NICKELIFEROUS GABBROIC INTRUSIONS OF THE PANTS LAKE AREA, LABRADOR, CANADA: IMPLICATIONS FOR THE DEVELOPMENT OF MAGMATIC SULFIDES IN MAFIC SYSTEMS

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ABSTRACT. The Pants Lake intrusions are located some 80 kilometers south of the world-class Voisey’s Bay Ni-Cu-Co sulfide deposit in Labrador, Canada. They are dominated by olivine gabbro, with subordinate troctolite, melagabbro, peridotite and leucogabbro. They form several sheet-like bodies that were emplaced into metasedimentary gneisses that locally contain sulfides. The largest of these, termed the North and South intrusions, have been dated by other workers at 1322 ± 2 Ma and 1337 ± 2 Ma respectively, indicating that they formed in two discrete events. The North intrusion is more varied petrologically, and its three units show ambiguous contact relationships implying that they partly coexisted as liquids. Disseminated sulfide mineralization is widespread near the basal contacts of both intrusions, but massive sulfide mineralization is rare. In the older South intrusion, sulfides are hosted by melagabbro and peridotite of cumulate origin, and probably represent a gravitational accumulation. In the younger North intrusion, they are hosted by a complex “mineralized sequence”, interpreted to represent two or more influxes of magma charged with sulfides and reacted country-rock fragments.

The older South intrusion is geochemically distinct from the younger North intrusion, and more closely resembles the Voisey’s Bay Intrusion. Mineralized rocks within both Pants Lake intrusions are geochemically similar to the associated unmineralized rocks, and must be closely related to them. The mafic rocks almost all have low Ni contents and low Cu/Zr ratios that imply extraction of metals by sulfide liquids. This pervasive depletion signature, coupled with consistent Ni/Cu and Ni/Co, and clustering of sulfide metal contents, suggests that sulfide liquids were developed on an intrusion-wide scale, probably at depth, rather than by local processes.

Sulfides at Pants Lake typically contain less than 2 percent Ni and 2 percent Cu. These values agree with predictions from the low Ni contents of silicate rocks, and imply a low mass ratio (R factor) of silicate magma to sulfide liquid (R < 300) compared to Voisey’s Bay (R = 600 to > 1000). The pervasive Ni and Cu depletion contrasts with the more localized metal depletion seen at Voisey’s Bay. This may indicate that the Pants Lake sulfide liquids were not as effectively “upgraded” by later batches of undepleted magma.

From the perspective of metallogenesis, data from the Pants Lake intrusions support several key concepts proposed in models for the formation of the Voisey’s Bay deposit, suggesting that these may apply more widely as controls on the formation of magmatic sulfide deposits in broadly gabbroic magma systems.

INTRODUCTION

The 1994 discovery of the world-class Ni-Cu-Co sulfide deposit at Voisey’s Bay, Labrador, Canada (fig. 1) led to intense mineral exploration, and the discovery of many other sulfide prospects, summarized by Kerr and Ryan (2000). The largest and best-known of these are associated with complex mafic bodies here termed the Pants Lake intrusions, located about 80 kilometers south of Voisey’s Bay (fig. 1). Strong similarities between these and the Voisey’s Bay deposits indicate that the Pants Lake intrusions may be important in assessing genetic models for the latter, and perhaps also in evaluating the mineral potential of Middle Proterozoic “anorogenic” plutonic suites elsewhere. This paper discusses the mafic rocks and Ni-Cu-Co sulfide mineralization of the Pants Lake intrusions, and the implications of these data for the formation of economic magmatic sulfide deposits in gabbroic and troctolitic intrusions. In
particular, it assesses the roles of crustal contamination processes and dynamic, multistage magmatic systems. The paper extends previous descriptive accounts in government survey reports (Kerr, 1999; Kerr and others, 2001), and amplifies summaries previously given by Kerr and Ryan (2000) and Li and others (2001).

The Pants Lake intrusions were explored from 1995 to 1998, under a program directed by Donner Minerals and Teck Corporation, and since 2001 via a Donner Minerals - Falconbridge joint venture. Relevant mineral exploration data that are now in the public domain (Fitzpatrick and others, 1998, 1999) are integrated into this paper. Thesis studies (MacDonald, ms, 1999; Smith and others, 1999, 2001) are also important in the context of the paper, and are discussed here.
Northern Labrador includes parts of two contrasting Precambrian structural provinces (fig. 1). Gneisses in the east are part of the Archean Nain Province (for example, Bridgwater and Schiøtte, 1991), but those in the west are part of the Archean to Paleoproterozoic Churchill Province, extensively reworked within the 1850 Ma Torngat Orogen (Wardle and others, 1990; Bertrand and others, 1993). A belt of granulite-facies pelitic paragneiss (the Tasiuyak Gneiss) lies to the west of the Nain-Churchill boundary along much of its length (fig. 1) and partly coincides with a major 1850 to 1820 Ma shear zone (Bertrand and others, 1993). Major Mesoproterozoic igneous complexes were emplaced across this boundary zone, and include the approximately 1450 Ma Harp Lake Plutonic Suite and 1350 to 1290 Ma Nain Plutonic Suite (for example, Emslie, 1980; Emslie and others, 1994; Ryan, 1998). Both the Voisey’s Bay Intrusion and the Pants Lake intrusions form part of the Nain Plutonic Suite on the basis of location and age (Ryan, 1998; Kerr and Ryan, 2000).

The Pants Lake intrusions sit within the Churchill Province, ~20 kilometers west of the Nain-Churchill boundary (figs. 1 and 2). Mafic rocks were initially recognized by Thomas and Morrison (1991), but their full extent and anatomy were defined during
mineral exploration (Fitzpatrick and others, 1998, 1999; Kerr, 1999). The country rocks to the intrusions are dominated by pelitic to semipelitic amphibolite-facies paragneisses containing minor sulfoide and graphite. Garnetiferous orthogneisses derived from granitoid rocks form several kilometer-scale concordant units (fig. 2). Paragneisses and orthogneisses are interleaved on all scales, and many orthogneisses probably formed by local anatexis during peak-metamorphic conditions. The paragneisses form part of the Tasiuyak Gneiss, which extends north to Voisey’s Bay and beyond (fig. 1). Uneformed leuconorite to anorthosite, iron-rich diorite, monzonite and granite typical of Mesoproterozoic “anorogenic” suites are assigned to the Nain Plutonic Suite in the north of the area, and to the Harp Lake Plutonic Suite in the south. Granitic rocks of the Harp Lake Plutonic Suite to the southwest were dated imprecisely (Rb/Sr) at about 1450 Ma (Emslie, 1980), but the anorthosites and granites to the north remain undated. U-Pb zircon ages of 1322 ± 2 Ma and 1337 ± 2 Ma (Smith and others, 1999, 2001) from the two principal intrusions confirm that the Pants Lake intrusions represent more than one magmatic pulse, as suggested on the basis of geochemistry (MacDonald, ms, 1999; Kerr and others, 2001). The collective term is retained here for consistency with existing literature, pending further age determinations.

