kean and Evans, 1988a). The bands ('Fox Neck-type' deposits of Swinden *et al.*, 1988), are essentially sulphide facies iron formations containing only minor base metals and no precious metals and are the only volcanogenic sulphides in the Western Arm Group.

Although the Lushs Bight Group has historically been interpreted as representing oceanic crust (Smitheringale, 1972) and the deposits as having formed at an oceanic or back-arc spreading centre (Kean, 1984), recent geochemical studies suggest that the story is much more complex (Jenner *et al.*, 1988). Several basalt units can be recognized in the volcanic rocks and in the dykes on the basis of their geochemistry, and most have a clear arc signature (Figure 7). Types I-N, I-S and III comprise dominantly normal arc-tholeiites (although Type I-N may also include some non-arc rocks, see Figure 8). Type II basalts are probably also arc-tholeiites, but are more depleted in incompatible elements than Types I and III and plot in the field of overlap between normal and strongly depleted rocks on Figure 8. Types IV and V are geochemically identical, very depleted boninites having high MgO contents and concave-upward REE patterns (Figure 7). Based on the very low contents of incompatible elements, rocks from Types IV and V and probably also those of Unit II are interpreted as the products of hydrous remelting of refractory mantle sources.

The island-arc geochemical signatures in the associated tholeiites suggest that the volcanism and mineral deposition did not occur at a well-established spreading centre as previously thought, but more likely in a supra-subduction setting. In the overlying Western Arm Group, the basalts in the basal Skeleton Pond tuff comprise a mixed arc—non-arc sequence and pass upward into pillow lavas of the Big Hill basalt, which have a non-arc signature (Figures 7 and 8) (Jenner and Szybinski, 1987). The Lushs Bight and Western Arm groups may, therefore, record a rifted-arc to back-arc transition similar to that interpreted for the Wild Bight Group with most, if not all, of the Lushs Bight Group having formed during the arc-rifting stage.

VMS deposits in the Lushs Bight Group show a distinct affinity for the incompatible element-depleted Type II tholeiites and Type IV and V boninites (Figure 6). However, it is not clear whether all deposits are actually hosted by the depleted rocks. Several major deposits including Rendall—Jackman, Lady Pond and Whalesback, apparently occur in normal arc-tholeiites, although more detailed sampling is still needed in the immediate vicinity of the deposits to confirm this. It may be significant that the Lady Pond deposit is spatially associated with boninitic dykes. Any genetic model that attempts to relate the occurrence of VMS deposits to the presence of depleted magmatic rocks must take this into account.

The Betts Cove Complex

The Betts Cove Complex (Figure 9) is a complete ophiolite, which outcrops in an arcuate belt on the eastern side of the Baie Verte Peninsula. The east-facing stratigraphic sequence consists of basal ultramafic rocks that pass upward into mafic cumulate and plutonic rocks, sheeted diabase dykes and an upper unit of mafic pillow lavas (Upadhyay, 1973). The ophiolite is stratigraphically overlain by the Snooks Arm Group, a sequence of epiclastic and mafic volcanic rocks that Jenner and Fryer (1980) have interpreted to represent an oceanic-island environment.

Sun and Nesbitt (1978) and Coish and Church (1979) first recognized unusual Mg-rich, incompatible element-depleted lavas in the Betts Cove ophiolite. Coish *et al.* (1982) presented geochemical and Nd-isotopic data showing that these very depleted melts are associated with normal tholeiites in the stratigraphy, and presented Nd isotopic data in support of an origin in a supra-subduction setting. The data (Figure 10) show that these very depleted rocks are geochemically similar to boninites and, as suggested by Coish *et al.* (1982), must represent remelting of refractory sources.

Elsewhere in the Betts Cove sequence, tholeiitic rocks with REE patterns ranging from flat to LREE-depleted, and distinct negative Nb anomalies, are present. The geochemical patterns and Nd isotopic data presented by Coish *et al.* (1982) suggest that these probably represent the melting of normal mantle sources in an island-arc environment. The most strongly LREE-depleted rocks are similar to MORB, both geochemically and isotopically, and plot in the non-arc field in Figure 11. This suggests that mantle sources, which were not influenced by the subducting slab, were involved in their petrogenesis. In the stratigraphically overlying Snooks Arm

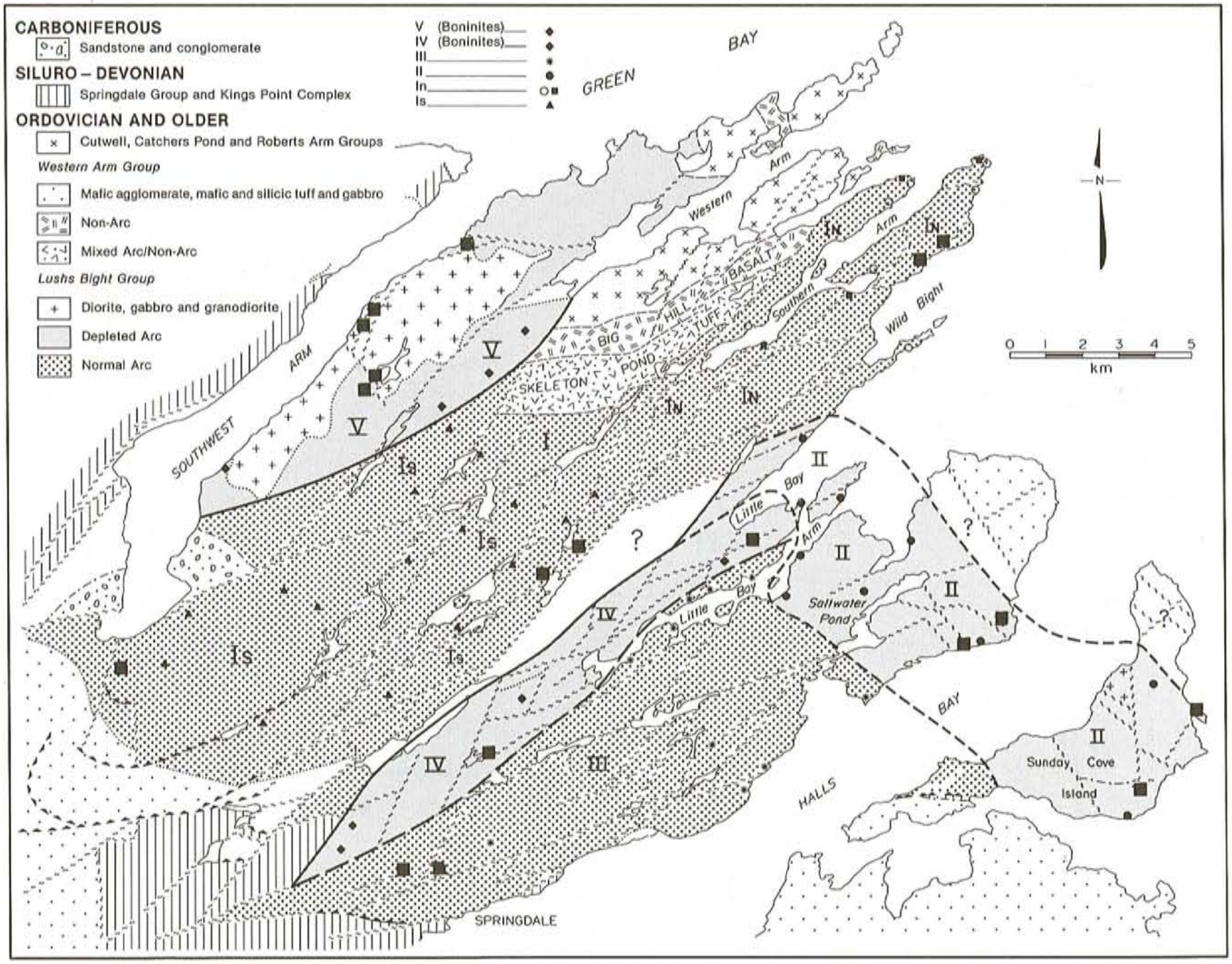

Figure 6. *Geological map of the Lushs Bight Group after Kean (1984) and Jenner et al. (1988) showing the geochemical affiliation of the volcanic rocks; large solid squares are volcanogenic sulphide deposits, and location indicator in legend refers to extended REE plots on Figure 7.*

Group, LREE-enriched tholeiites have clear non-arc signatures (Figures 10 and 11).

