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A DISCUSSION OF CONTROLS ON MAGMATIC BASE-METAL MINERALIZATION, WITH APPLICATION TO NORTHERN LABRADOR

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ABSTRACT

Two seasons of exploration activity in northern Labrador have detected widespread sulphide mineralization of broadly magmatic character, but have yet to locate an ore-deposit cluster comparable to that of the Voisey's Bay discovery. However, the fortuitous preservation of the Ovoid deposit at the erosion surface has had an important influence on project development at Voisey's Bay. The rapid discovery of two orebodies obscures the fact that magmatic Ni–Cu–Co deposits, despite immense potential value, represent small and difficult exploration targets, which (if deeply buried) require a large component of geological reasoning to discover. There are several critically important geological controls on such deposits, including the generation of a primitive magma under S-undersaturated conditions, rapid ascent, probable contamination with crustal sulphur at exactly the right stage in fractionation history, and the interaction of immiscible sulphide and silicate liquids in suitable proportions in the right physical environment. The preservation of the host intrusions at the correct erosion level is also essential if such deposits are to be found and exploited. Although superficially simple, the development of a magmatic Ni–Cu–Co deposit involves a complex interplay of geological processes, all of which must be appreciated in evaluating newly discovered mineralization, and planning further exploration programs here, and elsewhere in the province.

INTRODUCTION

The discovery of a world-class Ni–Cu–Co deposit at Voisey's Bay, south of Nain, Labrador, has had an enormous impact on mineral exploration in this province and across Canada. A staking rush started in the winter of 1995, and the 1995 and 1996 field seasons saw levels of exploration activity unprecedented in Labrador's history. Much of this exploration took place in areas that have never been systematically mapped or prospected, and numerous new mineral occurrences have been discovered since the summer of 1995. Several of these discoveries have now become the focus of more detailed and extensive exploration programs including diamond drilling.

In view of the limited background information for many areas of interest, the Geological Survey has initiated a metallogenic research project to provide a framework for regional exploration, and aid in the development of predictive genetic models. Activity for 1996 was focused in the Nain area, and consisted of initial field examination, mapping, sampling, and examination of diamond-drill core. Future activities will include more detailed work in the Nain area, coupled with expansion into other areas of Labrador with potential for magmatic sulphide mineralization.

At the time of writing, data collected in 1996 has yet to be fully assessed and the results of field and laboratory work undertaken by the exploration companies remains mostly confidential. For these reasons, it is not possible to present a detailed geological report. Instead, this article provides a brief review of the essential characteristics of the Voisey's Bay deposits, as revealed by recent publications, and discusses the controls on the formation of such magmatic sulphide deposits, and the possible application of models and geological reasoning in exploration of northern Labrador. One of the purposes of this discussion is to outline some of the directions that the metallogenic research project will take. A companion article (Kerr and Smith, *this volume*) presents a general overview of developing Ni–Cu–Co exploration properties, based on public-domain information contained in press releases, coupled with regional geological observations.

TARGET DEFINITION: THE VOISEY'S BAY DEPOSITS

REGIONAL GEOLOGY

All the regions of Labrador have seen increased mineral exploration activity since the staking rush of early 1995. The most intense activity has been within the Mesoproterozoic

Nain Plutonic Suite and equivalent rocks between Seal Lake (south of Figure 1) and Okak Bay (Figure 1). This reflects the association of ore deposits at Voisey's Bay with the Reid Brook Intrusion, considered to be a mafic member of the Nain Plutonic Suite (Ryan *et al.*, 1995).

The area includes parts of the Archean Nain Province, and the Archean to Paleoproterozoic Churchill Province, represented by the deeply eroded Torngat Orogen. Both regions are dominated by high-grade metamorphic rocks, but have very different origins and geological histories. The Nain Province is dominated by tonalitic to granodioritic orthogneisses, including rocks older than 3.8 Ga. These include minor remnants of Archean supracrustal rocks, of both igneous and sedimentary origin, and are overlain unconformably by Paleoproterozoic supracrustal sequences of the Ramah and Mugford groups (Figure 2). The Churchill Province includes orthogneisses of similar appearance in the west, but adjacent to its boundary with the Nain Province, is dominated by paragneisses (termed the Tasiuyak gneiss) derived from clastic sedimentary rocks. The Nain–Churchill boundary is abrupt on a regional scale, but there are many local complexities and uncertainties in positioning it, particularly where the distinctive Tasiuyak gneiss is absent (Ryan, 1996). The Nain and Churchill provinces were juxtaposed along this boundary by about 1.84 Ga, and the boundary region was a sinistral shear zone. Mainly undeformed Mesoproterozoic plutonic rocks, emplaced from about 1.35 to 1.29 Ga, transgress the Nain–Churchill boundary zone. These include the Nain Plutonic Suite, extending from Okak Bay to Davis Inlet, and the Harp Lake and Mistastin complexes, to the south and west, respectively (Figure 1). The Nain Plutonic Suite consists of four broad groups of plutonic rocks (Emslie *et al.*, 1994; Ryan *et al.*, 1995). The most abundant (over 90 percent by areal extent) are massive anorthosites and K-feldspar-rich granitoid rocks. Variably layered mafic intrusions of broadly troctolitic composition, and Fe-rich diorite to monzonite plutons make up the rest (Figures 1 and 2).

LOCAL GEOLOGY

The area around the Voisey's Bay deposits is dominated by orthogneisses of the Nain Province in the east, and by the metasedimentary Tasiuyak gneiss of the Churchill Province in the west (Figures 1 and 2). The Nain–Churchill boundary is interpreted to lie somewhere in the vicinity of the deposits, but its exact position is debatable (Ryan and Lee, 1989; Ryan *et al.*, 1995; Ryan, 1996). In the east, the Archean gneisses are intruded by layered to massive troctolite of the Reid Brook intrusion, which forms an elongate fault-dissected outlier interpreted to be the base and feeder zones of a mainly eroded layered mafic intrusion (Ryan *et al.*, 1995). The original discovery showing at Voisey's Bay is within an east–west-trending troctolitic dyke, assigned to the Reid Brook intrusion, which intrudes Archean gneisses. To both the east and the west, the gneisses and rocks equated with the Reid Brook intrusion are intruded by younger anorthosites and granites. The Makhavinekh Lake granite to the west includes rafts of Reid Brook-like material, and has been dated at 1322 Ma. This implies that the Reid Brook intrusion represents an early component of the Nain Plutonic Suite, in contrast to the well-preserved Kiglapait and Newark Island layered intrusions, dated at around 1305 Ma (see Ryan *et al.*, 1995).

THE VOISEY'S BAY SULPHIDE DEPOSITS

There are two main orebodies defined at Voisey's Bay, and several other areas of mineralization are under active exploration (Sparkes *et al.*, 1995; Naldrett *et al.*, 1996; Ryan, *in press*). The disposition of the sulphide deposits is illustrated schematically in Figure 3.

Initial exploration focused on the area around Discovery Hill, where sulphide mineralization is hosted within an east–west-trending, north-dipping dyke-like troctolite body. Exploration then shifted eastward to a prominent coincident magnetic–conductivity anomaly, where the seventh drillhole intersected 104.3 m of massive sulphide. This drillhole penetrated the central part of the "Ovoid Deposit", which has now been defined as a high-grade, bowl-shaped body containing 31.2 million tonnes grading 2.83% Ni, 1.74% Cu and 0.12% Co. Located just below the erosion surface, close to tidewater, and shaped like an open-pit mine, the Ovoid is a remarkable orebody, and its contained metals have a value exceeding US$10 billion (1996 prices). The Ovoid deposit sits upon the "Basal Breccia Sequence", which consists of fragments of basement gneiss, troctolite and peridotite within sulphide-bearing troctolite. This in turn sits upon Archean basement gneisses, but is locally absent, in which case massive sulphides are in direct contact with basement. The ore consists of coarsely crystalline pyrrhotite ($Fe_{1-x}S$), pentlandite ($[FeNi]_9S_8$) and chalcopyrite ($CuFeS_2$), containing dispersed magnetite beads.

In an article written in late 1994, Ryan *et al.* (1995) stated:

".....there is the probability that sulphide may underlie the massive troctolitic rocks directly east of the mineralized dyke."