GEOLOGY OF THE PANTS LAKE INTRUSIONS

Subdivisions and Areas

The Pants Lake intrusions include several discrete bodies spread over about 250 km² (fig. 2). The largest are referred to as the Pants Lake North intrusion and Pants Lake South intrusion, and are the principal focus of this paper; for brevity, the terms North intrusion and South intrusion are generally used in the text. The North intrusion has been dated at 1322 ± 2 Ma (Smith and others, 1999), and the South intrusion has been dated at 1337 ± 2 Ma (Smith and others, 2001). Small sill-like outliers of gabbro located south and southeast of Pants Lake, including those of the “Mineral Hill” area (fig. 2), are here correlated with the North intrusion on geochemical grounds (see below). Exploration drilling demonstrates that both intrusions are broadly sheet-like or slab-like in geometry, but their attitudes and internal anatomy vary. The North intrusion contains a greater variety of rock types than the South intrusion, but the fine-grained olivine gabbros from both are petrologically identical. The following account of the geology is organized into three subsections. The first describes the rock types, the second discusses the geometry and anatomy of the intrusions, and the third discusses relationships between geological units.

Rock Types and Petrology

There are three main rock types in the Pants Lake intrusions, that is, (1) fine-grained, layered, olivine-gabbro, (2) coarse-grained, massive leucogabbro, and (3) a distinctive black olivine gabbro of variable grain size. Subordinate rock types include chilled diabase-like rocks, mostly restricted to contact regions, and peridotite and melagabbro of cumulate origin. There are also unusual rock types within basal assemblages of sulfoide-bearing rocks (termed the mineralized sequences). These are discussed separately, in conjunction with the sulfoide mineralization.

Fine-grained, layered olivine gabbro.—This rock type dominates the South intrusion, and is also important in the North intrusion. It is typically red-weathering, but grey-green to dark grey where fresh. It is fine- to medium-grained (1-4 mm), variably plagioclase-porphyritic, and typically “granular” in appearance. Subtle layering is subhorizontal or gently-dipping, and defined by slight variations in olivine and plagioclase content; it is most easily seen in drill-core, but is rarely obvious. Component minerals are olivine (30-60%), plagioclase (40-60%; typically An₃₀-An₆₅), clinopyroxene (5-30%), minor red biotite, magnetite, orthopyroxene (after olivine), and serpen-
tine (after olivine). True troctolites (that is, containing < 5% pyroxene) appear to be more common at lower stratigraphic levels. Textural relationships indicate early formation of cumulus olivine, followed by plagioclase, and finally intercumulus clinopyroxene; magnetite and biotite are also late-crystallizing. For brevity, the term *layered gabbro* is used subsequently for this unit, although it should be noted that the layering is commonly cryptic.

**Melagabbro and peridotite.**—These are best-known near the base of the South intrusion, and are known mostly from drill-core. They are dominated by cumulus olivine and interstitial or poikilitic plagioclase, accompanied by variable amounts of clinopyroxene. Closely similar rocks also occur locally in the lower part of the North intrusion. The troctolitic variants of the layered gabbro (see above) and the melagabbro-peridotite unit share a common texture, and both are regarded as olivine cumulates. They are probably gradational with one another. For brevity, the term *melagabbro* is used subsequently for this unit.

**Coarse-grained, massive leucogabbro.**—This is the dominant unit on surface in the North intrusion, where it sits above the layered gabbro. It appears to be absent from the South intrusion (fig. 2), aside from a few thin cross-cutting veins seen in drill-core. It is light-weathering, coarse-grained, homogeneous, plagioclase-rich, and superficially resembles an anorhostite. Its texture is seriate to porphyritic, and it contains stubby (0.5-2 cm) plagioclase crystals, enclosed by intercumulus mafic minerals. Component minerals are zoned plagioclase (60-80%, typically < An53 at the rim), olivine (5-20%), clinopyroxene (10-20%), minor biotite, magnetite, orthopyroxene (rims on olivine) and secondary amphibole. The interstitial to subophitic habits of olivine and clinopyroxene show that they both crystallized late, in contrast to the early granular cumulus olivine of the fine-grained, layered gabbro gabro unit and the melagabbro-peridotite unit. A retrogressed, hydrated (amphibole-rich) variant of this rock type occurs locally near the upper contact of the North intrusion. For brevity, the term *massive leucogabbro* is used subsequently for this unit.

**Black olivine gabbro.**—This unit is presently known only in the North intrusion, and is at surface only in a small area (fig. 2). In drill core, it is dark grey to black, fine to coarse-grained, homogeneous, and superficially appears “ultramafic”. However, it actually contains >60 percent dark grey to black plagioclase, associated with green olivine and purple-bronze clinopyroxene. The plagioclase is commonly prismatic or tabular, in contrast to the more equant habit typical of the massive leucogabbro; its dark color appears to be related to numerous tiny iron-oxide inclusions (MacDonald, ms, 1999). Texturally, black olivine gabbro resembles the massive leucogabbro, that is, it contains large, optically-continuous, interstitial olivine and clinopyroxene crystals. However, it locally also contains early equant cumulus olivines, which are surrounded by intercumulus clinopyroxene, but not included in plagioclase. A fine-grained variant of the unit is a black rock containing poikilitic olivines and clinopyroxenes. Black olivine gabbro was originally considered to be a variant of the massive leucogabbro unit (Fitzpatrick and others, 1998), but key drillholes in the western part of the North intrusion demonstrate that it is a discrete unit (see below). “Melanocratic gabbro” might be an appropriate name for this unit, but would inevitably lead to confusion with “melagabbro”, as used above. Thus, for clarity, the full term *black olivine gabbro* is retained in all subsequent discussions.

**Diabase.**—Very-fine-grained to aphanitic mafic rocks showing ophitic textures are locally present in both the North and South intrusions. Although these rocks are chilled marginal phases rather than discrete intrusions, the term *diabase* is used subsequently for all of them. In the North intrusion, diabase locally sits at the basal contact, below the sulfide-rich rocks of the mineralized sequence. There is also one occurrence of diabase at the upper contact, which grades downwards into massive leucogabbro. Diabase occurs at the basal contact of the South intrusion, and also forms
sheets that appear to intrude layered gabbro in its upper part. Diabases are dominated by turbid, fine-grained intergrowths of clinopyroxene, olivine and plagioclase, and their mineral proportions are thus hard to estimate.

Anatomy and Geometry

Extensive exploration drilling completed since 1996 provides critical information about the geometry of the Pants Lake intrusions, summarized in figure 3. Additional cross-sections are presented and discussed in more detail by Kerr (1999).

South intrusion.—This is a gently west-dipping, slab-like body up to 600 meters thick, which has a basal mafic cumulate zone (fig. 3A). It is structurally overlain by at least two thin sill-like bodies that are believed to be the southernmost part of the North intrusion (see below). The South intrusion is dominated by layered gabbro, with melagabbro near its base. Sulfide mineralization is associated with the melagabbro sequence (see later discussion).