The data presented here are consistent with the paleotectonic models for the Betts Cove Complex presented by Coish *et al.* (1982). The ophiolite can reasonably be interpreted to have formed in a supra-subduction environment during rifting of an island arc. The rifting event is, in this interpretation, recorded by the boninite and arc-tholeiite volcanic rocks. Initiation of partial melting of dominantly normal mantle sources (i.e., not influenced by the subducting slab) is recorded by the MORB-like lavas in the Betts Cove Complex and by OIB-like lavas in the overlying Snooks Arm Group.

Pillow lavas in the Betts Cove Complex are host to a number of VMS deposits, the best known of which are the Tilt Cove and the Betts Cove deposits at the north and south ends of the complex, respectively (Figure 9). The former produced more than 8 mt of Cu–Zn ore and is the largest ophiolite-hosted VMS deposit in the Appalachians. In addition, there are a number of smaller deposits along strike between the two former producers (Strong and Saunders, 1988). The VMS deposits in this ophiolite, as elsewhere, show a close spatial association with the boninitic volcanic rocks. Strong and Saunders (1988) noted this association at Tilt Cove, suggesting that it resulted from metal and sulphur mass transfer from metalliferous sediments on the subducting slab into the mantle wedge, the localization of metals in immiscible sulphide droplets in the boninitic magmas, and their subsequent leaching and transport by hydrothermal fluids onto the sea floor.

The Pacquet Harbour Group

The Pacquet Harbour Group comprises polydeformed sedimentary and volcanic rocks that have been metamorphosed in the upper greenschist to lower amphibolite facies. Volcanic rocks comprise mainly pillow lavas and mafic schist that may have a tuffaceous protolith. Rhyolite is a

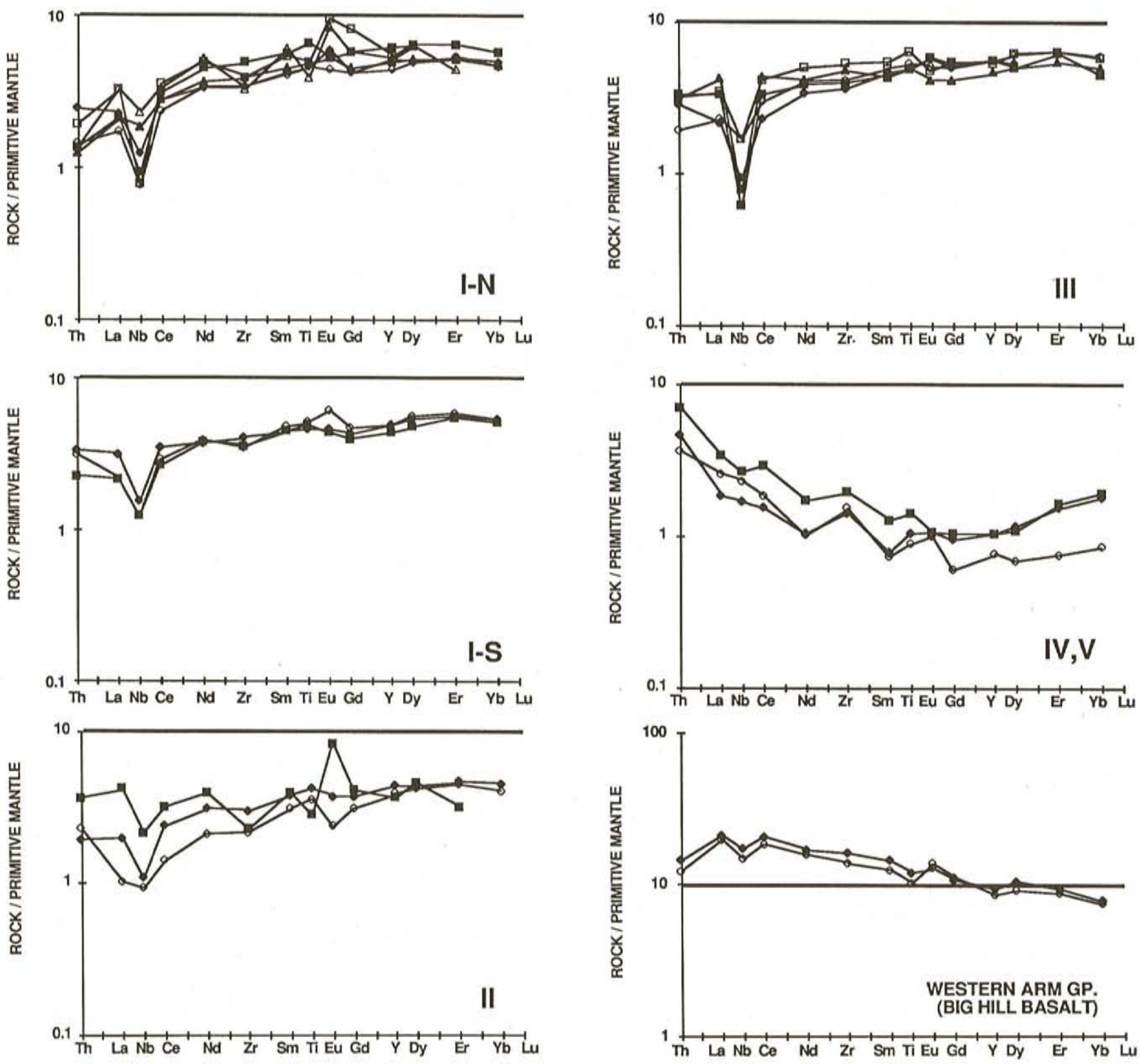

Figure 7. *Extended REE plots for volcanic rocks in the Lushs Bight Group: Subdivision described in text.*

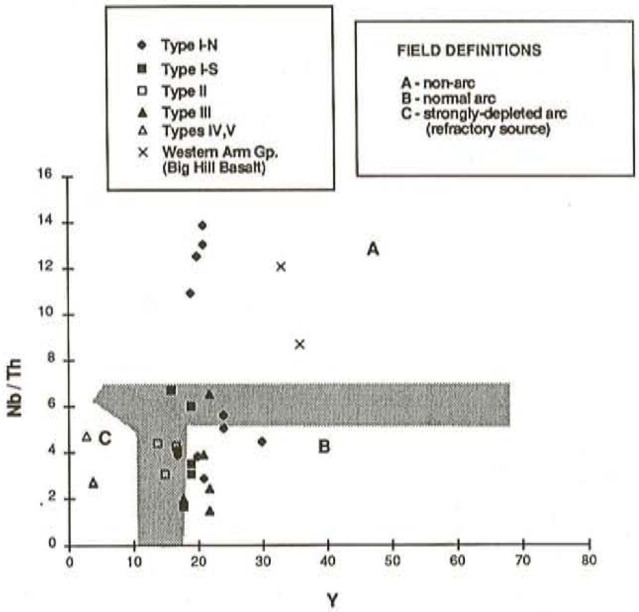

Figure 8. *Nb/Th versus Y plot for Lushs Bight Group rocks. Symbols are keyed to subdivisions illustrated in Figure 7.*

relatively minor constituent, occurring mainly in a circular outcrop area near the centre of the group (Figure 12). There is considerable uncertainty as to the internal stratigraphy of the group because of poor exposure and structural complexity (Hibbard, 1983).