In October, 1995, this prediction was verified by an intersection of 32 m grading 1.47% Ni, 0.67% Cu and 0.07% Co, within a wider 287 m interval grading 0.44% Ni, 0.22% Cu and 0.02% Co (Diamond Fields Resources, press release, November, 1995). This marked the discovery of the Eastern Deeps deposit, now outlined as an elongate, tabular body of massive sulphide, located along the basal contact of the Reid Brook troctolite, from 600 to 1000 m below surface outcrops

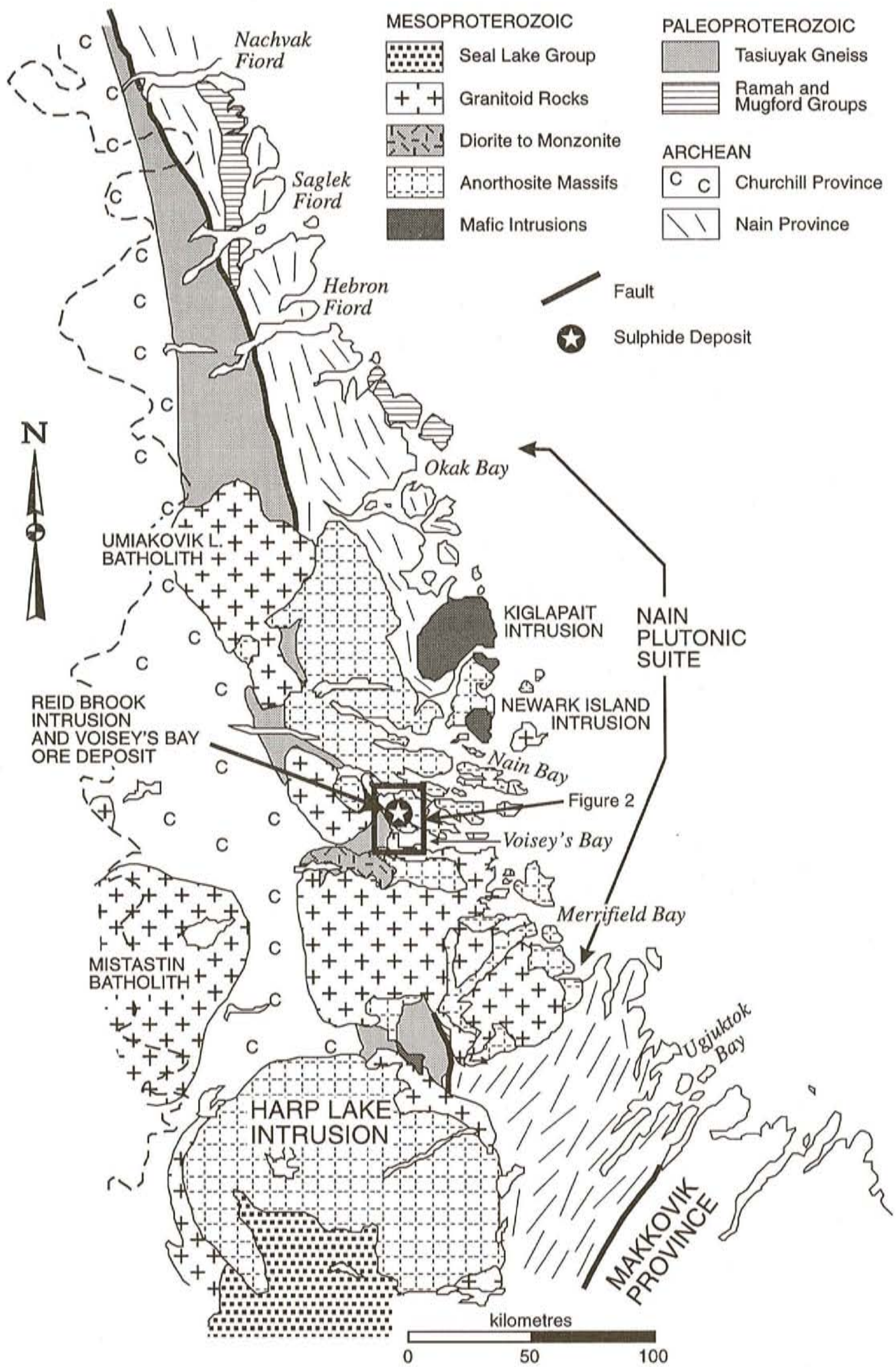

Figure 1. *Geological map of northern Labrador (mostly Nain and Churchill provinces) showing the location of the Voisey's Bay deposits and area of most intense exploration activity.*

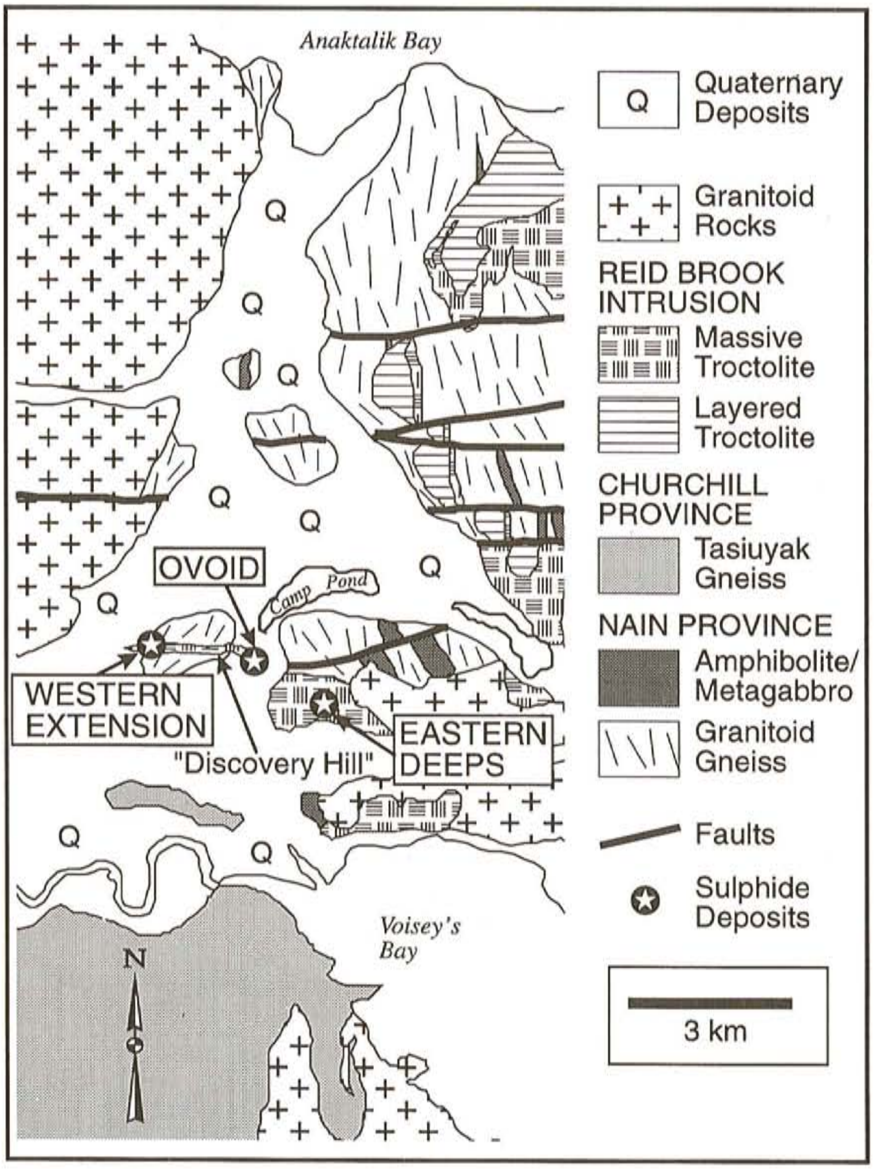

Figure 2. *Geological map showing details of local geology in the area around the Voisey's Bay deposits (after Ryan* et al., *1995).*

of unmineralized troctolite (Figure 3). Although the area of the Eastern Deeps is coincident with a positive magnetic anomaly, this is not readily separated from regional variations related to local rock types. The ore zone sits above complex basal breccias akin to those beneath the Ovoid, and is overlain by troctolites containing variable amounts of disseminated sulphide (Naldrett *et al.*, 1996). Continued deep drilling has shown that the troctolite intrusion is connected at depth to a north-dipping dyke-like body that probably represents a feeder system, with similarities to the Discovery dyke (Naldrett *et al.*, 1996). Sulphide ore in the Eastern Deeps resembles the material from the Ovoid, but pentlandite is finer grained, and the ore contains variable amounts of silicates. The reserves in the Eastern Deeps have been released as 50 million tonnes at 1.36% Ni, 0.67% Cu and 0.09% Co (INCO, press release, September, 1996), but total resources of 100 million tonnes or more appear probable. The Eastern Deeps deposit remains open at depth to the east (as of late 1996).