North intrusion.—The North intrusion has complex geometry, and is divided into three interconnected “lobes”, each of which has a distinct stratigraphy. The Happy Face Lobe is dominated by massive leucogabbro, and has only a thin sequence of layered gabbro at its base, associated with sulfide mineralization (fig. 3B). In contrast, the NDT Lobe contains up to 400 meters of layered gabbro, with massive leucogabbro sitting above it (fig. 3C). Sulfide mineralization is similarly located below the layered gabbro. The Taheke Lake Lobe has the most complete stratigraphy; black olivine gabbro sits beneath layered gabbro, which is locally capped by massive leucogabbro (fig. 3C and 3D). However, some layered gabbro also occurs at the base of the body, within the mineralized sequence (see below). There are many uncertainties to the northwest, where the intrusion is not present at explored depths (fig. 3D), and no high-angle or subvertical feeder system to the intrusion has yet been intersected beneath the body. The geometry is best illustrated by structural contours drawn on the basal contact (fig. 4), which resembles an eroded hillside, with its crest running north from Happy Face Lake through the Taheke Lake Lobe. A subsidiary ridge also separates the NDT and Taheke Lake Lobes, between which the basal contact must steepen considerably. A similar steepening must also occur southwest of Taheke Lake. The overall geometry resembles a gentle, north-plunging, open fold, with its axis parallel to the regional structural grain in the host gneisses (fig. 2). This may indicate mild regional deformation of post-1322 Ma age in Labrador, which would only be revealed by its effects on subhorizontal markers such as the Pants Lake intrusions. However, there are variations in the thickness and stratigraphy of the North intrusion that are clearly primary (figs. 3 and 5), and this fold-like pattern may in part reflect original intrusive geometry. The long, worm-like southern extension of the North intrusion (fig. 2) is stratigraphically similar to the Happy Face Lobe and appears to be an extension of it, dipping at about 30° to the northeast (Kerr, 1999). Sill-like bodies in the “Mineral Hill” area (fig. 2) contain layered gabbro overlain by massive leucogabbro; these are considered to be distal extensions of the North intrusion, although the exact nature of their connection remains unclear.

Unit Relationships

South intrusion.—This intrusion is dominated by fine-grained layered gabbro. In drillholes 97-79 and 97-94, there appear to be two subunits separated by a thin zone of sulfide-bearing gabbro, locally underlain by a screen of gneisses, at a depth of about 250 meters (fig. 3A). The upper unit contains a higher density of diabase intervals (probably sheets or dikes) compared to the thicker underlying gabbro sequence, and may thus be older, although there is no direct proof of this. Thin intervals of massive leucogabbro in the upper part of drillhole 97-79 are interpreted as younger intrusive sheets or dikes related to the North intrusion.
North intrusion.—Intrusive relationships between the three main units of the North intrusion are ambiguous. In outcrop, the contact of layered gabbro and overlying massive leucogabbro is sharp but uninformative; in drill core, vein-like zones
of leucogabbro apparently cut the layered gabbro. The contact between the layered gabbro and black olivine gabbro is a diffuse, gradational zone seen only in drill-core. Typically, rounded enclaves that resemble layered gabbro are surrounded by black olivine gabbro; this texture is similar in many respects to composite gabbro within the mineralized sequence (see below), and is interpreted to record liquid-state interaction. Contacts between black olivine gabbro and massive leucogabbro have not been defined on surface or in drill core.

Stratigraphic correlations within the North intrusion are illustrated schematically in figure 5. The mineralized sequence (see below) is viewed as the lowermost section of the black olivine gabbro, and is considered to be its lateral equivalent where the latter is not present as a discrete unit. Local occurrences of a fine-grained variant of the black olivine gabbro above the mineralized sequence in the NDT and Happy Face lobes (Kerr, 1999; Kerr and others, 2001) further support this interpretation.

MINERALIZATION IN THE PANTS LAKE INTRUSIONS

South Intrusion

In the South intrusion, disseminated sulfides occur within basal melagabbro (fig. 3), forming a discontinuous zone up to 50 meters thick. Sulfides (pyrrhotite, chalcopyrite and exsolved pentlandite) form interstitial patches, but the overall sulfide content is low (<10%). The host rocks also contain numerous dark grey to white gneissic fragments, commonly showing dark, spinel-rich reaction rims. There appear to be downward increases in both sulfide content and the proportion of gneissic fragments. Absolute grades are generally low (0.1-0.55% Ni, 0.1-0.32% Cu; Fitzpatrick and others, 1998), and some of the Ni is in olivine, rather than sulfides. Sulfide metal contents (that is, the Ni and Cu in the sulfides, calculated from whole-rock geochemical data, using sulfide contents estimated from sulfur analyses), are relatively high, at 2 to 5 percent Ni and 1 to 3 percent Cu. The Ni/Cu ratio of some South intrusion
mineralization is high (> 2) compared to the North intrusion, even when data are corrected for the presence of Ni in olivines. Ni/Cu ratios are highest in the upper part of the mineralized interval, and are associated with higher sulfide Ni contents (Kerr, 1999).

North Intrusion

In the North intrusion, mineralization is essentially restricted to a 5 meter to 60 meter thick zone located just above the basal contact (figs. 3 and 5), which exhibits a consistent bipartite stratigraphy (fig. 6). The upper part of this comprises a peculiar breccia-like rock, dominated by fine-grained troctolitic enclaves within a coarser-grained, gabbroic, sulfide-bearing matrix. The mafic enclaves are accompanied by diffuse plagioclase-corundum-spinel aggregates interpreted as reacted gneiss fragments. The mafic enclaves resemble the layered gabbro, and contain cumulus olivine, but the gabbroic matrix contains interstitial (late) olivine, and more closely resembles the massive leucogabbro and/or black olivine gabbro. The proportions of sulfides and digested gneiss fragments commonly increase downwards through this material (fig. 6). Rocks of this type are very difficult to label; thus, the simple, nongenetic term composite gabbro is used in all subsequent discussions.

The composite gabbro sequence is underlain by more homogeneous, fine-grained gabbro, typically containing round sulfide masses (frozen droplets?) and also fine-grained interstitial sulfides. This lower sequence is thicker in the Taheke Lake and Happy Face lobes than in the NDT lobe. These more homogeneous rocks texturally resemble the layered gabbro, aside from the presence of gneissic debris and sulfides. This lower sequence commonly also includes “leopard-textured gabbro”, in which poikilitic clinopyroxenes are surrounded by an olivine-rich matrix containing interstitial sulfides. A fine-grained gabbroic rock that contains poikilitic olivine, clinopyroxene (and variable amounts of sulfide) is also locally present; this closely resembles finer-grained unmineralized variants of the black olivine gabbro. The term poikilitic...
olivine diabase is used subsequently for this material. The lower part of the mineralized sequence exhibits local gravitational accumulation of sulfides, suggesting relatively tranquil conditions. The lowermost section of the mineralized sequence is commonly a barren, fine-grained gabbro, which is locally chilled against the basal contact. Massive sulfides are present only locally, and in many cases appear to have invaded this contact region and the underlying gneisises. Sulfide mineral assemblages consist largely of pyrrhotite, chalcopyrite and exsolved pentlandite. More detailed petrological studies of one massive sulfide intersection (Naldrett and others, 2000) also identified significant troilite, and minor cubanite.

The absolute grades of mineralization in the North intrusion range from less than 0.2 percent Ni to about 2 percent Ni, with subequal Cu contents. The most spectacular results came from a narrow (1.1 m) massive sulfide zone intersected below the basal contact in drillhole 97-75, which yielded 11.7 percent Ni, 9.7 percent Cu, 0.4 percent Co and 0.8 g/T Pd, and the thickest semimassive sulfide intersection to date was 15.7 meters of 1.2 percent Ni, 0.9 percent Cu and 0.22 percent Co in drillhole 97-96.

