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# VOLCANOGENIC MASSIVE SULPHIDE (VMS) DEPOSITS OF THE NEWFOUNDLAND APPALACHIANS: AN OVERVIEW OF THEIR SETTING, CLASSIFICATION, GRADE-TONNAGE DATA AND UNRESOLVED QUESTIONS

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## ABSTRACT

*The Newfoundland Appalachians host more than 40 volcanogenic massive sulphide (VMS) deposits, and each contain >100 000 tonnes of sulphide-rich material. Collectively, they represent an aggregate geological resource of about 112 million tonnes (geological resource) with production and reserves of ~46 million tonnes. The VMS deposits are predominantly hosted by Cambrian–Ordovician volcanic-arc, arc-rift, and back-arc basin assemblages within the Dunnage Zone. The deposits are classified into three main groups,* i.e.*, mafic-type deposits (Cu-rich, mostly hosted by ophiolitic rocks), bimodal-mafic-type deposits (Cu–Zn rich, hosted by bimodal sequences dominated by mafic rocks) and bimodal-felsic-types (Zn–Pb–Cu-rich, hosted by bimodal sequences dominated by felsic volcanic rocks). Some bimodal mafic- and mafic-type VMS deposits are also enriched in precious metals, but many felsic-bimodal deposits also show significant Au and Ag enrichment.*

*There is a very good database from previous research on these VMS deposits, and this has influenced wider models for the genesis of such deposits. However, many unresolved questions remain, especially in the light of research work conducted over the last two decades elsewhere in Canada and around the world. This short paper is intended to highlight these gaps in our knowledge, with the objective of stimulating further applied research on both regional and local scales.*

## INTRODUCTION

Volcanogenic massive sulphide (VMS) deposits have made important contributions to the economic development of Newfoundland over more than a century. Examples include important past producers (*e.g.*, Tilt Cove, Rambler, and the Buchans deposits), developing producers (*e.g.*, the Duck Pond deposit) and new discoveries that have future production potential (*e.g.*, the Rambler footwall zone and the Boomerang deposits). Volcanogenic massive suphide (VMS) deposits in Newfoundland have also made a significant contribution to our understanding of regional and deposit-scale controls on the localization and genesis of VMS mineralization. For example, the stratigraphic and volcanic-facies studies of the Buchans orebodies (*e.g.*, Thurlow and Swanson, 1981) were some of the first studies to illustrate the influence of local stratigraphic environments on the locations of VMS deposits. Similarly, regional lithogeochemical studies of mafic volcanic rocks in central Newfoundland outlined key relationships between magma types, tectonics, and VMS deposit formation, which appear to be linked to episodes of arc-rifting (Swinden *et al.*, 1989, 1990; Dunning *et al.*, 1991; Swinden, 1991; Jenner and Swinden, 1993; Kean *et al.*, 1995; Evans and Kean, 2002). These concepts have been applied elsewhere, and similar results have been obtained, suggesting that they have wider applicability (*e.g.*, Kerrich and Wyman, 1997; Syme *et al.*, 1999). Lead-isotopic studies in Newfoundland first illustrated the roles that local basement terranes played in the metal budgets of VMS systems (Swinden and Thorpe, 1984). Isotopic studies of VMS deposits in other areas have yielded similar conclusions (*e.g.*, Thorpe, 1999; Mortensen *et al.*, 2006).

Although there is a long history of exploration for, and mining of VMS deposits in Newfoundland, research on these deposits has been relatively limited since 1990. During that time, knowledge of ancient VMS systems elsewhere, and of modern VMS systems associated with spreading centres and island-arcs has grown significantly (*e.g.*, Bailes *et al.*, 1998; Hannington and Barrie, 1999; Large *et al.*, 2001; Goodfellow *et al.*, 2003a; Ayer *et al.*, 2005; Colpron and Nelson, 2006). In recent years, interest in the Newfoundland district has grown in the wake of interesting new discoveries (*e.g.*, Boomerang) and the development of the

Duck Pond deposit, originally discovered in the 1980s. There has also been sustained interest in the Buchans area, although no significant discoveries have been made there (Winter and Wilton, 2001; Moore, 2003; Squires and Moore, 2004; Hinchey, *this volume*). Currently, there is a high level of exploration in the region, reflecting the high commodity prices for Cu, Zn and Au.