GENETIC MODELS FOR THE VOISEY'S BAY DEPOSITS

It was clear at an early stage that the Voisey's Bay sulphide deposits were of magmatic origin, and very likely related to the Reid Brook intrusion. Following observations from other well-known magmatic sulphide deposits (e.g., *see* Naldrett and MacDonald, 1980; Lightfoot and Keays, 1994), a preliminary genetic model was suggested by Ryan *et al.* (1995). Subsequently, Naldrett *et al.* (1996) and Ryan (*in press*) have outlined a genetic model that incorporates many

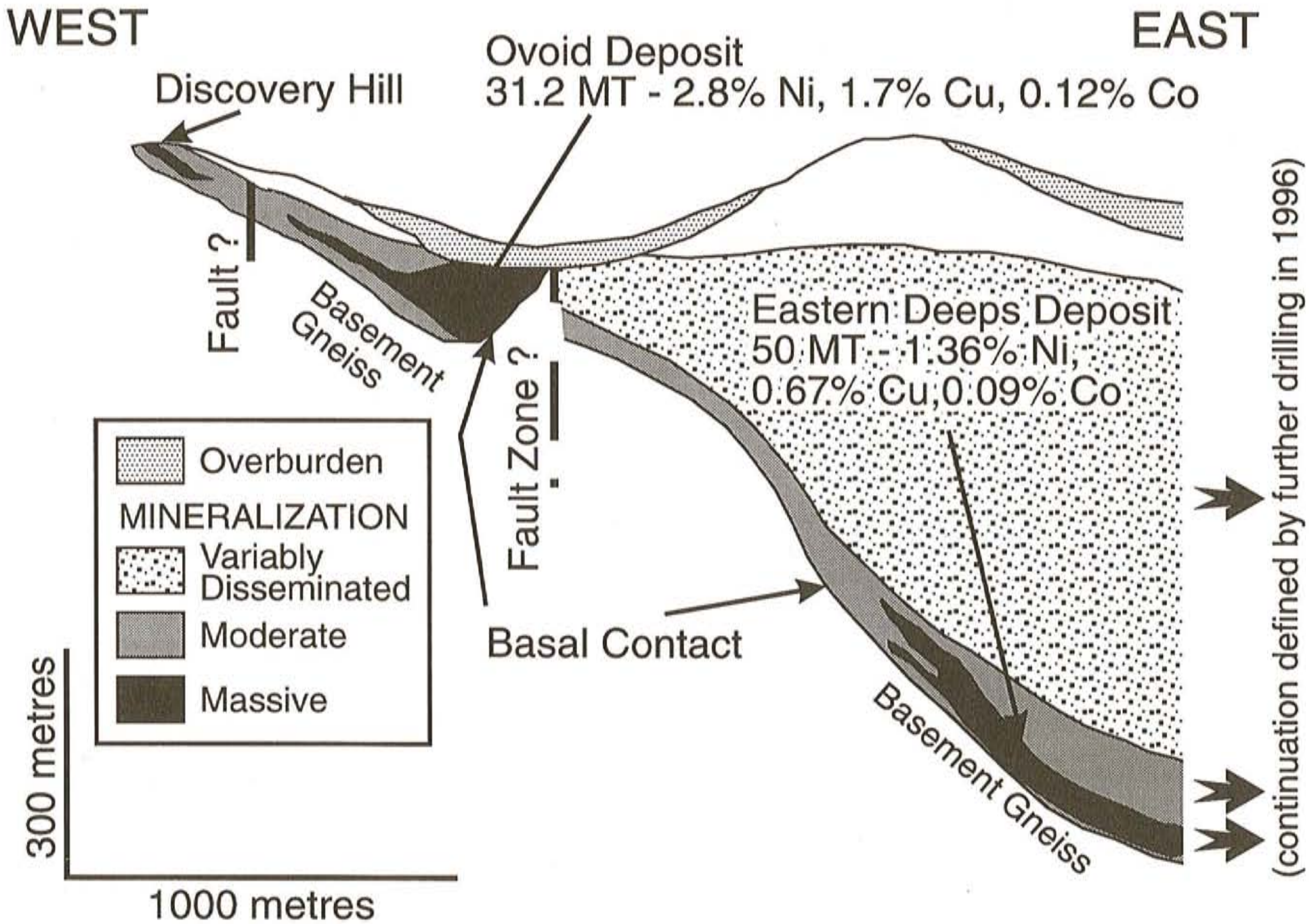

Figure 3. *Cross-section sketch in approximate east-west orientation, through the Voisey's Bay deposits and nearby rock units. (Adapted from Diamond Fields Resources press release, January 5th, 1996.)*

of the same concepts. This working model for the Voisey's Bay deposits is summarized below, to provide a framework for discussion in the remainder of this article.

A key element in these models is that the various settings of mineralization at Voisey's Bay represent different erosion levels of the same magma chamber and its related "plumbing" (Figure 4). The Discovery Hill dyke and nearby "Western Extension" are viewed as sections through the feeder conduit to the Reid Brook intrusion, which carried troctolitic magma and immiscible sulphide liquid. The Eastern Deeps is considered to represent the lower region of the magma chamber, where sulphide liquid accumulated along the basal contact, and the Ovoid represents a similar setting, possibly associated with a topographic "trap" in the basal contact. Fortuitously, erosion has removed the troctolite that originally overlay the Ovoid (and possibly also significant quantities of ore). The present disposition of the various crustal levels of the Reid Brook intrusion may reflect original geometry, block faulting, or a combination of both effects. The localization of mineralization is viewed as a product of changes in fluid dynamic regimes from turbulent (in the feeder system) to stagnant (in the magma chamber). The dense sulphide liquids and entrained country rock and cognate fragments settled out close to the entry point of the feeder system in a manner analogous to the deposition of sediment at a stream delta (Naldrett *et al.*, 1996).

In a wider sense, Ryan *et al.* (1995) suggest that the Reid Brook intrusion represents a primitive mantle-derived magma derived by extensive partial melting of the mantle at an early stage in the formation of the Nain Plutonic Suite. Ultramafic and mafic magmas of this type are typically sulphur-undersaturated, and Ni, Cu and Co are typically absorbed into silicate phases such as olivine and pyroxene, which crystallize at an early stage in fractionation. The development of a sulphide liquid was attributed to assimilation at depth of the sulphide-bearing Tasiuyak gneiss. Direct evidence for incorporation of such material is provided by distinctive spinel-bearing aluminous fragments observed in the basal breccia sequence (Naldrett *et. al.,* 1996). Under suitable circumstances (*see* later discussion) a sulphide liquid can