Gale (1971, 1973) was the first to recognize that the Pacquet Harbour Group is geochemically bipartite, comprising tholeiitic basalts and a suite of highly magnesian, incompatible element-depleted volcanic rocks, which he termed 'basaltic komatiites'. Hibbard (1983) reported additional analyses of both rock types and remarked upon the similarity of the magnesian rocks to boninites. The trace-element data presented here, clearly show the close affinity of these rocks to boninites, with highly depleted incompatible trace-element concentrations and concave-upward REE patterns (Figure 13). One sample (termed 'depleted arc tholeiite' on Figure 13) is significantly incompatible element-depleted but apparently not a boninite as it does not have the characteristic concave-upward REE pattern. It plots in the field of overlap on Figure 14. Most tholeiites in the Pacquet Harbour Group do not carry the arc signature (Figure 13). The geochemical association is very similar to that in the less structurally disrupted and metamorphosed Betts Cove Complex and Hibbard's (1983) conclusion is accepted by us, in that the two sequences are probably related.

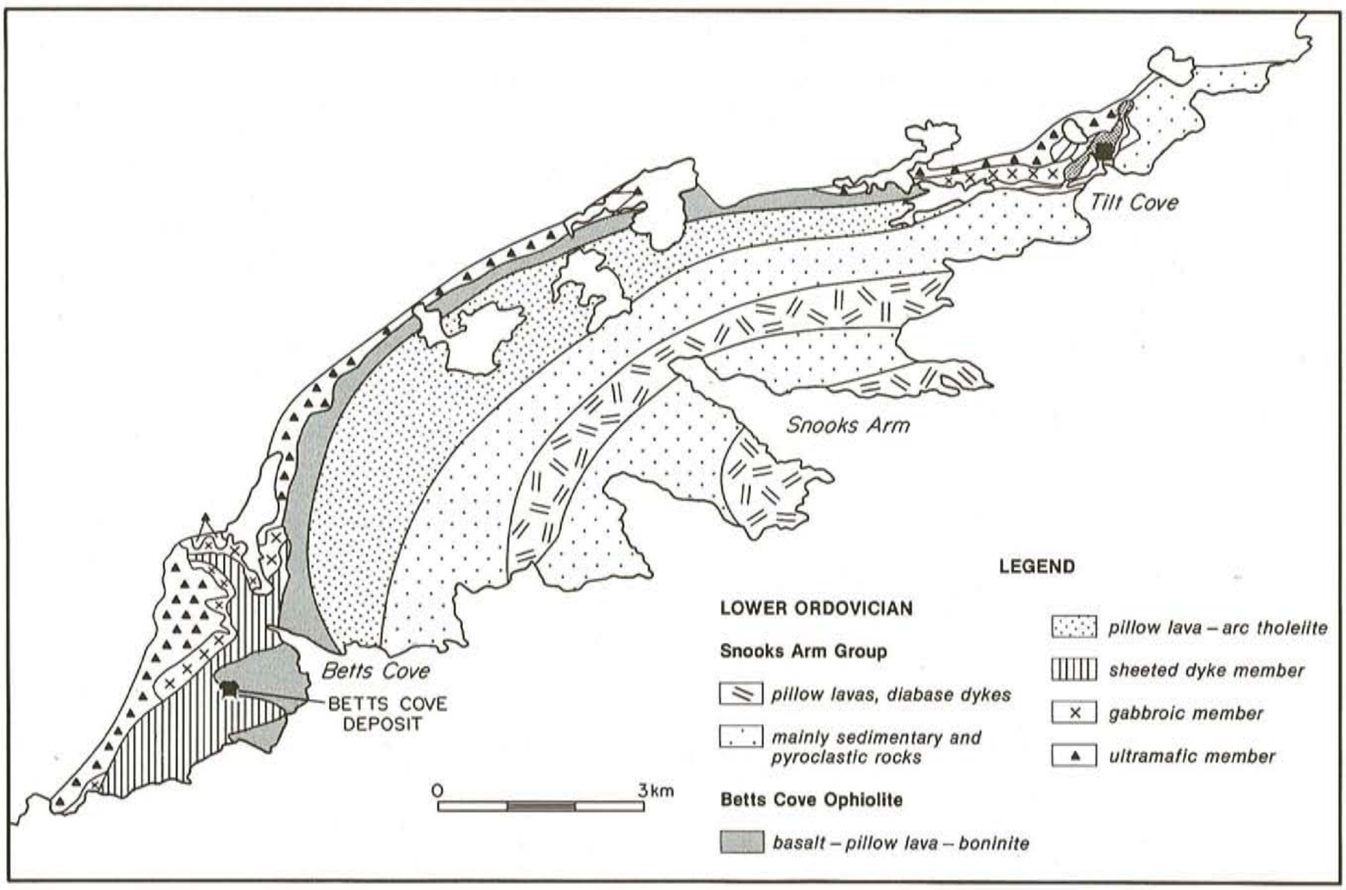

Figure 9. *Geological map of the Betts Cove area showing the geochemical affiliation of volcanic rocks in the Betts Cove Complex and the Snooks Arm Group; solid squares are volcanogenic sulphide deposits.*

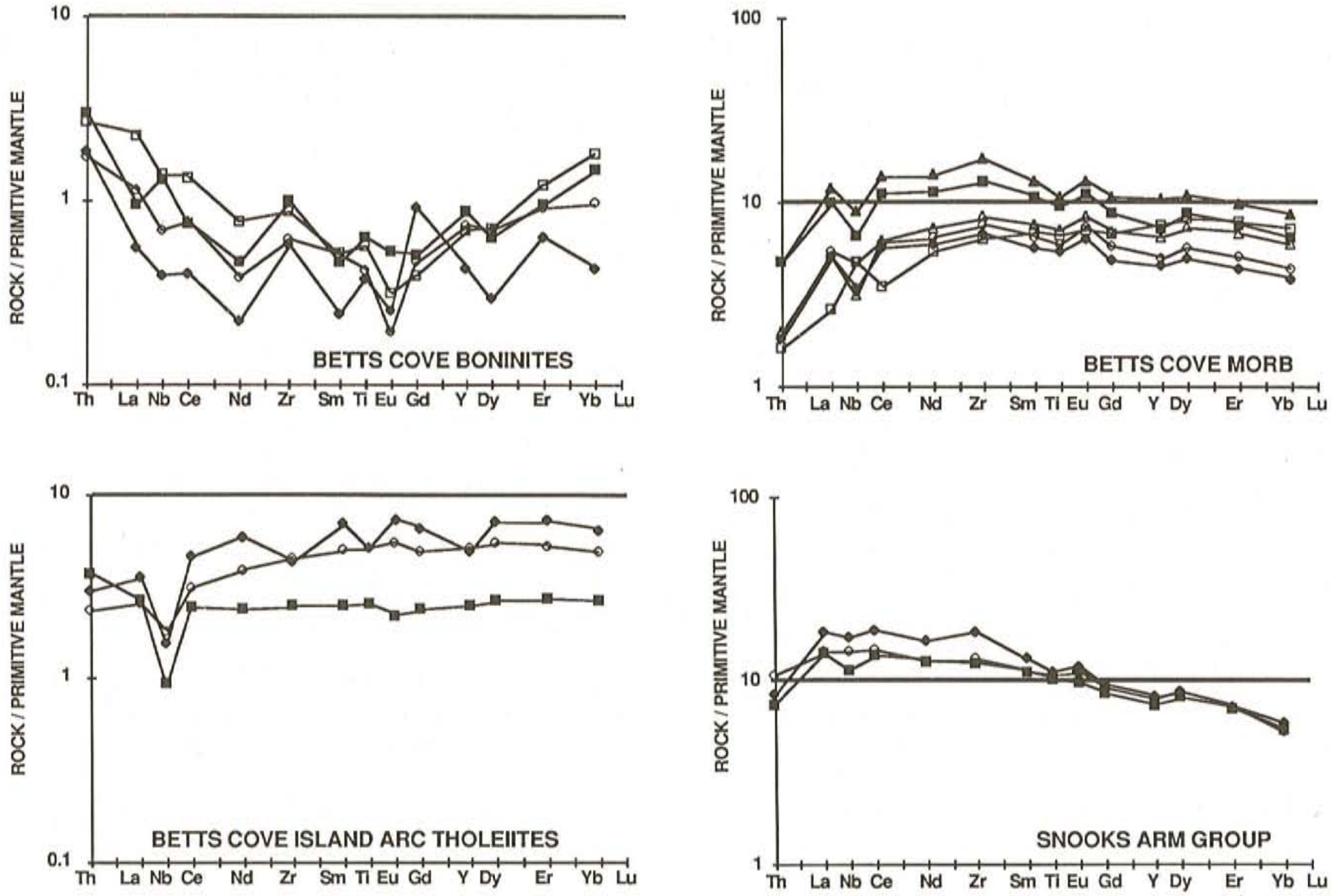

Figure 10. *Extended REE plots for volcanic rocks in the Betts Cove Complex and the Snooks Arm Group.*