This short paper provides an overview of the regional setting of the VMS deposits of Newfoundland, in the context of modern classifications for such deposits and their environments (Barrie and Hannington, 1999; Franklin *et al.*, 2005). Although previous classifications (Swinden and Kean, 1988; Swinden, 1991) have stood the test of time, this approach simplifies comparisons with VMS deposits and districts in Canada and around the world. The second part of this paper poses a series of questions that currently remain unresolved for Newfoundland VMS deposits, and provide avenues for future research on both regional and deposit scales. Some of these questions and problems may have direct implications in terms of exploration models, whereas others are concerned more with genetic issues. These points are raised to stimulate discussion and perhaps focus attention for research studies planned by the author and by other interested parties.

## GEOLOGICAL SETTING

The Appalachian orogen in Newfoundland is divided into four tectonostratigraphic zones based on rock types, age, faunal attributes, geophysical signatures, and metallogeny (Figure 1; Williams, 1979; Williams *et al.*, 1988; van Staal, *in press*). From west to east, they are the Humber Zone, which represents the ancient, Laurentian continental margin, the Dunnage Zone, which represents a series of Cambrian to Ordovician arcs and back-arc basin assemblages, the Gander Zone, which is dominated by metasedimentary rocks sourced from the Gondwanan margin, and the Avalon Zone, which contains Neoproterozoic rocks overlain by Cambrian-Ordovician sedimentary rocks that have Gondwanan affinities. The Dunnage Zone is further subdivided into the Notre Dame Subzone and the Exploits Subzone (Williams *et al.*, 1988). The Notre Dame Subzone represents arc and back-arc related rocks that have peri-Laurentian affinities (Williams *et al.*, 1988; Waldron and van Staal, 2001; van Staal, *in press*), whereas the Exploits Subzone consists of arc and back-arc related rocks that have peri-Gondwanan affinities (Williams *et al.*, 1988; O'Brien *et al.*, 1997; van Staal, *in press*).

## DEPOSIT CLASSIFICATION AND GRADE-TONNAGE DATA

The Newfoundland Appalachians contains over 40 VMS deposits, each of which has >100 000 tonnes of massive sulphide, based on historical geological resources (Galley *et al., in press*). These deposits are hosted by rocks of the Dunnage Zone or its obducted, ophiolitic equivalents in the Humber Zone (Figure. 1).

The deposits have been classified by previous workers based primarily on their tectonic setting and host-rock types (e.g., Swinden, 1991; Evans and Kean, 2002). They have not previously been assessed in the context of modern classification schemes for VMS deposits (Barrie and Hannington, 1999; Franklin *et al.*, 2005; Galley *et al., in press*). On this basis, Newfoundland VMS deposits fall into three broad groups (*cf.,* Galley *et al., in press*) as indicated in Figure 1. These are as follows:

1. Deposits hosted primarily by mafic rocks of ophiolitic affinity (also known as "Cyprus-type" deposits). Examples include the York Harbour and Skidder deposits, and the important deposits of the Betts Cove Ophiolite and the Lushs Bight Group.

2. Deposits hosted in bimodal sequences of mafic and felsic rocks in which the mafic rocks are much more abundant than the felsic rocks. Examples include the important deposits of the Rambler Camp in the Pacquet Harbour Group, and also deposits in the Wild Bight Group. Although some of these deposits of this group are hosted by felsic rocks, the overall lithological environment is one of dominantly mafic volcanism.

3. Deposits hosted in bimodal sequences dominated by felsic volcanic rocks and lesser mafic rocks. Examples include the rich deposits of the Buchans Camp, and numerous deposits in the Victoria Lake Supergroup, including Duck Pond, Tulks and Boomerang.

In the following discussion, these three classes are denoted as "mafic", "bimodal-mafic" and "bimodal-felsic" deposits, respectively (*e.g.*, Barrie and Hannington, 1999; Franklin *et al.*, 2005).