<table>
<thead>
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<th>UPPER SUBSEQUENCE</th>
<th>COMPOSITE GABBRO SEQUENCE WITH DOWNWARD INCREASE IN SULFIDE CONTENT AND DIGESTED GNEISSIC FRAGMENTS</th>
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<td>Intercalated leopard-textured gabbro or poikilitic olivine diabase</td>
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<tr>
<td>Composite gabbro</td>
<td>Fine-grained olivine gabbro, or poikilitic olivine diabase, with disseminated sulfides, and digested gneissic fragments</td>
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<td>Leopard-textured gabbro, gradational with overlying unit, with intercalated barren units, and gneissic fragments</td>
<td>Interbanded mineralized and barren gabbro, cut by rare massive sulfide veins</td>
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<td>Chilled, barren gabbro</td>
<td>Massive sulfides</td>
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| Footwall gneisses, invaded by sulfide zones, locally massive |}

Fig. 6. Idealized stratigraphy of the North intrusion mineralized sequence, showing its persistent bipartite pattern. Individual intersections of the mineralized sequence may lack some of the components, but the basic pattern is almost always present.
Other thin zones (\(<50 \text{ cm}\)) containing 3 to 5 percent Ni have also been reported during exploration. Pt and Pd values obtained on a subset of typical mineralized samples (Kerr, 2002a) are generally low (\(< 50 \text{ ppb combined}\)), with maximum values of 55 ppb Pt and 96 ppb Pd.

Sulfide metal contents (corrected for silicates) in the North intrusion exhibit a wide range, but most lie between 1 percent and 3 percent for both Ni and Cu (fig. 7). Ni/Cu ratios are remarkably consistent; averaging about 1.15, lower than most of the South intrusion mineralization (fig. 7). Sulfides from the heterogeneous upper part of the mineralized sequence generally have higher Ni and Cu contents than the underlying homogeneous section (fig. 7), and are enriched in the upper part by a factor of 2 to 3 (Kerr and Ryan, 2000). Data from individual drill holes (Fitzpatrick and others, 1998) commonly show a marked decrease in sulfide metal contents at the transition zone, although there are also examples showing smooth decreases throughout the mineralized sequence. Sulfide metal contents exceeding 3 percent Ni and 3 percent Cu are uncommon, and mostly occur in the Taheke Lake Lobe (fig. 7). Outliers of gabbro in the Mineral Hill area also contain basal sulfide mineralization, in homoge-
neous gabbro that contains scattered digested gneiss fragments. The inclusion-rich composite gabbros seen elsewhere in the North intrusion are rare in this area. Sulfide metal contents are low (typically <1% Ni and < 1% Cu), and resemble values from the lower (homogeneous) part of the mineralized sequence elsewhere (Fitzpatrick and others, 1998; Kerr, 1999).

**Geochemistry**

Major and trace element compositions of the principal units in the Pants Lake intrusions are summarized in table 1, rare-earth element (REE) data are summarized in table 2, and the compositions of mineralized rock types are summarized in table 3. The complete database is available via an open-file publication, in digital format (Kerr, 2002b).

*Major Element Patterns and Trends*

Major element patterns are typical of high-alumina mafic suites, and differences between the various units are predictable from mineralogy (table 1). For example, melagabbro has high MgO and Fe₂O₃ and low SiO₂ and Al₂O₃ compared to layered gabbro (fig. 8A). Similarly, the plagioclase-rich massive leucogabbro unit has higher Al₂O₃, and lower MgO and Fe₂O₃ (fig. 8B). There are no clear distinctions between massive leucogabbro and black olivine gabbro. Diabases, which represent the closest approach to “liquid” compositions, are in general more evolved than spatially associated layered gabbro, having higher TiO₂, K₂O and P₂O₅, and lower MgO (table 1; fig. 8C and 8D).

South intrusion units are enriched in TiO₂, Na₂O, K₂O and P₂O₅, and define a separate trend from North intrusion data (table 1; fig. 8C and 8D). This distinction is shown by the layered gabbro, melagabbro and diabase units, which are common to both intrusions. Pants Lake intrusion gabbros generally resemble the mafic rocks of the Voisey’s Bay and Mushuau intrusions (fig. 8A and 8B), and diabase samples correspond well with fine-grained gabbroic and troctolitic rocks grouped as part of the “conduit assemblage” at Voisey’s Bay by Li and others (2000). However, rigorous geochemical comparisons with the Voisey’s Bay area are hampered by a lack of published analytical data other than average compositions reported by Li and others (2000).

*Trace Element Patterns and Trends*

Trace element patterns echo the distinctions between South and North intrusions noted above. South intrusion units are consistently enriched in Ba, Nb, Ce, La and Dy, and variably enriched in Sr, Zr and Y at a given MgO content (table 1; fig. 9), and [Sr+Ba] versus [Ce/Y] provides an effective discriminant for the two areas (fig. 10). The higher Ce/Y ratio indicates a steeper REE pattern, as Y essentially mimics the HREE Yb. Contrasts were noted also by MacDonald (ms, 1999), who suggested that the South intrusion had average Ce/Yb of 22 and Th/Ta of 2, versus 8 and 4 respectively for the North intrusion.

Ni is strongly correlated with MgO, indicating control by olivine in sulfide-free rocks, but Cu is poorly correlated (fig. 11A and 11B). Very strong Ni-Co-MgO correlations suggest that Co is largely controlled by olivine, rather than by clinopyroxene or oxides (Kerr and others, 2001). Excluding South intrusion melagabbro, which contains sulfides, the highest Ni contents are from layered gabbro and black olivine gabbro (table 1; fig. 11A), but both units vary widely. The majority of samples contain less than 100 ppm Co and 150 ppm Ni. Ni/Cu ratios range from <0.5 to >20 (fig. 11C), contrasting with the strong covariance in mineralized samples (fig. 7). This pattern reflects the influence of cumulus olivine. Diabase samples have low Ni/Cu (0.5 to 2), and an average value of 0.95, slightly below that of mineralized rocks (Kerr, 1999; fig. 7). Ni/Co changes in a similar manner, from 0.25 to 1.0 in diabase, to > 4.0 in
**Mean and representative compositions of unmineralized units in the Pants Lake intrusions.**

See key for explanation of analyses.

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<tr>
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<td>100.29</td>
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</table>

**Canada: Implications for the development of magmatic sulfides in mafic systems**

---

**Table 1**

**Key to Individual Analyses:**

South intrusion

1. Melagabbro and peridotite (all data; samples contain sulfide mineralization)
2. Fine-grained, layered, olivine gabbro unit.
3. Diabase units in the upper section of drillhole SVB-97-86.

North intrusion

5. Melagabbro (unmineralized)
6. Fine-grained, layered, olivine gabbro unit (NDT and Happy Face lobes).
7. Fine-grained, layered, olivine gabbro unit (Taheke Lake lobe).
8. Basal diabase units (NDT lobe).
10. Massive, coarse-grained, leucogabbro (Happy Face lobe).
11. Massive, coarse-grained, leucogabbro (NDT and Happy Face lobes).
12. Black olivine gabbro (Taheke Lake lobe).
Table 2

Mean and representative REE compositions of unmineralized units in the Pants Lake intrusions. See key for explanation of analyses.