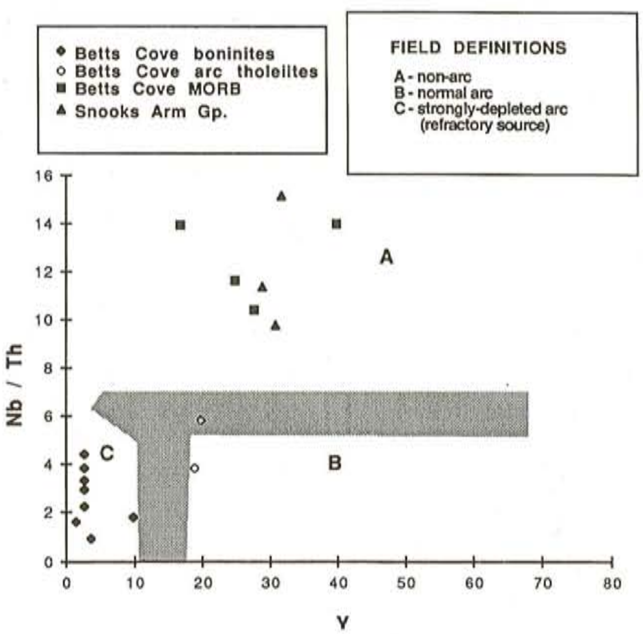

Figure 11. *Nb/Th versus Y plot for the Betts Cove Complex and the Snooks Arm Group. Symbols are keyed to subdivisions illustrated in Figure 10.*

There are five VMS deposits in the Pacquet Harbour Group, that together make up the Consolidated Rambler Mines camp (Tuach and Kennedy, 1978; Hibbard, 1983; Tuach, 1988). Three of these (Rambler, Ming, and the newly-discovered Ming West) are stratiform massive sulphides whereas the other two are footwall stockwork systems. The VMS deposits, although closely associated with the Rambler rhyolite (Tuach, 1988), are stratigraphically associated with the boninitic lavas, near the contact with the overlying tholeiites. The magnesian basalt–tholeiite transition, as in the case of the Betts Cove Complex, probably represents an arc-rifting to back-arc basin transition and as in the Betts Cove example, the VMS deposits appear to be associated with this tectonic transition.

The Tally Pond and Tulks Hill Volcanic Belts

The Tally Pond and Tulks Hill volcanic belts comprise Cambrian to Lower Ordovician mafic and felsic volcanic rocks that occupy the western and eastern margins, of the Victoria Lake Group, respectively (Figure 15). They include considerably greater proportions of felsic volcanic rocks than the sequences in Notre Dame Bay. Previous workers have included the volcanic sequence near the Victoria Mine as part

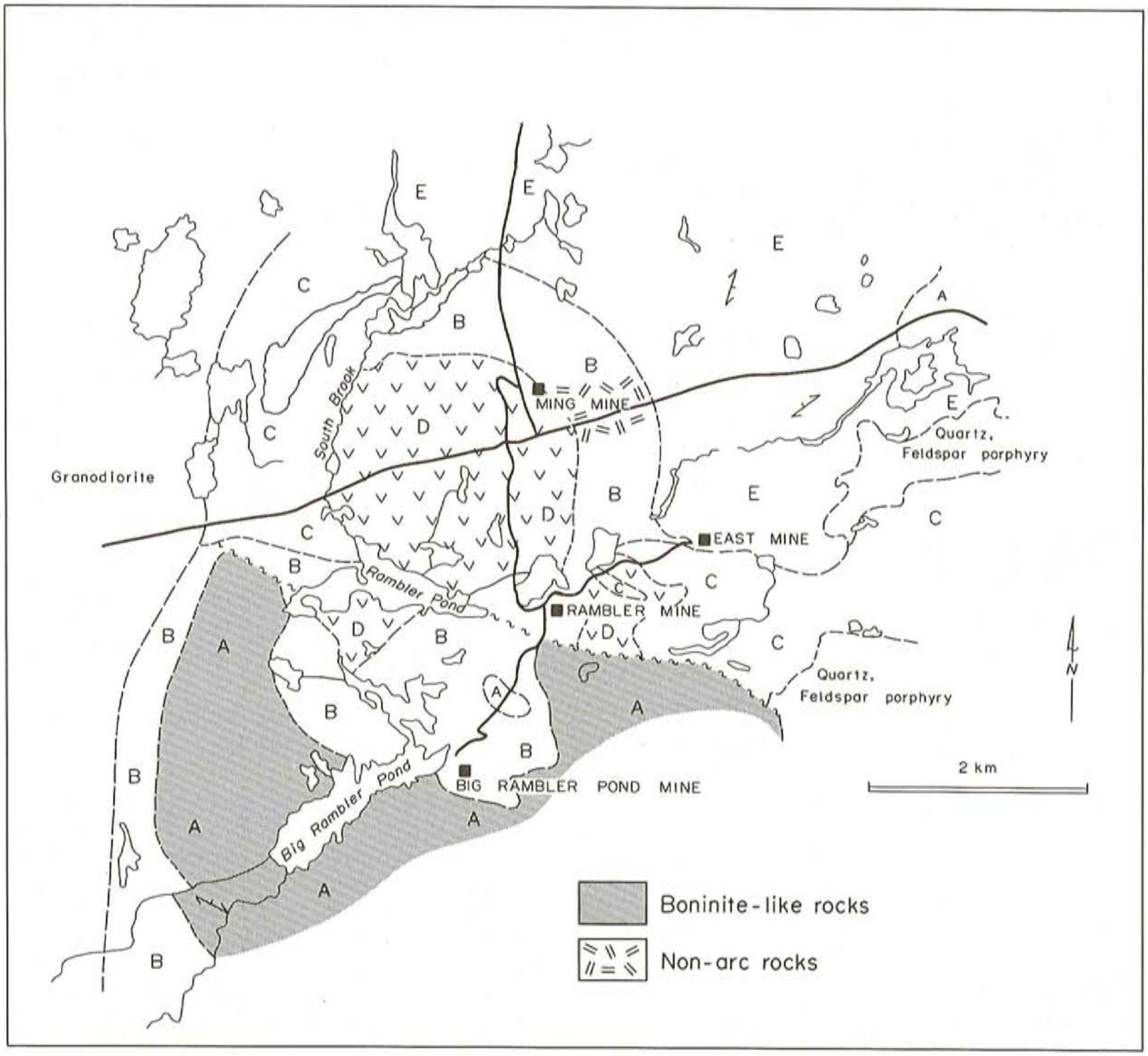

Figure 12. *Geological map of the Rambler Mine area after Tuach (1988) showing the geochemical affiliation of volcanic rocks in the southwestern part of the Pacquet Harbour Group: A, mafic flow rocks; B, mafic volcaniclastic rocks; C, mixed mafic and silicic rocks; D, silicic pyroclastic rocks; E, clastic sediments.*

of the Tulks Hill volcanic belt (e.g. Kean *et al.*, 1981). However, following Kean and Evans (1988b) and Swinden *et al.* (1988), the Victoria Mine sequence is considered to be younger than the main part of the belt and is not included in the following discussions.