The aggregate tonnage of all VMS deposits in the Newfoundland Appalachians is ~112 million tonnes. From this large resource, total production amounts to roughly 46 million tonnes (results calculated from the database of Galley *et*

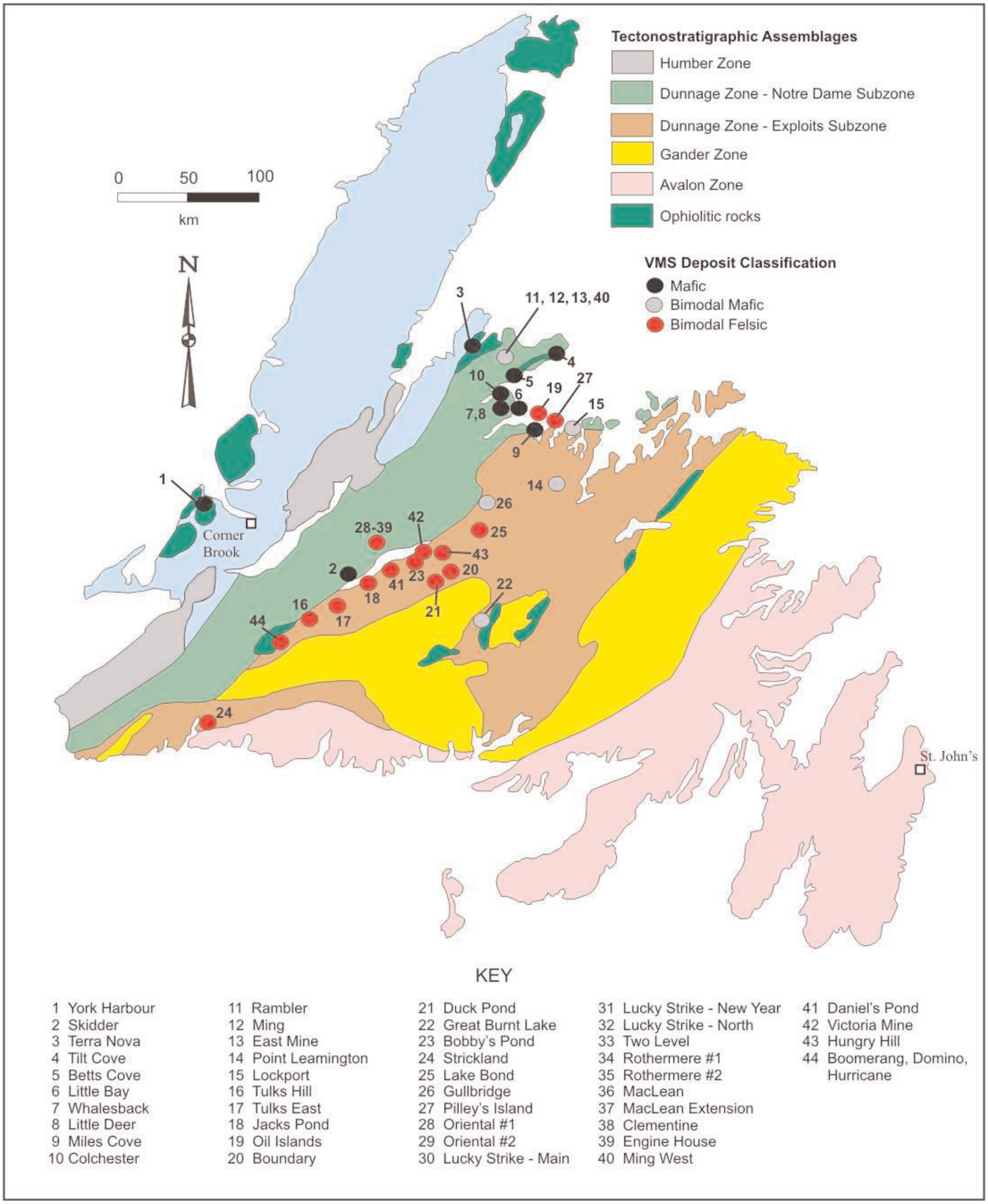


**Figure 1.** *Geological setting of the VMS deposits of the Newfoundland Appalachians modified from Swinden (1991) with tectonostratigraphic zones from Williams* et al. *(1988). Deposit classifications after Barrie and Hannington (1999) and Franklin* et al. *(2005). Classifications are from Galley* et al. (in press) *and modified by the author, where appropriate.*