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<tr>
<th>Unit</th>
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<th>Ce</th>
<th>Pr</th>
<th>Nd</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd</th>
<th>Tb</th>
<th>Dy</th>
<th>Ho</th>
<th>Er</th>
<th>Tm</th>
<th>Yb</th>
<th>Lu</th>
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<tr>
<td>Normalization Factors used in REE Charts (from Sun and McDonough, 1989)</td>
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South intrusion - Unmineralized Rocks

- Melagabbro* 2 9.1 22.0 3.0 13.8 3.2 0.9 3.0 0.4 2.5 0.5 1.3 0.2 1.1 0.2
- Fine-grained Ol-gabbro 4 10.8 25.6 3.5 16.0 3.5 1.5 3.4 0.5 2.7 0.5 1.4 0.2 1.2 0.2
- Basal diabase 2 38.1 85.8 10.9 45.5 8.7 2.7 8.0 1.1 6.4 1.2 3.6 0.5 2.8 0.4

North intrusion - Unmineralized Rocks

- Fine-grained Ol-gabbro 10 4.8 11.0 1.5 7.1 2.0 0.9 2.3 0.4 2.4 0.5 1.5 0.2 1.4 0.2
- Massive Leucogabbro 6 7.5 17.4 2.4 11.2 3.1 1.2 3.6 0.6 3.8 0.8 2.3 0.3 2.1 0.3
- Black Ol-gabbro 9 5.7 13.2 1.9 8.8 2.5 1.1 2.9 0.5 3.1 0.6 1.9 0.3 1.7 0.3
- Basal Diabase 2 8.8 20.1 2.7 12.5 3.2 1.3 3.8 0.6 4.0 0.9 2.7 0.4 2.3 0.3
- Upper diabase 1 15.8 33.4 4.2 17.0 3.8 1.4 3.8 0.6 3.7 0.8 2.2 0.3 2.0 0.3

Mineral Hill area - Unmineralized Rocks

- Fine-grained Ol-gabbro 2 7.7 17.7 2.4 11.2 3.1 1.2 3.5 0.6 3.7 0.8 2.2 0.3 2.1 0.3
- Massive Leucogabbro 2 6.0 14.3 2.0 9.8 2.8 1.2 3.2 0.5 3.5 0.7 2.2 0.3 2.0 0.3
- Basal diabase 2 16.0 34.7 4.5 20.0 4.9 1.7 5.3 0.8 5.4 1.1 3.2 0.5 2.9 0.5

South intrusion - Mineralized Rocks

- Melagabbro 2 9.1 22.0 3.0 13.8 3.2 0.9 3.0 0.4 2.5 0.5 1.3 0.2 1.1 0.2
- Mineralized gabbro 2 9.8 23.3 3.2 14.5 3.2 1.4 3.1 0.4 2.5 0.5 1.3 0.2 1.1 0.2

North intrusion - Mineralized Rocks

- S-poor Comp. Gabbro 4 5.8 13.6 1.9 8.9 2.6 1.1 3.1 0.5 3.2 0.7 2.1 0.3 1.8 0.3
- S-rich Comp. Gabbro 6 6.3 14.0 1.9 8.7 2.3 1.0 2.7 0.4 2.8 0.6 1.9 0.3 1.6 0.2
- Leopard gabbro 3 7.2 16.1 2.1 9.9 2.5 1.2 2.9 0.5 3.0 0.6 1.8 0.3 1.7 0.3
- Mineralized Gabbro 3 4.4 10.1 1.4 6.6 1.9 1.0 2.2 0.4 2.3 0.5 1.5 0.2 1.3 0.2
- Poikilitic Ol diab 1 5.6 13.2 1.9 8.9 2.5 1.2 3.0 0.5 3.4 0.7 2.2 0.3 1.9 0.3

Mineral Hill area - Mineralized Rocks

- Leopard gabbro 2 6.0 13.8 1.9 8.8 2.4 1.0 2.8 0.4 2.8 0.6 1.8 0.2 1.6 0.2

All data are in ppm

*Contains sulfides-analysis is repeated with mineralized rocks in the lower part of the table.
olivine-rich melagabbro (Kerr and others, 2001). These values are significantly lower than those of mineralized rocks, in which Ni/Co averages about 8, albeit with wide variation (Kerr, 1999).

Virtually all unmineralized rocks have low Cu/Zr (0.2-0.8), and Cu/Zr is poorly correlated with Ni (fig. 11D). Two diabase samples from the North intrusion have high

---

**Table 3**

Mean and representative compositions of mineralized units in the Pants Lake intrusions. See key for explanation of analyses.

<table>
<thead>
<tr>
<th>Area</th>
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<td>n=5</td>
</tr>
<tr>
<td>4</td>
<td>n=3</td>
<td></td>
</tr>
</tbody>
</table>

| SiO₂          | 41.14           | 45.86           |
| TiO₂          | 1.34            | 1.03            |
| Al₂O₃         | 8.24            | 18.18           |
| Fe₂O₃         | 18.35           | 14.78           |
| MnO           | 0.20            | 0.17            |
| MgO           | 21.77           | 7.05            |
| CaO           | 4.17            | 9.04            |
| Na₂O          | 1.61            | 2.77            |
| K₂O           | 0.39            | 0.42            |
| P₂O₅          | 0.30            | 0.10            |
| LOI           | 2.83            | 1.16            |

| Total         | 100.34          | 100.32          |

| Li            | 5.9             | 8.1             |
| Be            | 0.3             | 0.3             |
| Sc            | 10.5            | 21.8            |
| V             | 82              | 145             |
| Cr            | 121             | 62              |
| Co            | 149             | 119             |
| Ni            | 820             | 546             |
| Cu            | 340             | 560             |
| Zn            | 118             | 106             |
| Rb            | 2               | 7               |
| Sr            | 160             | 296             |
| Y             | 12              | 18              |
| Zr            | 72              | 65              |
| Nb            | 4               | 3               |
| Mo            | 1               | 1               |
| Ba            | 172             | 164             |
| La            | 7               | 5               |
| Ce            | 21              | 15              |
| Dy            | 2.3             | 2.8             |
| Pb            | 5               | 4               |

Key to Individual Analyses

1. Melagabbro and peridotite (also listed in table 1)
2. Composite gabbros (sulfide- and fragment-poor varieties).
3. Composite gabbros (sulfide- and fragment-rich varieties).
4. Leopard-textured gabbro.
5. Homogeneous, sulfide-bearing gabbro (not subdivided).
7. Barren gabbro from the lowermost part of the mineralized sequence.
Cu/Zr, but these are known to contain minor sulfide; all other diabases appear to be Cu-depleted. Cu/Zr < 1 in mafic rocks is generally considered to record the effects of sulfide liquid removal, which affects Cu, but not Zr (for example, Lightfoot and others, 1994; Li and Naldrett, 1999). Low Cu/Zr and Cu/Hf ratios were noted by MacDonald.

Fig. 8. Selected major element trends for unmineralized rocks in the Pants Lake intrusions. (A) CaO versus MgO; (B) Al₂O₃ versus SiO₂. Each plot is split into two to increase legibility; the right hand plot shows only data from massive leucogabbro and black olivine gabbro units. Fields for Voisey’s Bay and Mushuau Intrusions are from Li and others (2000).
ms, 1999), and suggested to be indicative of sulfide liquid removal; the larger database considered here indicates that this feature is truly pervasive.