The two volcanic belts together make up approximately 60 percent of the Victoria Lake Group, the remainder being a large epiclastic basin in the central and northern parts of the group (Figure 15). Both volcanic belts are characterised by laterally extensive, predominantly felsic, pyroclastic rocks. Mafic pillow lavas and massive flows are common in the Tally Pond volcanics. In the Tulks Hill volcanics, mafic rocks are dominantly tuffaceous, consisting of aquagene tuff, lapilli tuff, agglomerate and breccia. Exposure is generally poor throughout the Victoria Lake Group and contact relationships can seldom be demonstrated on the ground.

Both sequences are prolific hosts to volcanogenic sulphide deposits. The Tulks Hill volcanics contain major massive sulphide deposits at Tulks Hill and Tulks East (Barbour and Thurlow, 1982; Kean and Evans, 1986; Evans and Kean, 1987), and several other minor prospects. The Tally Pond volcanics host the recently discovered Boundary and Duck Pond deposits (Kean, 1985; MacKenzie, 1988; MacKenzie *et al.*, 1988) as well as a number of minor prospects.

Although our data for this particular area are very preliminary, they do suggest a relationship between host-rock geochemistry and volcanogenic sulphide deposits. In the Tulks Hill belt, three geochemical subdivisions of mafic volcanic rocks are recognized, from east to west: 1) several outcrop areas of arc-tholeiites (probably including all of the Harmsworth Steady volcanics, Figure 15) that range from

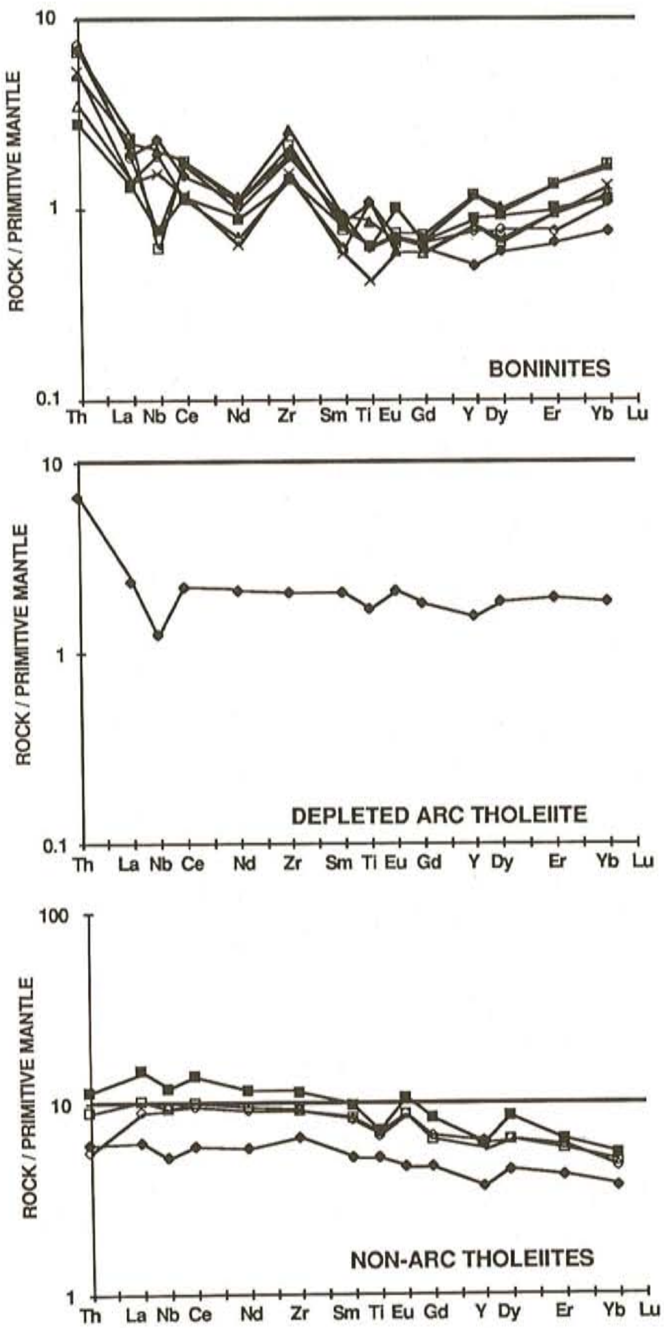

Figure 13. *Extended REE plots for volcanic rocks in the Pacquet Harbour Group.*

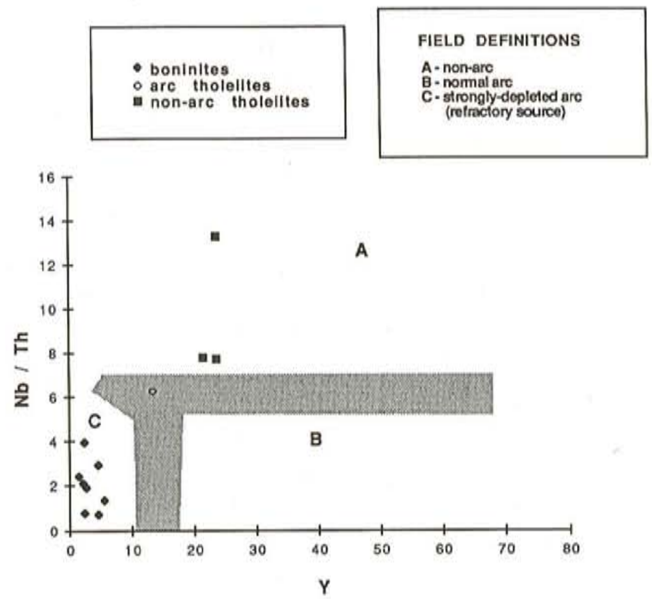

Figure 14. *Nb/Th versus Y plot for the Pacquet Harbour Group. Symbols are keyed to subdivisions illustrated in Figure 13.*

slightly to strongly LREE-enriched (Figure 16); 2) a sequence of dominantly felsic volcanics that locally are interbedded with strongly depleted arc-tholeiites; and 3) a sequence of non-arc tholeiites (the upper basalts). All of the volcanogenic sulphides in this belt are hosted by felsic volcanic rocks. However, analyses of relatively unaltered pillow lavas, massive flows and mafic dykes from outcrop and drill core near many of these deposits, have shown that there is commonly a spatial association beween VMS deposits and highly depleted arc-tholeiite volcanic and/or subvolcanic rocks. Both the eastern arc-tholeiite sequences and the western upper basalts of non-arc origin are apparently barren.

The interpretation of the geochemical relationships in the Tulks Hill volcanics is consistent with the generally west-facing stratigraphic succession proposed by Kean and Jayasinghe (1980), which appears to record the transition from island arc to back arc. Because of the lack of exposure in the area, it is not possible to document this interpretation with the same confidence as in the better exposed sequences in Notre Dame Bay. It is possible that the contacts are structural and the different basalt types are not genetically related. However, the presence of highly depleted arc-tholeiites near the major sulphide deposts (Figure 17) does suggest that at least these sequences probably formed in an arc-rifting environment.

In the Tally Pond area, the data to date are even less definitive. Rocks in the Lake Ambrose area are mainly arc-tholeiites having REE patterns varying from relatively flat to somewhat LREE-enriched (Figure 18). As yet, there are no detailed data from volcanic rocks near the Duck Pond and Tally Pond VMS deposits. In the northeastern part of the volcanic belt, highly depleted rocks (Figure 19) with concave-upward REE patterns have been identified in outcrops near Sandy Lake (Figure 15). These rocks may be boninites and are spatially associated with the recently discovered Old Sandy Road massive sulphide prospect (Kean and Evans, 1988c). This prospect was found during reconaissance prospecting following initial recognition that this rock type was present in the area. Based on whole rock geochemistry, the Sandy Lake belt would appear to be a highly prospective area for volcanogenic sulphide exploration.