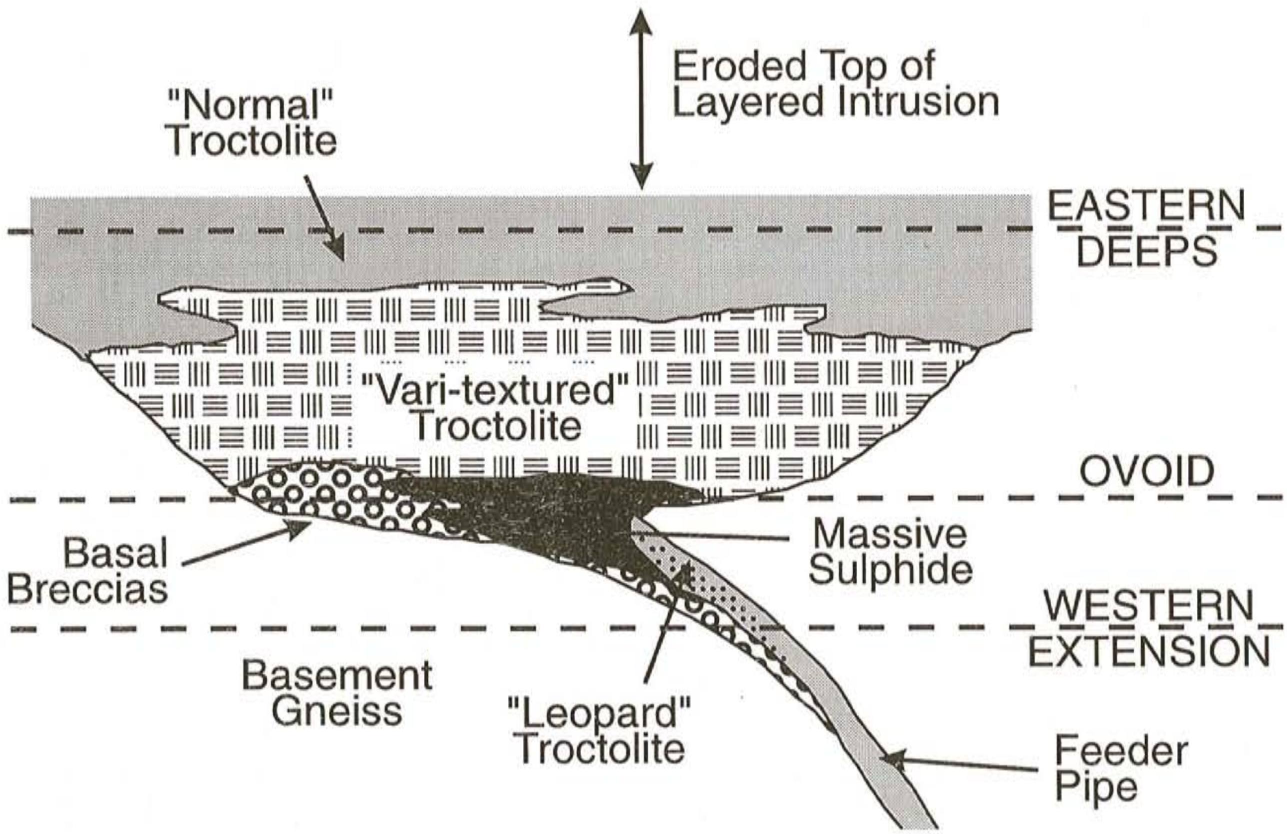

Figure 4. *Conceptual model of the Reid Brook troctolite intrusion and associated Voisey's Bay ore-forming system, showing the inferred erosion levels of the Western Extension, Ovoid Deposit and Eastern Deeps Deposit (after Naldrett* et al., *1996).*

extract large quantities of Ni, Cu and Co from an associated silicate magma. Faults associated with the crustal-scale Paleoproterozoic shear zone associated with the Nain–Churchill boundary are suggested to have provided conduits that allowed rapid ascent of mafic magmas with associated sulphide liquids to suitably high crustal levels, where they could accumulate in suitable "traps" (Ryan *et al.*, 1995; Ryan, *in press*).

THE IMPORTANCE OF THE OVOID DEPOSIT

The Voisey's Bay Ovoid deposit is an incredible orebody, and its discovery at an early stage in the exploration process, after only seven drillholes, had important consequences for the project. Most importantly, it secured the capital required to continue and expand a high-cost exploration program, and conduct the deep stratigraphic drilling program that led to the Eastern Deeps discovery. From a geological perspective, the recognition of the setting of the Ovoid deposit, and its relationship to Archean country rocks, provided the rationale for drilling deep holes collared in barren troctolite to the east. On a regional scale, this same reasoning opens up large areas of the known Reid Brook intrusion to deep exploration in the years to come.

But what if the Ovoid deposit was *not* present, or *not* preserved? The interpretation of various mineralization settings as differing erosion levels of a single system (Figure 4) clearly raises this possibility; for example, if the interpreted fault block containing the Ovoid (Figure 3) had been up-thrown by a few hundred metres more, the entire deposit would have long been eroded. In such a scenario, the Voisey's Bay property would consist of a high-grade but relatively small prospect at Discovery Hill, and a large, blind, orebody hidden beneath up to a kilometre of barren rock. Although the geological link would probably still have been made, would there have been sufficient resources to eventually locate the Eastern Deeps?

The above may seem like idle speculation – after all, the Ovoid *does* exist – but it is important in the context of the other exploration programs in northern Labrador, where these exact circumstances may apply. The preservation of any orebody at mineable depths is fortuitous, and the preservation of most of the Ovoid just below the erosion surface is unusually so. Every junior exploration company working in northern Labrador wants to find another Ovoid deposit, but the Eastern Deeps represents a more likely model target – i.e., a large, blind orebody overlain by barren intrusive rocks, with very limited (if any) surface geophysical or geochemical expression. Fundamentally, the Eastern Deeps is a target that requires a high component of geological reasoning and logic.

Target Size

The physical dimensions of the Voisey's Bay orebodies are relatively small, which is a direct consequence of their high grade and high density. A tonne of massive sulphide ore from Voisey's Bay (calculated density about 4.6 g/cm^3) would be represented by a block only 60 cm (2 ft) on each side, about the size of an average packing carton.

From an exploration perspective, the most important constraint on target size comes from the processes involved in forming the deposits. The orebodies are products of high-temperature (>1000°C), andydrous, magmatic processes. In this respect, they are entirely different from other major sources of base metals, notably porphyry and volcanogenic massive sulphide (VMS) deposits, which are formed through the actions of hydrothermal fluids. Porphyry and VMS deposits are both characterized by zones of alteration and low-grade mineralization that are up to two orders of magnitude larger in size than the actual orebodies. Although alteration introduces its own set of geological problems, it vastly increases the target size, and, through variations in character and intensity, provides directional indications that can be used to target exploration. In contrast, the size of the target for a magmatic sulphide deposit is essentially defined by the orebody alone. Thus, a typical VMS deposit containing 5 to 10 million tonnes of sulphide ore forms an exploration target as much as 10 times larger than the Eastern Deeps. The Ovoid deposit alone contains as much copper as many mid-size porphyry deposits, and its total metal value approaches even the largest, but it is a miniscule exploration target, at least two orders of magnitude smaller. Although its near-surface location generated a small but loud geophysical anomaly, this would be greatly muted if it were covered by a few hundred metres of variably magnetic rock.

To summarize, magmatic sulphide deposits of the Voisey's Bay type, despite their immense potential value, represent small and difficult targets that require a large component of geological reasoning, in addition to the powerful geophysical imaging techniques available to today's explorationist. This is so even in areas with detailed mapping coverage and a history of exploration and development for such deposits, and doubly so in areas like that north of Nain, which have never been systematically mapped or explored. It is against this background that the results of two years of exploration in northern Labrador, which resulted in the discovery of numerous new Ni and Cu occurrences, should be assessed.

CONTROLS ON THE FORMATION OF MAGMATIC SULPHIDE DEPOSITS

The recognition of Voisey's Bay as a magmatic Ni–Cu deposit places it in a family of world-class deposits including the Sudbury Basin, the Bushveld Complex, the Noril'sk area of Siberia, the Kambalda area of Australia and Jinchuan of China (e.g., Naldrett, 1989a). Although diverse in detail, deposits of this type share common threads in regional setting and evolution. These, and the ideas summarized above for the Voisey's Bay deposits (Ryan *et al.*, 1995; Naldrett *et al.*, 1996), have been used as guides in exploration through 1995 and 1996. This section of the article summarizes and discusses factors that control the formation and localization of such deposits, and the degree to which current genetic models can, or should, be applied. It also highlights directions that will be considered in research under this project.

COMPOSITIONAL CHARACTERISTICS OF HOST INTRUSIONS

The association of the Voisey's Bay deposits with a troctolitic intrusion has influenced exploration strategies in northern Labrador. "Troctolite" has become almost a mantra in press releases, with the implication that it represents the most favourable host. In the International Union of Geological Sciences (IUGS) mafic rock classification (Figure 5a; Streckeisen, 1975), troctolite is defined as a rock consisting essentially of plagioclase and olivine, with less than 5 percent modal (clinopyroxene + orthopyroxene). The name is a very poor definition, in that it includes everything from rocks with 90 percent olivine and 10 percent plagioclase (essentially dunites) to rocks with 90 percent plagioclase and 10 percent olivine (essentially anorthosites). These extremes are obviously very different in origin, composition and nickel content. When present in small quantities, olivine is very difficult to identify in the field, and it is also likely that the term "troctolite" has been widely misused. Even if used accurately, it has doubtful genetic significance, as most troctolites are probably cumulate rocks, and olivine–gabbro and olivine–norite are equally favourable as host intrusions for Ni deposits. The presence of olivine may be an important factor, as it is characteristic of the early fractionation history (Figure 5b), when Ni contents in magmas remain relatively high, but it is by no means an absolute requirement. The closed-system fractionation of mafic magmas, as exemplified by localities such as the Palisades Sill in New Jersey (Figure 5b), commonly includes a feature called the "olivine gap", where ortho- and(or) clinopyroxene replace olivine as the dominant liquidus phases. Although previous olivine removal will re-