**Rare Earth Element (REE) Patterns**

Layered gabbros from the North intrusion have gently-sloping patterns, with normalized La/Lu of 2 to 3, and a positive Eu anomaly, indicating cumulus plagioclase (fig. 12A). The amplitude of the Eu anomaly is inversely correlated with the total REE.
abundance, indicating dilution of the other REE by plagioclase. A troctolite sample has similar overall REE content to the more common gabbroic rocks. North intrusion diabases have REE abundances and patterns akin to those of the most REE-enriched gabbros, but negligible Eu anomalies (fig. 12A). Gabbros from the Mineral Hill area have gently-sloping REE patterns that closely resemble those from the North intrusion.

Fig. 9. Selected trace element trends for unmineralized rocks in the Pants Lake intrusions. (A) Sr versus MgO; (B) Ba versus MgO. (C) Nb versus MgO and (D) Ce versus MgO. Legend and arrangement as for figure 8.

Andrew Kerr—Nickeliferous gabbroic intrusions of the Pants Lake area, Labrador,
This suggests that they do correlate with the North intrusion, despite a superficial resemblance to the South intrusion in terms of some major and trace elements (table 1; figs. 8 and 9). The South intrusion layered gabbros have a steeper REE pattern, with a normalized La/Lu ratio of about 6 to 8 (fig. 12B); modest positive Eu anomalies are inversely correlated with total REE abundance. South intrusion diabases are REE-enriched, show LREE enrichment, and lack significant Eu anomalies.
Melagabbro from the South intrusion has a steep REE pattern similar to that of layered gabbro (fig. 12D). Massive leucogabbros from the Happy Face and NDT lobes of the North intrusion have identical REE patterns to the layered gabbro in this area (fig. 12E). Diabase from a chill at the upper contact of the massive leucogabbro unit (Happy Face Lobe) is slightly LREE-enriched, which may reflect gneiss xenoliths noted in drill-core, but is otherwise also identical. Coarse-grained leucogabbro from the Mineral Hill area is identical to that elsewhere in the North intrusion (fig. 12E). The REE profile of the black olivine gabbro closely resembles those of other units in the North intrusion. Its overall REE abundances are intermediate between those of layered gabbro and massive leucogabbro, but overlap both (fig. 12F).

The REE profiles for the Pants Lake intrusions resemble those reported from the Voisey’s Bay and Mushuau Intrusions (Emslie, 1996; Lightfoot and Naldrett, 1999; Li and others, 2000). Troctolites from the Voisey’s Bay Intrusion have distinctly steeper REE profiles than the North intrusion gabbros, but show the same inverse correlation between their Eu anomalies and total REE content. The Voisey’s Bay Intrusion REE profiles are closely similar to those from the South intrusion (fig. 12B), as noted previously by MacDonald (ms, 1999). REE profiles of melagabbro from the South intrusion resemble those of melatroctolite inclusions at Voisey’s Bay (Li and others, 2000), but show higher REE contents (fig. 12D). The North intrusion REE patterns, regardless of unit, more closely match the patterns from the Mushuau Intrusion (fig. 12).
Geochemistry of Mineralized Rocks

Table 3 lists the average compositions of rock types within the mineralized sequences of the North and South intrusions; mineralized melagabbro from the South intrusion is also listed in table 1. The North intrusion mineralized sequence is divided into four main units: (1) sulfide-poor composite gabbro, (2) sulfide-rich composite gabbro, (3) leopard-textured gabbro, and (4) undivided, mineralized, fine-grained gabbro. Average analyses of the lowermost barren gabbro and poikilitic olivine diabase are also listed. The distinction between varieties of composite gabbro is purely visual; in most cases, increased sulfide content is accompanied by an increase in the proportion of digested gneiss fragments (Kerr, 1999). The sulfides in these rocks make interpretation of data far more difficult than for the unmineralized rocks.

Average major element compositions of sulfide-poor and sulfide-rich composite gabbro differ little, aside from higher total Fe and lower SiO₂ in the latter, due to sulfides. Digested gneiss fragments, which are dominated by plagioclase and spinel (Kerr, 1999), may account for higher mean Al₂O₃ concentrations in sulfide-rich gabbros. The average trace element compositions are essentially identical, aside from differences in Ni, Cu and Co, again due to sulfides. Otherwise, composite gabbros are geochemically similar to unmineralized North intrusion gabbros. There is thus no obvious geochemical signature from the digested gneiss fragments, although extremely fragment-rich examples were avoided during sampling. Leopard-textured gabbros are sulfide-rich, as indicated by very high total Fe, Ni, Cu and Co, and rigorous comparisons to unmineralized units are very difficult. Undivided, mineralized fine-grained gabbro resembles its unmineralized counterpart, aside from a higher K₂O content. However, the barren fine-grained gabbro from the lowermost part of the mineralized sequence is richer in TiO₂ and K₂O than unmineralized fine-grained gabbro, and also shows a twofold relative enrichment in La, Ce and Dy.

In general, mineralized rocks have more variable compositions than their unmineralized counterparts, but cannot be distinguished from them, although they do tend to have higher K₂O, particularly at lower MgO contents. Differences in trace element patterns are mostly connected to the effects of sulfides. For example, Ni and Co are no longer correlated with MgO but there are strong correlations between Ni, Cu and Co indicating control by sulfides (fig. 7; Kerr, 1999; Kerr and others, 2001). The Ni/Cu and Ni/Co ratios of mineralized rocks resemble those in unmineralized rocks that have low MgO contents, that is, those that are least influenced by cumulus olivine.

REE patterns are more useful, because they are not affected by sulfides. Composite gabbros have REE profiles that closely resemble those of North intrusion layered gabbro, but tend to have higher LREE abundances. Their REE patterns most closely resemble those of the black olivine gabbro (fig. 13A and 13B). Only one sample shows LREE enrichment suggesting a signature from gneissic debris. Homogeneous sulfide-bearing gabbros (including leopard-textured rocks) have patterns that closely resemble those of unmineralized layered gabbro (fig. 13C). In summary, REE patterns from the North intrusion mineralized sequence closely resemble those of its unmineralized rocks. A mineralized medium-grained gabbro from drillhole 97-79 in the South intrusion has the steeper REE pattern characteristic of this area (fig. 13D), and resembles closely the mineralized cumulate rocks (fig. 12D). These similarities indicate a close genetic link between both of the mineralized sequences and their host intrusions.