*al., in press*). Figure 2 shows plots of tonnage versus aggregate base-metal grades and Au contents for the VMS deposits of Newfoundland, and some other prominent Canadian examples. Figure 3 shows the relative abundances of Cu, Pb and Zn, and relationships between Au, Ag and base metals. It is clear from the diagram (Figure 3) that aggregate base-metal grades are highest in the bimodal-felsic types of deposits (Figure 2), but this is partly skewed by data from the Buchans Camp, which are some of the highest grade VMS deposits anywhere in the world. The bimodal-felsic deposits are also enriched in Pb and Zn relative to the other deposit classes (Figure 3). The bimodal-mafic and mafic deposits have lower aggregate base-metal grades and higher relative Cu contents compared to the bimodal-felsic systems, as expected (Figures 2 and 3).

Gold grades are elevated in some of the VMS deposits in the Newfoundland Appalachians, particularly those of the Rambler Camp. The value shown for the Ming deposit is likely underestimated given new drilling results from the footwall zone at this deposit (Rambler Metals and Mining PLC, Press Release, Sept. 8, 2006). The highest gold grades come from deposits of the bimodal-mafic and mafic classes, but many of the bimodal felsic types also have Au grades up to 1 g/T. The Buchans deposits are in fact the largest Au producer, to date, in Newfoundland, having yielded some 713 000 ounces (Neary, 1981; Thurlow and Swanson, 1981). Recent results from deposits in the Victoria Lake Supergroup (*e.g.*, Boomerang) indicate that there is significant gold potential in other deposits within the bimodal-felsic class. (*e.g.*, Messina Minerals, Press Release, Oct. 4, 2006).

## UNRESOLVED QUESTIONS

There is an excellent database of research work on VMS deposits in the Newfoundland Appalachians, (*e.g.*, Swinden, 1991; Evans and Kean, 2002; Moore, 2003; Squires and Moore, 2004), which provides an important starting point for more detailed studies on both regional and local scales. However, in the light of knowledge gleaned from wider studies of VMS deposits and camps elsewhere in the world, there appear to be important gaps in our understanding. These are phrased below through a listing of unresolved questions.

1. What are metal inventories, in particular trace metals, in VMS deposits of the Newfoundland Appalachians? Can the minor-element compositions of the sulphide ores provide additional information for classification and subdivision of deposit types? Some insight into this has been provided by Santaguida and Hannington (1996), but much work is left to be done.

2. What is the cause of the Au enrichment in the Rambler camp deposits? Is the gold truly part of a syngenetic, VMS-related process, or was it introduced via a later epigenetic overprint?

3. Although the general classification of VMS deposits in Newfoundland outlined herein levels their classification to facilitate comparison to global deposits, it is at a rudimentary stage and will likely have to be refined in the light of further research and new data (*e.g.*, Hinchey, *this volume*). For example, the Victoria Lake Supergroup deposits are presently all classified as belonging to the bimodal-felsic group, but some of them are associated with abundant sedimentary and volcaniclastic rocks. There may be room for further subdivision of the classification as some of these deposits may represent a discrete type perhaps better termed "siliciclastic-felsic"-type deposits (*e.g.*, Hinchey, *this volume*).

4. The morphology and depositional mechanism for many VMS deposits in Newfoundland remain poorly known. There is certainly evidence for replacement-style sulphide deposition in deposits of the Victoria Lake Supergroup (Squires and Moore, 2004; Hinchey, *this volume*), and this mechanism may be more abundant than previously supposed. However, exhalative sulphide deposition is known to be important in other examples, and Buchans is well-known for its transported "debris-flow" ores (*e.g.*, Thurlow and Swanson, 1981). Detailed studies of individual deposits, with emphasis on drill-core examination, are required to examine the relationships between emplacement mechanisms and the morphologies of individual deposits.