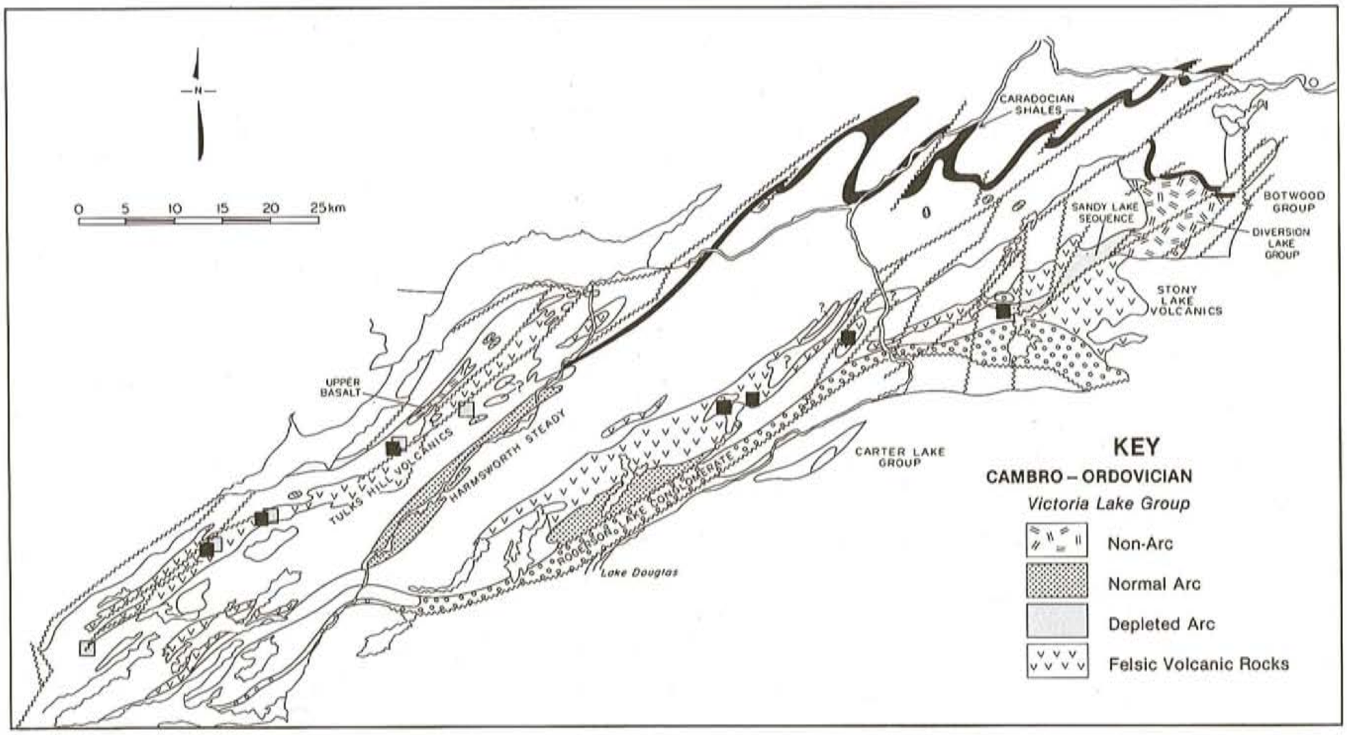

Figure 15. *Geological map of the Victoria Lake Group after Kean and Evans (1988c) showing the geochemical affiliation of the volcanic rocks in the Tulks Hill and Tally Pond volcanic belts; solid squares are volcanogenic sulphide deposits and grey squares are pillow lava outcrops too small to show at this scale.*

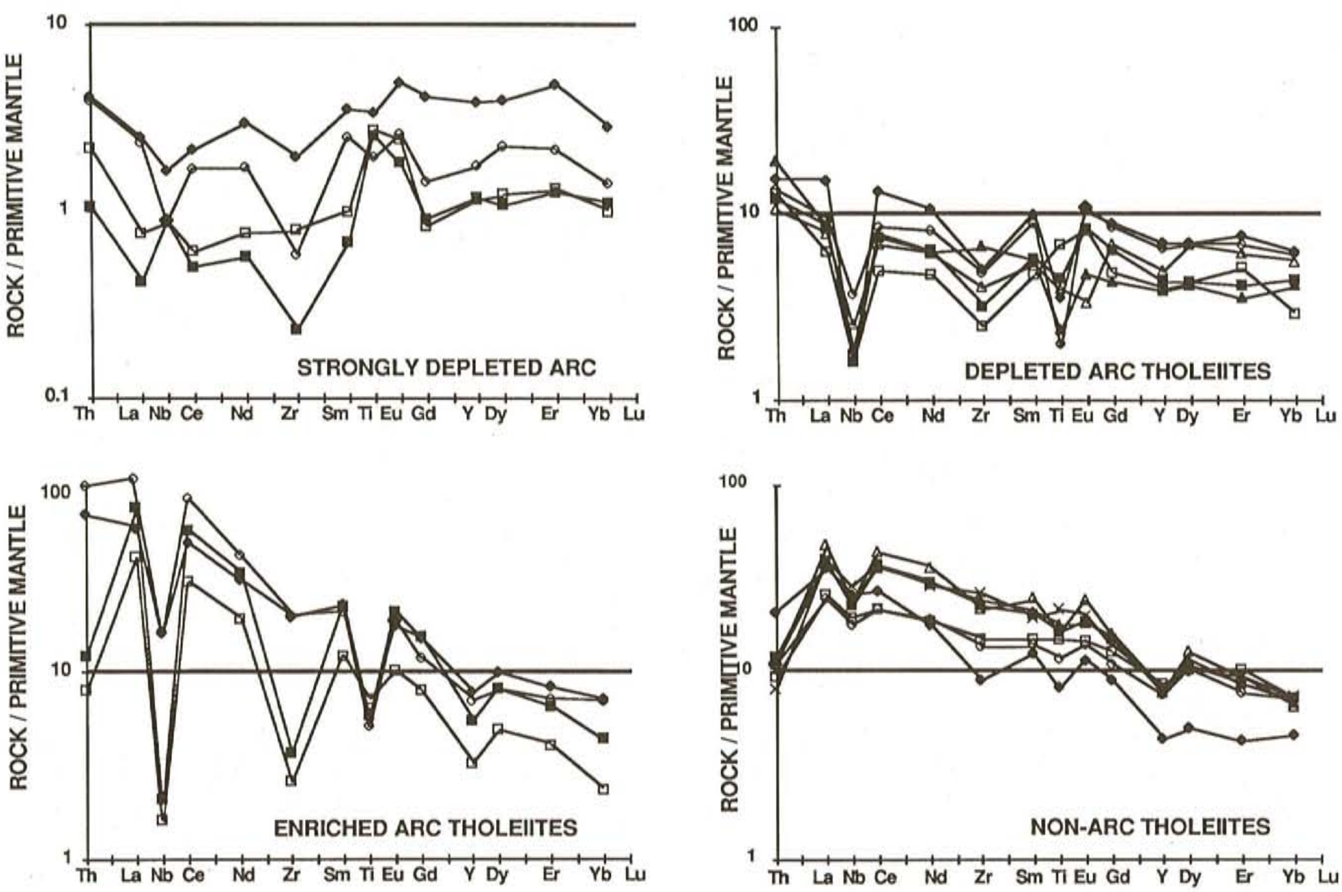

Figure 16. *Extended REE plots for volcanic rocks in the Tulks Hill volcanic belt.*

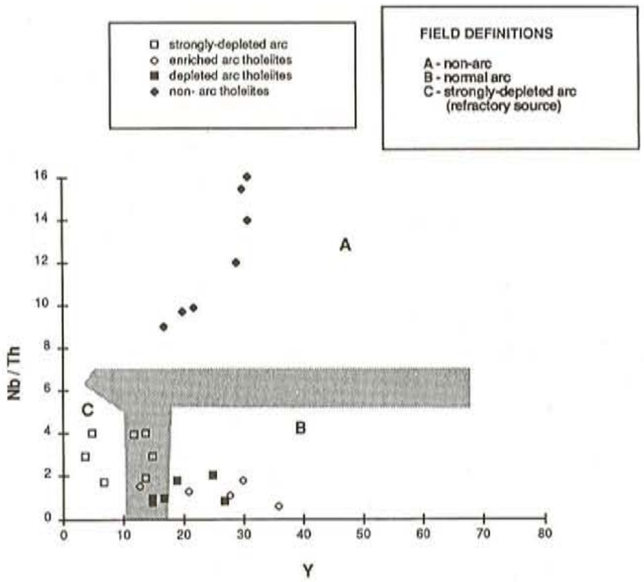

Figure 17. *Nb/Th versus Y plot for the Tulks Hill volcanic belt. Symbols are keyed to subdivisions illustrated in Figure 16.*

The data for the Diversion Lake group at the extreme northeastern end of the belt suggest that they are dominantly LREE-enriched non-arc tholeiites (Figure 18) and unlikely to be prospective.