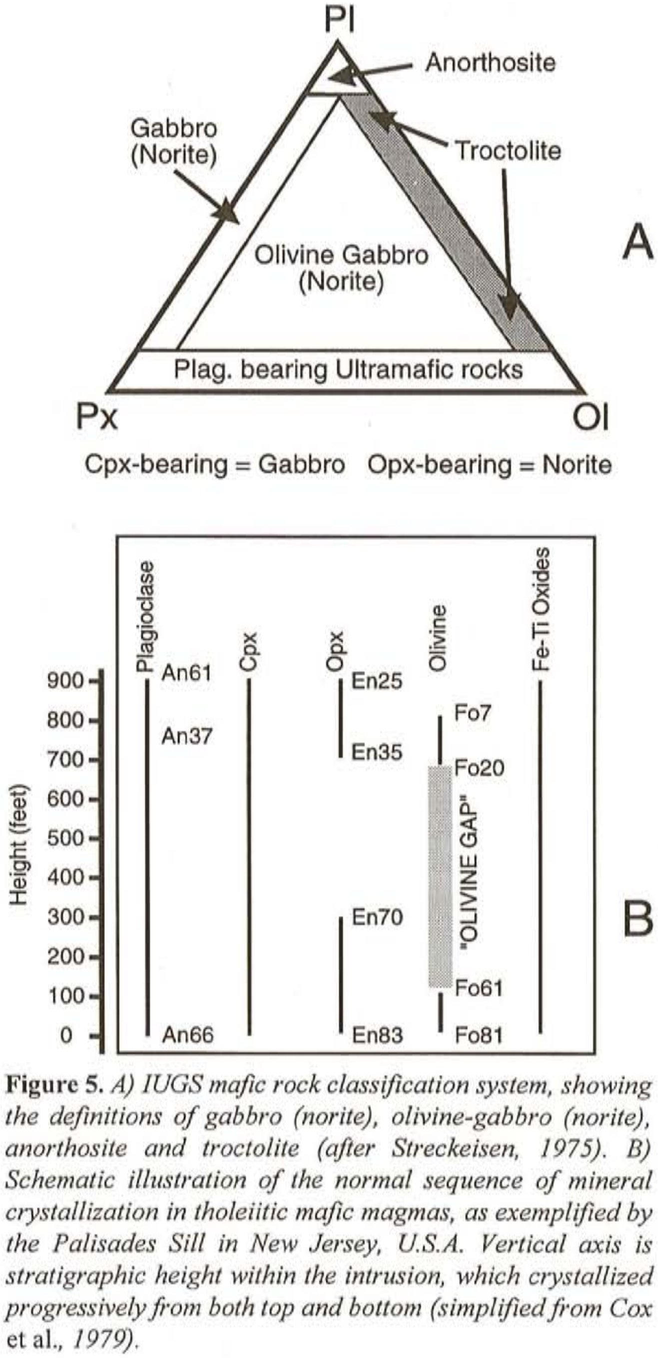

Figure 5. *A) IUGS mafic rock classification system, showing the definitions of gabbro (norite), olivine-gabbro (norite), anorthosite and troctolite (after Streckeisen, 1975). B) Schematic illustration of the normal sequence of mineral crystallization in tholeiitic mafic magmas, as exemplified by the Palisades Sill in New Jersey, U.S.A. Vertical axis is stratigraphic height within the intrusion, which crystallized progressively from both top and bottom (simplified from Cox* et al., *1979).*

duce Ni contents in the remaining magma, substantial amounts of Ni may remain available at this point. Processes such as contamination, notably by siliceous rocks, will influence the fractionation sequence of the magma, and promote the early formation of orthopyroxene. Last, but not least, olivine commonly also occurs late in the fractionation of a mafic magma, but is a Fe-rich (fayalitic) rather than the Mg-rich (forsteritic) variety typical of early crystallization. It is entirely possible to develop olivine- and plagioclase-rich rocks from such late-stage magmas, and many of these could be described as "troctolite" in the field. They are, however, entirely different in character and, by virtue of extended fractionation, have relatively low Ni and Cu contents.

Generally, magmatic Ni–Cu deposits are almost universally associated with ultramafic to mafic intrusive or extrusive rocks. The diverse igneous suites associated with Ni–Cu mineralization all appear to represent primitive, MgO-rich compositions derived by fairly extensive mantle melting, possibly associated with mantle plumes (Naldrett, 1989a; Keays, 1994; Lightfoot and Keays, 1994; Ryan *et al.*, 1995). To extract Ni, Cu and other elements of interest during partial melting of the mantle, two conditions must be met. First, the degree of melting must be significant, as these are "compatible" trace elements that preferentially stay in residual minerals such as olivine and pyroxene. Second, any sulphur in the mantle source region must be consumed and entirely dissolved in the magma. This is essential because sulphides have a great affinity for Ni, Cu and other chalcophile elements (*see* later discussion), and will withold them from a silicate melt. Sulphur-undersaturation is promoted by larger degrees of partial melting, and also by previous melt extraction events, which will remove some sulphur (Keays, 1994). As the magma migrates from its mantle source region toward its eventual destination, it must remain sulphur-undersaturated, as development of a sulphide phase will quickly remove Ni and Cu.

It follows that magmas with potential to generate Ni–Cu deposits should have a distinctive geochemistry, and it has been suggested that many were broadly picritic to komatiitic (e.g., Keays, 1995), with high MgO and chalcophile element contents, and trace element and REE patterns indicative of large (>25 percent) degrees of partial melting. This is certainly the case for Ni deposits in extrusive and shallow intrusive environments, where the hosts are komatiitic (e.g., Kambalda, Australia). However, it is more difficult to use geochemical fingerprints in mafic plutonic rocks because the compositions of the original magmas have been extensively modified by subsequent fractionation, assimilation and, in some cases, saturation in sulphur. Also, most mafic plutonic rocks are cumulates, and their whole-rock composition bears little relationship to that of their parental magma. In Labrador, there are abundant mineralogical and chemical data from areas such as the Kiglapait Intrusion (e.g., Morse, 1969, 1971–83), but large areas are unrepresented, and the available data from mafic rocks have never been fully integrated. Much of the effort in terms of petrogenetic studies has been directed at the anorthositic components of the Nain Plutonic Suite (e.g., Emslie *et al.*, 1994). Only a small amount of data is available from the Reid Brook intrusion (Emslie, 1996), and this does suggest higher Ni, Co and Co/Ni compared to other mafic rocks in the area. However, the total amount of data is small, and the relationship to parental liquids far from direct. Also, these data mainly represent the layered subdivision of the Reid Brook intrusion, and not the massive phase, which appears to have a closer relationship to sulphide mineralization (Ryan, *in press*).

Presently, it is not feasible to use lithogeochemistry as a grass-roots exploration tool in Labrador, other than in the most general way, i.e., by targeting mafic rocks having relatively primitive compositions. However, one of the long-term objectives of this project is to develop a systematic geochemical database for mafic intrusions in Labrador, including mineral chemistry data, that may lead toward this objective. The use of mineral data gets around some of the problems associated with cumulate rocks, and there are also methods for calculation of model-melt compositions from whole-rock chemical data and modal analyses (e.g., Bédard, 1994). However, although a suitable parent magma is an important prerequisite, the subsequent fractionation and/or contamination history of a magma, and the crustal level at which it is exposed, are probably far more important in terms of ore genesis and mineral exploration.

EROSIONAL LEVEL AND AGE OF HOST INTRUSIONS

Magmatic Ni–Cu sulphide deposits are almost invariably associated with the lower regions of their host intrusions, implying that gravitational segregation is important in their genesis (Naldrett, 1989a, b). This is clearly the case at Voisey's Bay, where sulphide ores lie just above or at the basal contact of the Reid Brook intrusion, and appear to be spatially associated with the line of entry of a feeder dyke or sill into the main body (Naldrett *et al.*, 1996).

This feature suggests that recognition of areas representing deeply eroded parts of mafic intrusions should be a first-order priority in regional exploration. The geology in the immediate area of the Voisey's Bay deposits is dominated by older basement gneisses, and not by Nain Plutonic Suite rocks. The discontinuous, fault-dissected outcrop pattern of the Reid Brook intrusion (Figures 1 and 2) is quite different from that of the well-preserved, concentrically zoned Kiglapait and Newark Island layered intrusions, which are younger and presumably less eroded. Although these may have potential for magmatic ore deposits of other types (e.g., Skaergaard-type PGE–Au mineralization; Nielsen and Brooks, 1995), the basal regions with greatest potential for Ni–Cu sulphides may be deeply buried. Areas where layered intrusions are extensive and well-preserved probably represent some of the least favourable areas to look for their exposed basal zones and feeder systems. Indeed, if the Voisey's Bay local geology is applied in a strict manner, it suggests that areas dominated by basement gneisses should be accorded a higher priority than those dominated by Nain Plutonic Suite rocks. Although these gneissic terranes have received attention, their evaluation is complicated by poor exposure and an extremely noisy geophysical signature related to syngenetic sulphides and graphite in the Tasiuyak gneiss.