5. Volcanic, intrusive, and sedimentary facies reconstructions of host sequences only exist for a few deposits (*e.g.*, Buchans). These types of reconstructions are required to understand what the facies controls on deposit formation are at both the regional and deposit scales. Detailed data of this type will also help to constrain the depositional environment of the sulphide bodies themselves, as outlined above.

6. Studies elsewhere indicate an important role for subvolcanic intrusions and intrusive complexes in generating heat for hydrothermal fluid circulation and contributing directly to the metal budgets of hydrothermal systems (*e.g.*, Campbell *et al.*, 1981; Large *et al.*, 1996; Galley, 2003). To date, this aspect of VMS formation has not been investigated for many Newfoundland examples.

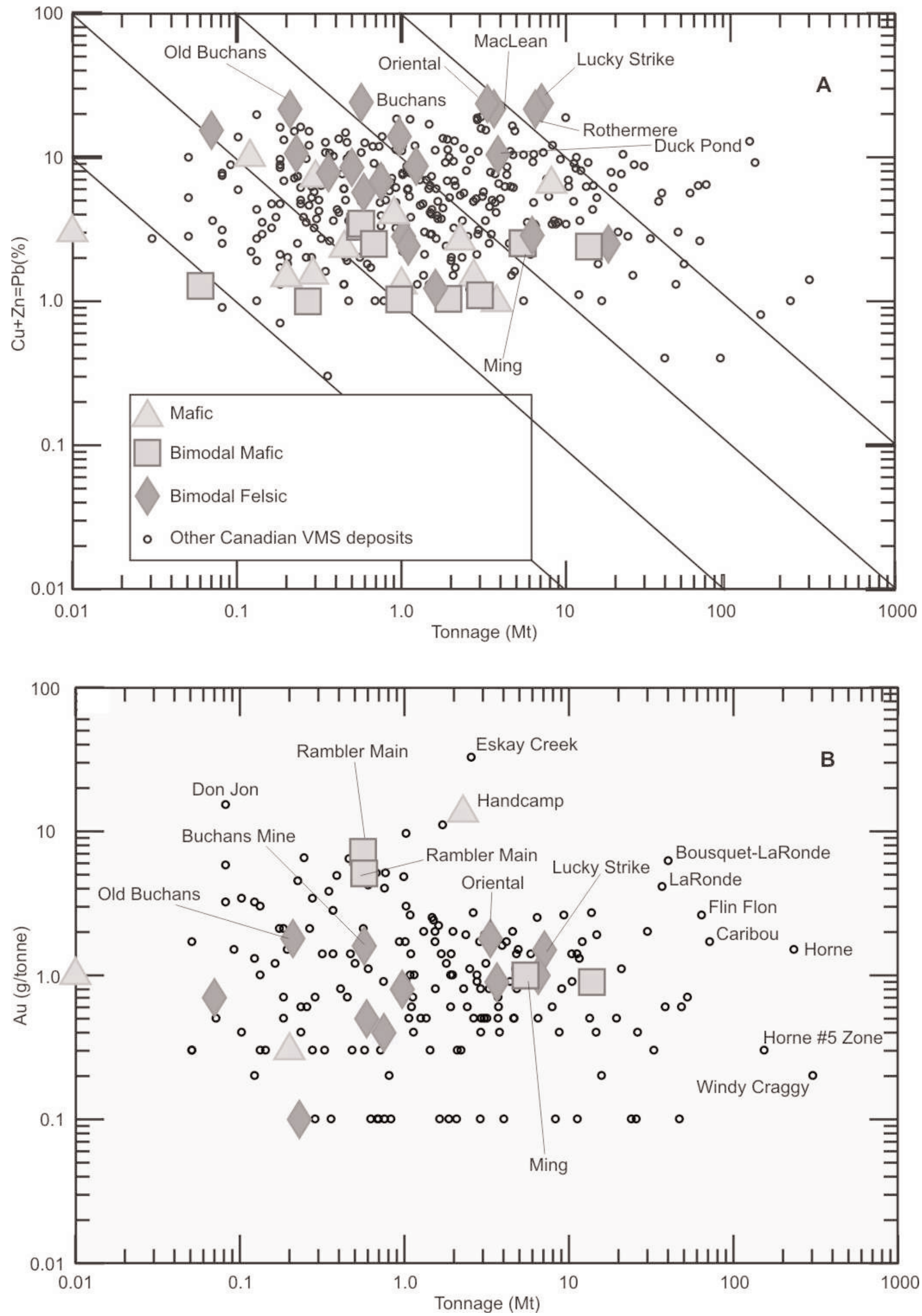


**Figure 2.** *Grade-tonnage data for VMS deposits of the Newfoundland Appalachians (data from Galley* et al., in press*; geological resources, not NI-43-101 compliant). (A) aggregate base-metal contents versus tonnage. (B) Au-grade versus tonnage. Data for other significant Canadian Au-bearing VMS systems are also shown.*