WHERE ARE THE MASSIVE SULPHIDES?

In the five sequences studied, there are some obvious consistencies in the settings of volcanogenic sulphide deposition, as well as some significant differences. Some points of comparison are:

1) *Geochemical associations in the volcanic sequences:* A geochemical association that includes both rocks with arc signatures and those with non-arc signatures can be recognized in all areas. In two areas (the Wild Bight Group and the Betts Cove Complex), the field relationships are sufficiently well established to show that there is a geochemical progression upward through the stratigraphy from island-arc rocks to non-arc rocks and these sequences are interpreted to record the rifting of an island arc and the subsequent establishment of a back-arc basin. This interpretation serves as a model for other less well exposed or more structurally-disrupted sequences, where the elements of the model appear to be present but cannot be unequivocally related to each other, stratigraphically. The Lushs Bight–Western Arm groups, the Pacquet Harbour Group and the Tally Pond and Tulks Hill volcanics all contain elements of a similar tectonic transition. Because the units are not all the same age (Swinden *et al.*, 1988), island-arc rifting probably occurred more than once during the long history of Iapetus. By analogy with modern environments such as the southwest Pacific Ocean, it may have been a relatively common event.

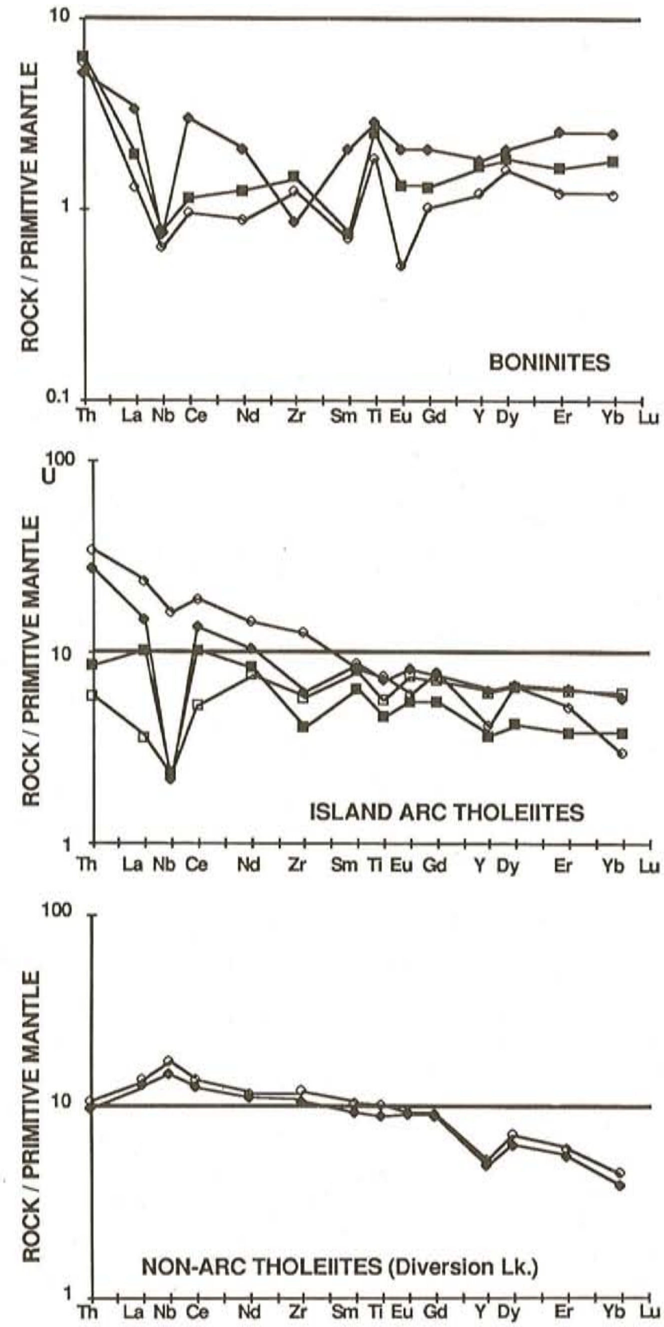

Figure 18. *Extended REE plots for volcanic rocks in the Tally Pond volcanics.*

2) *Geochemical association of VMS deposits:* Volcanogenic sulphide deposits are generally associated with rocks having a clear island-arc geochemical signature. From the preliminary studies reported here, and from studies of other sequences reported elsewhere (see review, Swinden, 1987), we are aware of only one exception, this being the Great Burnt Lake deposit in south-central Newfoundland (Swinden, 1988).

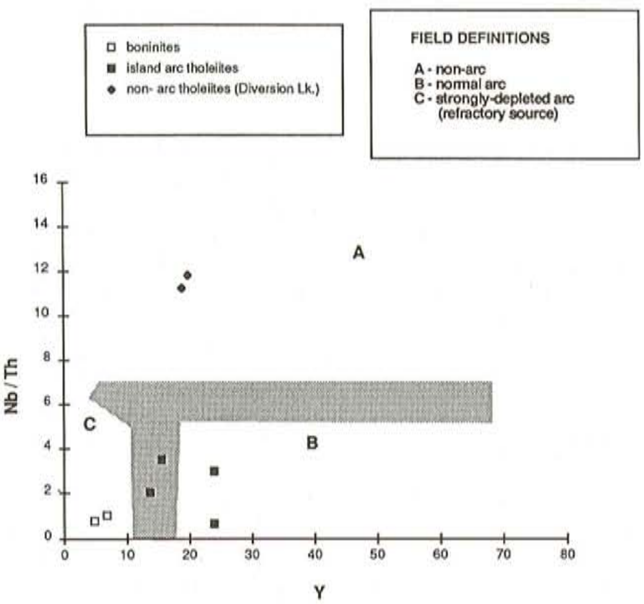

Figure 19. *Nb/Th versus Y plot. Symbols are keyed to subdivisions illustrated in Figure 18.*

3) *Paleotectonic setting of mineralization and association with refractory source melts:* It appears that in the central Newfoundland VMS districts, mineralization took place mainly during the arc-rifting stage. In all areas, volcanogenic sulphide deposits are spatially associated with highly incompatible element-depleted mafic lavas that must represent the product of complex hydrous remelting of refractory mantle sources. This association is not always intimate; in many cases, deposits are hosted by felsic volcanics (e.g., Point Leamington, and most deposits in the Tulks Hill and Tally Pond volcanics) or by normal arc-tholeiites (e.g., many deposits in the Lushs Bight Group). However, there are usually highly incompatible element-depleted lavas (i.e., refractory source melts) nearby. It would appear that although the presence of this type of magma is important to the mineralizing process, it is not always the host of the associated mineral deposits.

Clearly, the close association of these peculiar depleted rocks and volcanogenic sulphides implies a genetic connection. However, the exact nature of this genetic connection is by no means clear. A brief consideration of the contrasts between different mineralized settings may help constrain or eliminate some interpretations by eliminating from consideration processes that can not be demonstrated in all areas. These contrasts include:

1) *Stratigraphy of the mineralized sequences:* The Betts Cove Complex is an ophiolite. The Pacquet Harbour and Lushs Bight groups may also be derived from an ophiolite, as suggested by previous workers, although this cannot be unequivocally demonstrated. The Wild Bight and Victoria Lake groups are thick sequences of volcanic and volcaniclastic rocks. In the former, mafic rocks dominate the volcanic successions, with felsic volcanics restricted to small accumulations that make up less than 5 percent of the volcanics. In the latter, laterally extensive felsic volcanic sheets make up more than 35 percent of the volcanic succession.