It could be inferred that the basal regions and feeder systems of the older mafic intrusions in the Nain Plutonic Suite are more likely to be exposed because the crust is progressively uplifted in response to erosion. The contrast noted above between the outcrop patterns of the 1305-Ma Kiglapait and Newark Island intrusions, and the pre-1322-Ma Reid Brook intrusion suggests that this is true in a general sense, but it is an oversimplification. The crust is not uplifted in a uniform manner, but in blocks separated by faults, and there is no guarantee that intrusions of a given age all ascended to exactly the same level in the crust. Thus, the basal sections of younger intrusions may sit at or above the crustal level of older intrusions, or could intrude through them. The recognition of such relationships in areas dominated by massive plutonic rocks would require careful mapping.

Emplacement age may also be an important control on the composition of the host magmas and their capacity to extract and transport Ni and Cu from the mantle, e.g., earlier magmas may be of more primitive composition. Also, if crustal sulphur is important in ore formation, early magmas may have the best chance to obtain it through assimilation during ascent. Later intrusions would encounter a crust of a different bulk composition, which would be significantly modified by the crystallized products of earlier magmatic pulses. Anorogenic magmatism of the type exemplified by the Nain Plutonic Suite represents crustal growth via magmatic underplating, and it will inevitably alter the character of the lower crust.

In summary, there are general links between age of intrusions and their erosion level, and possibly also links between age and compositional traits, which need to be assessed through geochronological and petrochemical studies, as outlined above. There is also a need for regional thermobarometric studies of contact-metamorphic assemblage associated with mafic intrusions that provide direct information about their emplacement depth.

NATURE AND COMPOSITION OF COUNTRY ROCKS

In the models of Ryan *et al.* (1995) and Naldrett *et al.* (1996), the formation of sulphide ore at Voisey's Bay is linked to the contamination of the Reid Brook intrusion magmas by the sulphide-bearing Tasiuyak gneiss. The assimilation of sulphur-rich crustal rocks has also been invoked to explain the genesis of other important Ni–Cu deposits, such as Nor'ilsk, and Duluth in Minnesota (e.g., Naldrett, 1992) and many komatiite-hosted Ni deposits (Lesher, 1989). As the solubility of sulphur in a magma is limited, any significant addition of crustal sulphur can lead to the development of a discrete sulphide liquid, which will then concentrate Ni, Cu and other metals. The assimilation of silica-rich rocks also leads to a decrease in sulphur solubility in mafic magmas, and has been invoked as an important control at Sudbury, where a meteorite impact is suggested to have caused widespread crustal anatexis (e.g., Dietz, 1972; Naldrett and MacDonald, 1980). In the case of the Tasiuyak gneiss, which is both siliceous and sulphide-bearing, both factors could have been involved. Stable isotope studies and S/Se ratios are capable of assessing the link between the sulphur in magmatic deposits and the sulphide present in the Tasiuyak gneiss. As yet, there is no published information that answers this question conclusively, although the ϵ_{Nd} and initial $^{87}Sr/^{86}Sr$ of the layered phase of the Reid Brook intrusion (−3.0 and 0.70343, respectively, at 1300 Ma) are apparently inconsistent with large-scale bulk assimilation of the Tasiuyak gneiss (Emslie, 1996).

This question is of critical importance. If the Tasiuyak gneiss is the source of sulphur in the ore deposits, the present Nain–Churchill Province boundary zone (Figures 1 and 2) provides an approximate eastern limit to the region of highest potential. Regional considerations (Ryan, 1996) suggest that the boundary zone dips eastward, but the isotopic data of Emslie *et al.* (1994) imply that the subsurface extent of Churchill Province crust is rarely more than 30 km east of the surface boundary. If this is the case, several important exploration areas, including the Kiglapait and Newark Island layered intrusions, lie on the "wrong side of the tracks", because their Archean country rocks are in general sulphide-poor. Regional stable isotope and S/Se studies aimed at evaluating the sources of sulphur in mineralization throughout northern Labrador are thus an important priority for this project.

SPATIAL ASSOCIATION WITH THE NAIN–CHURCHILL BOUNDARY

The location of the Voisey's Bay deposits near to the Nain–Churchill boundary zone has led to suggestions that crustal-scale faults associated with this line tapped mantle-derived magmas, and allowed their rapid ascent without significant fractionation (Ryan *et al.*, 1995). Regionally, many of the newly discovered sulphide zones described in the accompanying report (Kerr and Smith, *this volume*) lie close to the projection of the boundary zone north of Nain (*see* Figure 9 of Ryan, 1996). However, this apparent link must be viewed with caution, as the model itself may have influenced property acquisition and exploration expenditure. It would be premature to write off areas that do not lie along this line, particularly if they are in the west, where sulphide-bearing country rocks are abundant.

DEVELOPMENT AND SEGREGATION OF SULPHIDE MAGMAS

The development of a magmatic sulphide deposit is a direct result of the formation of immiscible sulphide liquid droplets, which equilibrate with a larger volume of silicate magma, coalesce and accumulate through gravity settling. Metals such as Ni, Cu, Co and PGE are partitioned strongly into the sulphide liquid, along with iron, and the eventual result is a metal-enriched sulphide sublayer within the magma chamber. As depicted schematically (Figure 6a) this appears a simple process, but in nature is likely to be far more complex. Several important factors will influence the volume of sulphide liquid and its potential to be economic ore.

Composition of the Silicate Magma

The immediate source of ore metals is the host silicate magma, which must contain suitable levels of these elements. For example, it is theoretically possible to generate a magmatic sulphide deposit from a dioritic or monzonitic magma, but its base-metal content would be minimal because the silicate liquid would be depleted in compatible trace elements. A magma of suitable composition is thus an important prerequisite.

Timing of Sulphide Saturation and Separation

The immiscible sulphide liquid must also develop at a critical stage in the evolution of a suitable magma. As a mafic magma crystallizes, the early formed cumulate rocks contain significant amounts of olivine and pyroxene (Figure 5b). In particular, olivine has a high partition coefficient[1] for Ni (K_d = 14 to 20 in basalts), and its removal will deplete Ni in the magma rapidly. For example, 20 percent crystallization of a mafic magma with olivine and pyroxene on the liquidus would remove more than 90 percent of the available Ni (Figure 6b). Sulphur, on the other hand, is incompatible with silicates, and is concentrated in the residual magma, but its

[1] A partition coefficient, commonly abbreviated to K_d, is the ratio of the concentration of a given element (e.g., Ni) in two phases, which can be solid crystals, liquids or a liquid and a crystal. It is an expression of the preference of that element for a particular phase. For example, the olivine/melt Ni K_d value is about 15 in basalts, indicating that about 15 times more nickel will enter olivine than remain in the melt, and Ni behaves as a compatible element. The olivine/melt sulphur K_d value is close to zero, and virtually all sulphur will stay in the melt, i.e., it is incompatible. Partition coefficients only apply strictly to trace elements, which have negligable effects on mineral stabilities, and are more difficult to predict and apply in sulphide/silicate systems, where Ni becomes a major percent-level constituent of the sulphide. Nevertheless, the same general principles apply.