SUMMARY AND DISCUSSION

Some General Features of the Pants Lake Intrusions

The Pants Lake intrusions are not “primitive” in the absolute sense of the word (that is, they are not ultramafic or picritic), but they are certainly amongst the least evolved intrusions within the Nain Plutonic Suite, and resemble other such examples
listed by Scoates and Mitchell (2000). The mafic rocks are mineralogically simple, but those of the North intrusion show evidence for at least two different crystallization sequences. The layered gabbro unit in both South and North intrusions had olivine on the liquidus at an early stage, together with plagioclase. In contrast, massive leucogabbro and black olivine gabbro units in the North intrusion have textures indicating late

Fig. 11 Patterns for “ore elements” and related parameters for unmineralized rocks in the Pants Lake intrusions. (A) Ni versus MgO; (B) Cu versus MgO; (C) Ni versus Cu, showing variations in Ni/Cu, and (D) Cu/Zr versus Ni. Note that these plots include only unmineralized samples; see figure 7 for an indication of Ni/Cu ratios in mineralized rocks.
(post-plagioclase) crystallization of both olivine and clinopyroxene. Thus, in addition to the approximately 15 Ma age difference between South and North intrusions, the North intrusion must include at least two discrete “batches” of mafic magma. Thus, in all senses of the word, the Pants Lake intrusions are composite in nature. The Pants Lake intrusions are flat-lying or gently dipping (fig. 3), and strongly discordant to regional tectonic fabrics. They were thus likely emplaced under static or extensional tectonic regimes, unaccompanied by penetrative deformation. However, there is
Fig. 12. REE patterns for unmineralized rocks in the Pants Lake intrusions. (A) layered gabbro and diabases, North intrusion; (B) layered gabbro and diabases, South intrusion; (C) layered gabbro and diabases, Mineral Hill area; (D) melagabbro, South intrusion; (E) massive leucogabbro and associated diabases, North intrusion and (F) black olivine gabbro, North intrusion. Fields for Voisey’s Bay and Mushua Intrusions are derived from summary data of Li and others (2000). Normalization after Sun and McDonough (1989); values listed in table 2.
evidence that the North intrusion has been gently folded (fig. 4), suggesting some previously unrecognized post-1322 Ma gentle deformation, which is otherwise unconstrained. Such late structures may be widespread elsewhere in the region, but would largely be invisible because of the absence of flat-lying structural elements to define them.

**Geochemical Contrasts and Similarities Amongst the Pants Lake Intrusions**

The overall geochemical similarities of gabbros from the Pants Lake intrusions are hardly surprising in view of their common mineralogy. However, subtle yet systematic geochemical contrasts (figs. 8, 9 and 10) point to differences in the parental magmas to the South and North intrusions (MacDonald, ms, 1999; Kerr and others, 2001). Layered gabbro from the South intrusion is consistently enriched in TiO₂, K₂O, Na₂O and P₂O₅ (fig. 8), and variably enriched in Cr, Sr, Ba, Nb, Zr, Y, La and Ce (figs. 9 and 10), compared to its North intrusion counterpart. The same distinctions are shown by spatially associated mafic cumulates and diabases. The REE profiles for South intrusion units are distinctly steeper (that is, LREE-enriched) than those of the North intrusion (MacDonald, ms, 1999; fig. 12).
Within the North intrusion, there is a general evolutionary progression from “primitive” melagabbro, through layered gabbro and black olivine gabbro, to the more “evolved” massive leucogabbro (for example, fig. 8). Such patterns do not necessarily indicate differences in parent magma compositions, as they could be controlled simply by mineral proportions. However, the textural differences do suggest that individual North intrusion units crystallized from discrete (but very closely related) batches of magma. The identical REE profiles of all North intrusion units (fig. 12) provide strong evidence for a close genetic link amongst them, and also with gabbro outliers of the Mineral Hill area. The ambiguous relationships between the North intrusion units make reconstruction of its emplacement sequence difficult. There is some evidence that the massive leucogabbro unit postdates crystallization of both the layered gabbro and black olivine gabbro units. However, the diffuse nature of the contacts observed between the latter two units implies that they coexisted in a semiliquid state, and are of closely similar age.

**Geochemical Comparisons with the Mafic Rocks of the Voisey’s Bay Area**

Mafic rocks of the Pants Lake intrusions are compositionally similar to those of the Voisey’s Bay area. Table 4 provides comparisons with the Voisey’s Bay and Mushuau Intrusions (Li and others, 2000). The layered gabbro units are similar to the “normal troctolite” and “variable-textured troctolite” units of the Voisey’s Bay Intrusion, and there is a particularly good match in the case of the South intrusion. The Voisey’s Bay Intrusion troctolites have higher Sr, Ni, Co and Cu, but the high Ni and Cu of the variable-textured troctolite reflect dispersed sulfide mineralization, and are not indicative of magmatic concentrations (Li and others, 2000). Geochemical variation diagrams indicate a general correspondence between the Pants Lake intrusions and both the Voisey’s Bay and Mushau Intrusions for some major elements (fig. 8), but more rigorous comparisons are presently impossible. REE Profiles from South intrusion units closely match those of the Voisey’s Bay Intrusion (MacDonald, ms, 1999; fig. 12), whereas those from the North intrusion more closely resemble the Mushau Intrusion (fig. 12). Extended-trace element profiles (normalized to primitive mantle) lead to essentially the same conclusions (Kerr and others, 2001).

Lightfoot and Naldrett (1999) and Li and others (2000) suggest that the Mushuau and Voisey’s Bay Intrusions have differing contamination histories, that is, the former was contaminated by Archean crust whereas the latter assimilated more material from the metasedimentary Tasiuyak Gneiss. The Pants Lake data cannot be so interpreted, because the country rocks to both intrusions are identical. Differences could perhaps instead be related to the *amounts* of contamination by metasedimentary gneisses, but the abundant reacted gneiss fragments in the North intrusion mineralized sequence attest to significant contamination. If the South intrusion experienced more contamination, the physical evidence for it is far less obvious. Thus, the geochemical differences between South and North intrusion parental magmas may in part be source-related, rather than linked to a specific contamination history. The answers to this question lie ultimately in radiogenic isotopic studies, which can more directly measure the influence and type of contamination. These are in progress as of writing.

The geochemical affinities to the Voisey’s Bay Intrusion highlight the South intrusion as a future exploration target. As noted previously, some sulfides associated with the South intrusion have metal contents and ratios akin to those at Voisey’s Bay. The South intrusion is also far less explored, partly because of the greater depths to its prospective basal contact (fig. 3).

**Origins of Mineralization in the South Intrusion**

Sulfides in the South intrusion are essentially restricted to melagabbro, within which they are interstitial and appear syngenetic. Reacted country-rock fragments are also more abundant in the basal melagabbro than elsewhere in the body. As the host
## Table 4
Comparison between mean compositions of the Pants Lake intrusions and troctolitic rocks of the Voisey’s Bay area, as presented by Li and others (2000).

<table>
<thead>
<tr>
<th>Key</th>
<th>Area</th>
<th>South intrusion</th>
<th>North intrusion</th>
<th>Voisey’s Bay Intrusion</th>
<th>Mushuau Intrusion</th>
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Key to Individual Analyses
South intrusion
1: Fine-grained olivine gabbro (all data, also listed in table 1)
North intrusion
2: Fine-grained olivine gabbro (all data, including Mineral Hill area)
3: Massive, coarse-grained leucogabbro (all data, including Mineral Hill area)
4: Black olivine gabbro, North intrusion (all data, also listed in Table 1)
Voisey’s Bay Intrusion
5: ‘Normal troctolite’ (mostly from the Eastern Deeps area)
6: ‘Variable troctolite’ (mostly from the Eastern Deeps area)
7: ‘Conduit rocks’ (various locations)
8: ‘Melatroctolite inclusions’ (various locations)
Mushuau Intrusion
9: ‘Melatroctolite’ unit
10: ‘Variable troctolite’ unit
rocks are cumulates, mineralization is logically attributed to gravitational accumulation of mafic minerals, gneissic fragments (dominated by calcic plagioclase and spinel) and sulfide droplets. The variation in sulfide metal contents within the South intrusion mineralized sequence suggests progressive changes in the ratio of sulfide liquid to silicate magma (R factor) as the magma chamber evolved and grew, and the variation in Ni/Cu ratios suggests at least some changes in magma composition. Sulfides appear to become more metal-rich and possibly more Ni-rich with stratigraphic height, implying that there was a progressive increase in the R-factor, perhaps reflecting a longer residence time for sulfides within the magma chamber, or a greater settling distance, both of which would provide more opportunity for individual droplets to scavenge metals. Compared to the North intrusion (see below), there is no strong evidence for multiple influxes of sulfide-charged magma in the lower part of the South intrusion. However, the upper subunit in drillholes 97-79 and 97-94 also contains a basal sulfide accumulation, which suggests that the intrusion as a whole may have been emplaced in two stages, each of which involved the formation and accumulation of sulfides.