2) *VMS host rocks:* Although generally associated with highly depleted mafic volcanic rocks, massive sulphides may be hosted by a variety of lithologies including felsic volcanics, normal arc-tholeiites and depleted rocks (see above).

3) *Spatial association with rhyolites:* Volcanogenic sulphides are closely associated with felsic volcanics in many areas (Wild Bight, Pacquet Harbour and Victoria Lake groups and the western part of the Lushs Bight Group). However, in the Betts Cove Complex and in the central and eastern parts of the Lushs Bight Group, there are no associated felsic volcanics.

4) *Diverse geochemical characteristics of refractory magmas:* The highly-depleted mafic volcanic rocks are not all of uniform geochemical characteristics. In the Betts Cove Complex and in the Pacquet Harbour Group, all have concave-upward REE patterns, positive Zr and negative Ti anomalies (on a normalized basis, see Figures 10 and 13) similar to boninites (similar rocks occur in the Sandy Lake belt of the Tally Pond volcanics). In the Wild Bight Group, they are tholeiitic, having peculiar and distinctive flat REE patterns with a step-up between Sm and Eu, negative Zr and positive Ti anomalies (Figure 4). In these two rock types, Zr and Ti have been decoupled from the REE during petrogenesis but apparently in a different fashion. The Lushs Bight Group contains both highly depleted tholeiitic rocks and boninite-like rocks, and both are associated with volcanogenic sulphide deposits.

GENETIC ASPECTS

In all the cases examined, VMS deposition occurred during a period of magmatic activity that is best interpreted as rifting of an island arc. This appears to be true irrespective of the nature of the host sequence, i.e., whether it is an ophiolite or a volcanic–volcaniclastic sequence. As previous authors have noted, rifting events of any kind provide an uncommonly good opportunity for volcanogenic mineralization (Sillitoe, 1982; Cathles *et al.*, 1983). This is particularly true in oceanic environments, where the rifting provides deep open fractures that enhance the permeability of the substrate, and promote deep access of sea water. The rifting is generally accompanied by crustal thinning, resulting in enhanced heat flow that may be an order of magnitude greater than in normal arc settings (Cathles *et al.*, 1983). The combination of high heat flow and enhanced permeability provides an ideal opportunity for enhanced hydrothermal circulation with concomitant metal transport and sulphide deposition (Cathles, 1983). The presence of volcanogenic mineralization in this setting in central Newfoundland is, therefore, entirely consistent with current concepts of island-arc metallogenesis.

In the sequences that have been studied, mineralization is spatially associated with rhyolitic volcanism. However, this does not seem to be a necessary condition in this environment, as deposits in the Lushs Bight Group and the Betts Cove Complex do not have associated rhyolite. Conversely, there are major accumulations of rhyolite in the Wild Bight Group that have no associated VMS deposits. This is in accord with the conclusions of Cathles (1978), Urabe and Sato (1978), Ohmoto (1978) and Cathles *et al.* (1983) who have suggested that rhyolite domes like those commonly associated with ore deposits in the Kuroko District, Japan, are probably too small to have had a cause and effect relationship with the VMS deposits. However, the formation of rhyolite through melting in the basal arc crust would undoubtedly be promoted by the anomalous heat flow and fluid circulation during the arc-rifting stage and, therefore, the association of rhyolites with VMS deposits is probably not fortuitous.

The unifying characteristic in all mineralized rifted arc settings in central Newfoundland is the presence of basalts that are best interpreted as hydrous melts of refractory sources. The tectonic and magmatic conditions that allowed these rocks to be erupted at surface are apparently both necessary and sufficient for VMS deposition in these settings.

This implies a genetic link between the refractory source melts and the VMS deposits. This genetic link may be the favourable tectonic environment for fluid circulation coupled with increased heat flow during ascent of these melts. Because the refractory source melts require so much heat of fusion, they must rise to the surface rapidly (or they would freeze on the way up), and probably do not pool in shallow magma chambers for extended periods. They probably make use of deep, throughgoing fractures related to the rifting to make their quick ascent to surface. The opening of fractures in this environment would promote additional heat flow irrespective of the rise of the hotter magmas. Because the bulk fluid/rock ratio in a sub-seafloor hydrothermal convection cell is dependant upon heat flux (among other things), this would result in increased fluid circulation, an expanded volume of rock that would see fluid at a temperature appropriate for leaching metals, and a corresponding increase in the amount of metal available to the system for eventual deposition at the surface. The fracturing related to rifting would also have the effect of focussing fluid flow on the up-flow side of the hydrothermal cell, allowing a greater volume of metal-charged fluid to reach the subsurface with the metals intact.

The overall effect would be an enhanced environment for the generation of VMS deposits. Geological intervals in which these refractory source melts occur are places where the chances of discovering a VMS deposit appear to be considerably enhanced. The combination of tectonic and hydrothermal circumstances that are extant during arc rifting, and particularly during eruption of very hot refractory source melts, are the necessary and sufficient conditions that make these environments so prolific.

This interpretation, is at odds with the models of Strong and Saunders (1988) for the deposits at Tilt Cove. Although the highly depleted melts may locally contain sulphide droplets, the connection between these sulphides and subducted metalliferous sediments seems tenuous and in most areas of the present study, there does not appear to be a sufficient volume of depleted mafic volcanic rock to have provided the metals to the associated massive sulphide deposits (this is particularly true in the Wild Bight Group). Although sulphides in the depleted magmas may contribute some metals to the hydrothermal system, there would seem to be no need to rely on them solely for enhanced metal concentrations in the hydrothermal cells. The increased heat in the rifted-arc environment, driving larger and hotter hydrothermal cells, is probably sufficient to account for the increased VMS production in this setting.

SUGGESTIONS FOR USE IN EXPLORATION

The presence of refractory source melts in oceanic volcanic sequences may be useful as a regional exploration tool for volcanogenic sulphides. We offer the following conclusions based upon our preliminary results:

1) The prime utility of whole rock geochemical studies is likely to be in the early stages of exploration in a volcanic belt. Geochemical studies of mafic volcanic rocks provide a rapid means of discriminating areas of high potential from those of lower potential within a given volcanic belt, or as a means of assigning exploration priorities when looking at more than one volcanic belt.

2) In order to make the best use of this approach, careful sampling and sample preparation techniques are required. It is essential that the rocks being sampled are correctly identified. Taking indiscriminant samples from a heterogeneous assemblage of mafic igneous rocks with no evidence as to whether they represent flows or intrusives will inevitably lead to considerable geological noise in the data and may yield incorrect interpretations. As a general rule, if the field evidence is not clear as to the origin of the rock, it is better not to sample it. Pillow lavas are the prefered sample lithology. In particular, the crystalline interiors of the pillows are the preferred sample medium as they are less likely to have experienced mass transport during alteration.

3) Analytical techniques must be chosen with care and closely monitored for accuracy and precision. In particular, the depleted volcanic rocks have trace-element concentrations that are well below reliable determination by routine analysis in commercial laboratories. To make most effective use of this technique, confidence in the data at very low detection limits is necessary.

4) Volcanic sequences in which the rocks have a non-arc signature can probably be assigned a very low exploration priority at this stage.

5) Within sequences where the rocks have an arc signature, the presence of highly depleted lavas (i.e., that plot in Field 'A' on the Nb/Th versus Y diagram) is a positive exploration indicator. Note that the VMS deposits may not necessarily be hosted by the depleted lavas. For example, the hydrothermal fluids may have vented in an area somewhat removed from the eruptive centres and lie upon a different volcanic rock. Alternatively, there may be a time gap between eruption of the depleted lavas and venting of the hydrothermal systems, with other volcanic or sedimentary rocks having been deposited in the interim. The important point is that the presence of these rocks appears to be a better than average indicator that the mineralizing process may have occurred, and that economic deposits may profitably be sought in the vicinity.

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