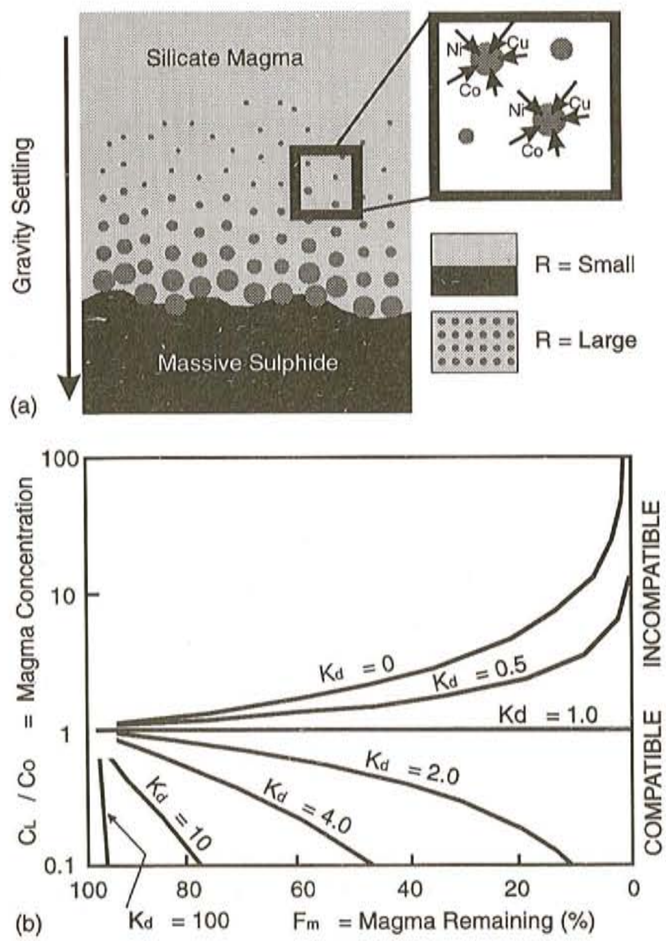

Figure 6. *a) Schematic illustration of the process of immiscible sulphide liquid segregation in mafic magmas hosting Ni–Cu sulphides. b) Graph showing the behaviour of compatible and incompatible elements in closed-system continuous fractionation of either a solid phase or an immiscible liquid from a magma. Numbers on curves are partition coefficients (K_d) expressed as solid/magma or sulphide/magma. C_l/C_0 = concentration in magma, normalized to original concentration; F_m = volume fraction of magma remaining, in percent. Note the extremely rapid depletion of compatible trace elements at high K_d values (after Arth, 1976).*

relative concentration increases far more slowly than that of Ni decreases (Figure 6b). Under normal circumstances, sulphur saturation occurs at a late stage in fractionation, when most of the Ni and Cu are stored in cumulates and unavailable for ore formation. Sulphur saturation must occur early in the fractionation history, and an external source of sulphur, or a process that decreases sulphur solubility, can facilitate this — but only if the timing is right. The timing of sulphide segregation also has an important influence on metal ratios, because Ni is extracted more rapidly by fractionation than Cu, for which partition coefficients are more moderate. Early formed deposits will likely have high Ni/Cu ratios, whereas slightly later formation (or less primitive parent magmas) will favour lower Ni/Cu ratios such as those shown by Voisey's Bay (ca. 2). Sulphide deposits that are formed too late may have Cu>>Ni, but will probably contain very little of either element.

Sulphide Segregation Processes

Even if all of the above conditions are met, i.e., the magma has a suitable composition and becomes sulphur-saturated at an early stage, there is no guarantee that an orebody will result. Once an immiscible sulphide liquid has formed, a mafic magma becomes a three-component system, i.e., it comprises a silicate liquid, a sulphide liquid and solid silicate minerals. The behaviour of a given element (e.g., Ni) then depends on the respective liquid-liquid and liquid-solid partition coefficients, and also on the manner in which the sulphide liquid is segregated. An excellent discussion of the complexities of sulphide liquid fractionation is provided by Naldrett (1989b), from which the following is partly drawn.

A sulphide liquid can separate from its companion silicate magma in two ways. Batch segregation is defined as the development of a "batch" of sulphide liquid, which then equilibrates with a "batch" of associated silicate magma, and is removed from the system by settling. The process may then repeat itself. The scale of such a process can vary enormously, from a sulphide-rich reaction halo around a single xenolith to an intrusion-wide process caused by large-scale assimilation of sulphur-rich sediments. Fractional segregation is a slightly different mechanism where sulphide liquid is continuously exsolved, but is quickly removed from the system by settling. This would occur in a sulphur-saturated magma that was also crystallizing silicates, such that removal of sulphide was balanced by a build-up of sulphur in the residual magma. Fractional segregation is in effect a special case of batch segregation where the batches become small, and the most likely situation in nature is an intermediate one, where "increments" of sulphide liquid are progressively removed.

Both processes have the same general effect in that the sulphide liquid extracts Ni, Cu and Co from the silicate liquid. The relevant partition coefficients are difficult to measure experimentally, but are probably one to two orders of magnitude higher than the olivine/magma K_d values of 14 to 20; for calculation purposes, Naldrett (1989b) uses a sulphide/magma K_d for Ni of 275. At such high values, the separation of any sulphide liquid from a silicate liquid will cause very rapid removal of Ni (Figure 6b). The concentration of Ni (and other elements) in the sulphide liquid depends on two factors, i.e., the concentration in the associated silicate magma, and the relative proportions of the sulphide liquid and the silicate liquid with which it is able to equilibrate. The latter is probably more important, because there is only a finite amount of Ni available for incorporation into a given sulphide droplet, and this governs the eventual Ni content of the sulphide liquid. The ratio of silicate liquid to sulphide liquid is termed the "R-value" (after Naldrett, 1989b).

If the R-value is large (i.e., a small amount of sulphide liquid equilibrates with a large volume of silicate magma) the concentration of Ni and Cu in the sulphide liquid can be substantial, leading to high ore grades, but the actual quantity of metals may be small, because the sulphide fraction is small. Thus, although the grade may be attractive, the deposit may be of uneconomic size. In the opposite case, where the R-value is low (i.e., there is a relatively large volume of sulphide liquid), very large quantities of metals can be extracted from the silicate magma, but they may be dispersed through a large volume of sulphide liquid, leading to low-grade material dominated by pyrrhotite. Thus, although the tonnage may be attractive, the deposit may be of uneconomic grade. Naldrett (1989b) cites the Katahdin deposit in Maine, which consists of 200 million tonnes of nearly massive sulphide averaging only 0.3% combined Ni and Cu, as an example of batch segregation with a low R-value. Conversely, smaller deposits associated with the nearby Moxie gabbro pluton, which contain average Ni contents up to 2%, are cited as examples of batch segregation with relatively high R-values. Unfortunately, both examples are uneconomic, but for entirely different reasons.

Thus, in addition to the delicate balancing act between fractionation and sulphur saturation, ore formation requires exactly the right amount of sulphide liquid for the circumstances. Contrary to intuition, it is possible to have too much sulphur introduced to a magma, and end up with Ni and Cu dispersed in low-grade material, as at Katahdin. The total metal value of the Katahdin deposit is greater than US $5 billion (December 1996 metal prices), and compares favourably with the US $10 billion value of the Voisey's Bay Ovoid. Clearly, if the R-value at Katahdin had been 10 times higher, the host intrusion could have generated a 20-million-tonne deposit with grades approaching those of the Ovoid.

It follows from the above that there may be more than one episode of sulphide segregation in the history of a magmatic system, and that there may be both spatial and temporal variations in the R-value. This will have significant effects on the eventual grade of sulphide deposits. For example, an early episode of sulphide segregation will seriously deplete the remaining magma in Ni, reducing the chances of a later episode producing economic mineralization. Similarly, grade variations in komatiite-hosted "Kambalda-type" Ni deposits, which typically consist of numerous small, high-grade lenses, partly reflect spatial variations in the R-value (e.g., Lesher, 1989). A corollary of this is that the grade of a particular showing may not be representative of the grade throughout the mineralizing system, and that the common practice of predicting the grade of potential massive sulphide zones by extrapolating results from disseminated mineralization may be misleading, as the two may form under different R-values.

Last, the R-value does not reflect the ratio of total silicate to total sulphide liquid (total-mass ratio) in the magmatic system, but the ratio of sulphide liquid to silicate liquid with which it is able to equilibrate. This distinction is important, because diffusion rates in magmas are finite (albeit poorly known), and a pocket of sulphide liquid can only extract Ni from a limited volume of silicate magma. From this, it follows that the fluid dynamic environment that applies within a magmatic system will determine the effective R-value. In a turbulent environment where the sulphide liquid is suspended as tiny droplets in the magma (analogous to a shaken oil-and-vinegar), the surface area available for metal extraction is very large, and the R-value can be high, even if there are large amounts of sulphide liquid. In a stable environment where there is a limited, single interface between the two liquids (analogous to an oil-and-vinegar that is allowed to stand), the surface area available for metal extraction is far smaller, and the R-value will be small, even if the total mass ratio is high.

As noted previously, the sulphide ores at Voisey's Bay are spatially associated with the line of entry of a feeder system into the Reid Brook magma chamber, and may have been localized at the transition from turbulent to stagnant flow regimes (Naldrett *et al.*, 1996). This association with a feeder system may be highly significant, as this turbulent environment could have facilitated the extraction of metals from a large volume of silicate magma. The public-domain drill intersection data from the Voisey's Bay Ovoid deposit suggest that it is remarkably homogeneous in terms of Ni, Cu and Co contents, which implies that it was unaffected by spatial or temporal variations in the R-value. It is not yet clear if the more varied mineralization hosted by the Eastern Deeps deposit represents more than one episode of sulphide development. Published results indicate that grades are more variable, but this must in part be related to dilution by silicates.