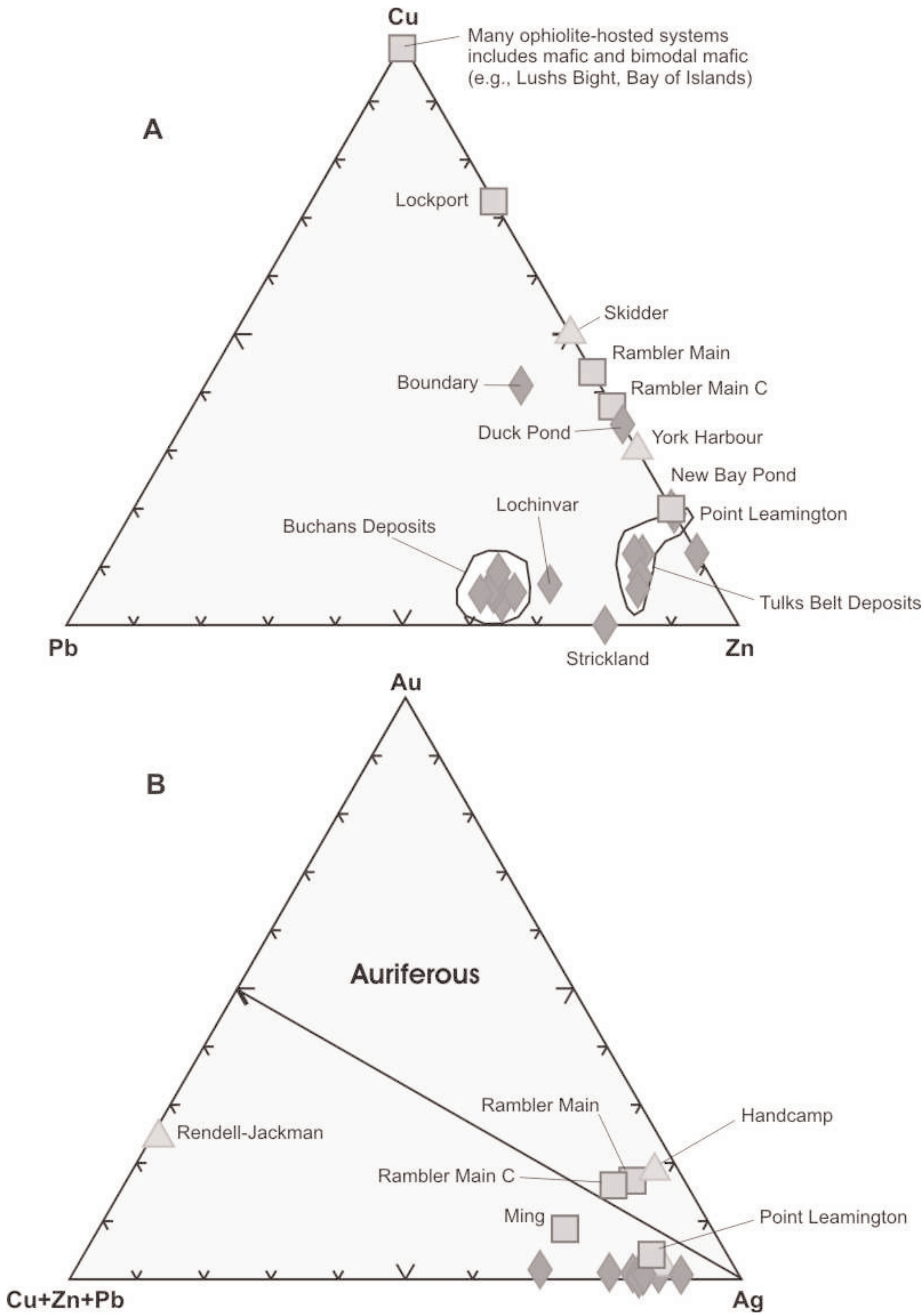


**Figure 3.** *Lead–Zn–Cu (A) and base-metal–Au–Ag (B) ternary plots for VMS deposits of the Newfoundland Appalachians. Diagram (B) after Hannington* et al. *(1999).*

7. It is now known that there are VMS systems that represent "hybrid" environments such as VMS-SEDEX (*e.g.*, the Bathurst #12. N.B., and Wolverine, Yukon, deposits) or VMS-epithermal (*e.g.*, the Eskay Creek deposit, B.C.). Such deposits are often precious metal-enriched, high-grade and polymetallic, and some of them are extremely large (*e.g.*, Neves Corvo, Portugal). They have immense value and represent extremely

attractive targets. Does the diverse inventory of VMS deposits in Newfoundland include potential examples of such hybrid deposit types?

8. The regional and local hydrothermal alteration systems associated with Newfoundland VMS deposits are not well understood. These require detailed surface mapping and particularly assessment in three dimensions using drill-core data. The objectives of such work would be to outline regional (semi-conformable) and proximal (pipe-like) alteration systems (*e.g.*, Galley, 1993; Franklin *et al.*, 2005). Knowledge of zonation within alteration systems would allow explorationists to use lithogeochemical and mineralogical data as a vectoring tool in detailed exploration.

9. There are large amounts of data concerning the geochemistry of the mafic volcanic rocks and their potential relationships to VMS mineralization in the Newfoundland Appalachians (Swinden, 1991). Although there is some information on the geochemistry of felsic volcanic rocks (*e.g.*, Winter and Wilton, 2001; Squires and Moore, 2004) much remains to be learned in this respect, especially as many deposits are hosted by felsic volcanic rocks (*e.g.*, Rambler, Buchans). There is abundant research on the characteristics of felsic volcanism associated with VMS mineralization in similar settings elsewhere (Lesher *et al.*, 1986; Lentz, 1998; Syme, 1998; Piercey *et al.*, 2001; Hart *et al.*, 2004), and the results of these studies may be useful in research and exploration for both mafic-bimodal and felsic-bimodal deposit types.

10. Non-traditional lithogeochemical exploration media (*e.g.*, exhalites, iron formations, shales) have proved useful in other VMS camps as vectors to mineralization (*e.g.*, Peter and Goodfellow, 1996; Goodfellow *et al.*, 2003b; Peter, 2003). Some work of this type was undertaken in Newfoundland many years ago by Dean and Meyer (1982), but regional studies of such potential "distal indicators of mineralization" have yet to be applied throughout the district.

11. There is an outstanding database of geochronology, geochemistry, and isotopic data for the volcanic rocks of the Newfoundland Appalachians, but the precise ages for the host sequences to individual VMS deposits are not always known with certainty. More detailed geochronological information may be useful in refining the general classifications suggested in this note.

## SUMMARY CONCLUSIONS

The VMS deposits of the Newfoundland Appalachians have a long history of production and exploration, and there is an impressive database from previous research, which has contributed significantly to our wider understanding of VMS systems. However, many questions remain regarding the classification, settings, style, and genesis of these deposits. The new exploration results and recent scientific studies from central Newfoundland indicate that there is much wealth left to be found, and much insight left to be learned. The questions posed in this short paper provide a possible framework for targeted research that may assist in the evaluation of mineral potential, and perhaps also of direct value in exploration programs.

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