Fractionation of the Sulphide Liquid

The development of a magmatic sulphide orebody does not end when the sulphide liquid accumulates in some suitable setting, because it must then solidify and cool through over 1000°C. Although referred to here as a sulphide liquid, it actually consists of 5 major constituents (Fe, S, O, Ni and Cu) with minor components such as Co and PGE. In effect, it is a "magma", and it is subject to the same processes of crystallization, fractionation, and subsolidus adjustment (Naldrett, 1989b). The characteristics of sulphide liquids are not well-known, and the details of their evolution are beyond the scope of this article. Their liquidus temperatures are estimated to be 1120 to 1160°C, and they are capable of melting and digesting many silicate rock types. "Thermal erosion" is thus very likely, and is documented in many extrusive Kambalda-type deposits. It should be expected wherever such liquids interact with silicate materials having lower melting points (e.g., quartz-rich country rocks). The solidus temperatures of sulphide ores are slightly above 1000°C, and are generally independent of Ni content, but are reduced significantly with increased Cu. Thus, Cu-rich material will remain mobile longer and has the potential to migrate farther from the accumulation site. Also, solidified sulphides can be partially melted and remobilized through the thermal effects of higher temperature mafic and ultramafic magmas. The initial sulphide crystallized from the liquid is a pyrrhotite containing substantial Ni and Cu in solid solution, which may precede or postdate the crystallization of magnetite (Naldrett, 1989b). The crystallization of the ore is a progressive process, and (just like silicate crystallization), it will cause fractionation of the remaining liquid, usually driving it toward more Cu-rich compositions.

To summarize, sulphide-oxide magmas can thermally erode and assimilate silicate material, and will undergo fractionation processes that may produce sharp local grade variations and lead to late-stage mobile fractions that may migrate elsewhere. These factors provide additional complications in assessing the characteristics and grade of a specific showing.

Consequences and Fingerprints of Sulphide Segregation

The removal of large amounts of metals from a magma inevitably affects the concentration of those elements in the remaining silicate liquid, and this phenomenon also depends on the R-value. For batch segregation, significant depletion of Ni in the magma occurs when the R-value falls below 1000, and the Ni content is halved when R=100 (Naldrett, 1989b); these figures are relatively insensitive to the actual sulphide/magma partition coefficient employed, as long as it is high. At high R-values, the depletion is negligable because only a small amount of the total magma metal content has been extracted. In fractional segregation, an additional complication is given by the simultaneous crystallization of silicates and segregation of sulphide liquid. Both processes deplete Ni in the remaining magma, but the sulphide is far more efficient, so the magnitude of depletion is also affected by the ratio of sulphide to silicate extraction. If the proportion of sulphide liquid is high (i.e., the R-value is low), Ni is depleted very quickly (Figure 7a). MgO is a major consitituent of olivine and orthopyroxene, but it is not incorporated into sulphide liquids, so mafic magmas that have experienced sulphide segregation are characterized by a disruption of the "normal" sympathetic behaviour of MgO and Ni (Figure 7a). As discussed by Naldrett (1989a), the trends illustrated in Figure 7a can be recognized in host komatiite flows of the Kambalda mining district, which show depletion of Ni at a given MgO content compared to barren komatiites.

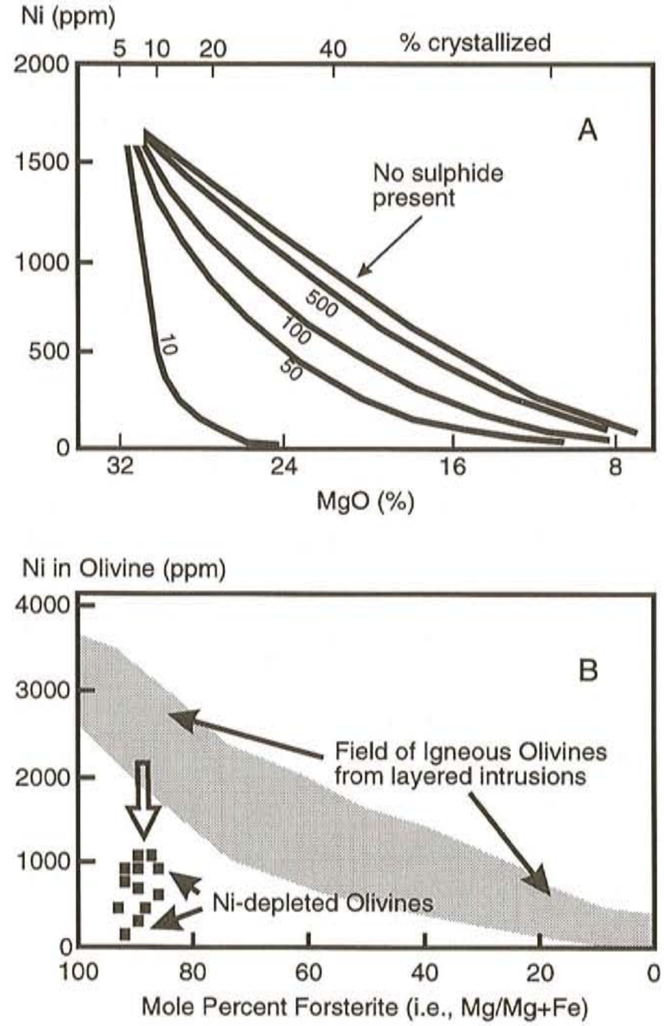

Figure 7. *a) Calculated Ni–MgO fractionation curves for a mafic to ultramafic magma simultaneously crystallizing sulphides and olivine. Numbers on curves represent the ratio of olivine removal to sulphide removal, i.e., low numbers indicate a large component of sulphide (low R-value). Note the rapid depletion of Ni at low R-values, and disruption of the "normal" linear correlation typical of pure olivine fractionation. b) Schematic illustration of the depletion of Ni in olivines in mafic intrusions that have experienced significant sulphide segregation. Both examples are drawn from Naldrett (1989b). Field of "normal olivines from layered intrusions" from Simkin and Smith (1970).*

In extrusive environments, whole-rock geochemistry is a feasible grass-roots exploration tool because the rocks approximate liquid compositions. Nickel is well-suited as an indicator element because it is relatively insensitive to hydrothermal processes. Deep-level intrusive environments such as the Nain Plutonic Suite present a more difficult problem, because most mafic rocks represent cumulates in which the variation of Ni and MgO is determined by mineral phases and proportions, and the amount of trapped intercumulus liquid that remained in the system. Nevertheless, the levels of Ni in the parent liquid can be assessed through mineral geochemistry, most easily through olivine compositions. As olivine has a strong affinity for Ni, it is a sensitive indicator of the Ni content of magmas, and comparisons of rocks from different areas are less sensitive to variations in the details of cumulate processes. Olivines that crystallize from magmas that were simultaneously segregating sulphide liquids, or which experienced prior sulphide separation (at suitable R-values), should show Ni-depletion at a given MgO content (Figure 7b). This depletion has been demonstrated for komatiitic sills that host Ni deposits, and for the Moxie and Katahdin plutons discussed above (Naldrett, 1989b). In order to use such methods as exploration tools, a local background needs to be established, in addition to the general field of olivines from layered intrusions (Simkin and Smith, 1970). Typically, olivines from the Nain Plutonic Suite have Ni contents from a few hundred ppm to 2500 ppm, and lie in the middle of the "layered intrusion field", with Fo_{50} to Fo_{80} (Emslie, 1996). Five olivine analyses from the Reid Brook intrusion (Emslie, 1996) do not show striking Ni depletion, but it should be noted that these samples are mostly from the layered subunit. Olivines from the massive subunit, closely associated with mineralization, have significantly lower Ni contents (Ryan, *in press*).

The depletion of Ni in rocks and minerals that crystallized from magmas that experienced large-scale sulphide segregation provides a method that may be useful in assessing the mineral potential of individual intrusive complexes. This may provide a partial substitute for the alteration zones that are invaluable tools in exploration for hydrothermal ore deposits, but it by no means replaces them. To use such techniques effectively, an understanding of the behaviour of Ni in the Reid Brook intrusion is needed, as is a comprehensive regional database that allows background trends to be established.

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