Origins of Mineralization in the North Intrusion

The mineralized sequence of the North intrusion is complex, and readers are referred to Kerr (1999) for full descriptive details. It contains unusual rock types that are not seen elsewhere, and in most cases it is not gradational with the overlying unmineralized rocks, but has a sharp boundary against them. It has a persistent bipartite stratigraphy, consisting of a heterogeneous, breccia-like upper section, and a more homogeneous lower section that contains disseminated sulfides (fig. 6). The mineralized sequence is present in all areas of the intrusion, and its development must therefore have been part of (an) intrusion-wide event(s). It probably represents one or more discrete pulses of magma that carried immiscible sulfide liquid and reacted gneiss fragments. These were probably early influxes of magma, as the mineralized sequence is always situated near the base of the intrusion. However, the normal laws of stratigraphic superposition do not always apply in magmatic environments, and there was probably some resident, partially crystallized magma in the chamber at the time of their emplacement.

Upper (Heterogeneous) Subsequence.—The distinctive rock type termed composite gabbro provides fundamental clues to development of the mineralized sequence. This rock type has many similarities to “basal breccia” or “feeder breccia”, as described from the Voisey’s Bay deposit (Naldrett and others, 1996; Li and Naldrett, 1999). It is here interpreted to form through the emplacement of a sulfide- and fragment-charged magma batch into partially consolidated mafic magma that was already resident in the chamber. The result is a “mixed” rock, of variable appearance. Ellipsoidal troctolitic inclusions resemble mafic enclaves interpreted to have formed in environments where one magma “froze” upon contact with the other (for example, Vernon, 1984; Weibe, 1987). Textural variations amongst composite gabbros probably reflect the material and thermal states of the end-member magmas, and the degree of mixing, which are interdependent (Kerr, 1999). Thus, they range from rare examples containing angular mafic fragments (representing disruption of largely solid resident material) to blotchy, “curdled” rocks in which matrix-inclusion relationships are indistinct (representing more extensive liquid-liquid mixing). In most cases, the resident magma froze during mixing, to form the ellipsoidal mafic enclaves. The fabrics defined by enclave alignment are commonly subparallel to the base of the intrusion, and thus likely result from lateral flow as the sulfide-bearing magma spread out within the magma chamber. Most mafic enclaves in composite gabbro resemble the layered gabbro unit, but the sulfide-bearing matrix resembles the massive leucogabbro and black olivine gabbro units. In the Taheke Lake lobe, black olivine gabbro appears to pass directly down into sulfide-bearing composite gabbro, locally interlayered with mineralized poikilitic
olivine diabase, which resembles a fine-grained version of black olivine gabbro. Poikilitic olivine diabase also occurs locally within and above the mineralized sequence elsewhere in the North intrusion, where the thick sequence of black olivine gabbro is absent. Composite-gabbro-like rocks are also locally developed at the upper contact of the black olivine gabbro in the Taheke Lake lobe, where they are similarly interpreted to record mixing between black gabbro parent magma and layered gabbro parent magma. Overall, there appears to be a very close relationship between composite gabbro and black olivine gabbro, and it is suggested that the matrix material in the former is directly equivalent to the latter. The mineralized sequence in the NDT and Happy Face lobes is therefore interpreted as the lateral equivalent of black olivine gabbro and mineralized sequence in the Taheke Lake lobe, as indicated previously in figure 5. The extensive digestion and reaction of gneissic fragments in composite gabbro implies that most came from deeper levels, and had long residence times in the magma. These inclusions are dominated by Ca-rich plagioclase, corundum and spinel, and resemble those described from Voisey’s Bay (Li and Naldrett, 1999; Li and Naldrett, 2000).

Lower (Homogeneous) Subsequence.—Rocks that resemble the layered gabbro unit, but contain disseminated sulfides dominate the lower part of the mineralized sequence. In contrast to the upper sequence, which is interpreted to be a dynamic environment, it represents a quieter environment in which sulfides were able to settle gravitationally. “Leopard-textured” gabbro, which consists of clinopyroxene oikocrysts sitting within a mineralized, troctolitic matrix, has many affinities to “leopard troctolite” from Voisey’s Bay. The latter was interpreted to form by growth of clinopyroxene crystals in sulfide-bearing magma (Naldrett and others, 1996; Li and Naldrett, 1999). However, the texture could also form via the introduction of sulfides into a partially crystalline magma in which clinopyroxene oikocrysts already existed, that is, through liquid-state mixing processes. The lower part of the mineralized sequence probably developed as sulfide droplets and gneissic fragments derived from an influx of sulfide-rich magma (now represented by the composite gabbros) “rained down” into underlying, partly-crystallized, mafic magma. However, this underlying magma already contained some sulfide liquid, because very fine-grained interstitial mineralization typically accompanies larger, droplet-like accumulations. The lowermost section of the mineralized sequence is commonly barren, and is thus interpreted to have cooled and solidified prior to the arrival of the sulfide- and fragment-charged magma batches that now sit above it.

Variations in Metal Contents.—Sulfides in the upper heterogeneous subsequence have higher Ni and Cu contents (typically 1.5-3% Ni) compared to those in the lower homogeneous subsequence (typically 0.4%-1% Ni). These differences imply that the latter already contained a low-grade sulfide liquid, and that variable amounts of higher-grade sulfide liquid were subsequently added when a second batch of sulfide-charged magma was emplaced above it. The time lapse between emplacement of these two pulses is interpreted to be brief, but cannot be constrained.

Geochemistry of the Mineralized Sequences

Mineralized melagabbros in the South intrusion mineralized sequence are geochemically akin to unmineralized layered gabbros higher in the intrusion, and thus probably formed as mafic cumulates. Similarly, the rocks of the North intrusion mineralized sequence closely resemble those of its unmineralized units, aside from differences in total Fe and chalcophile elements, due to sulfides (table 3). The REE patterns of mineralized and unmineralized rocks in the North intrusion are essentially identical (figs. 12 and 13). The geochemical data thus fully support other indications that both mineralized sequences have close genetic relationships to the larger intrusive bodies with which they each are associated.
In the North intrusion, most composite gabbros are geochemically indistinguishable from homogeneous gabbros. This is in part predictable, because many composite gabbros are essentially troctolitic inclusions in a gabbroic matrix, but sulfide-rich composite gabbros, in which gneissic fragments are abundant, also show little geochemical evidence of this material (fig. 13). However, the residual plagioclase-spinel assemblages of reacted gneiss fragments are dominated by CaO, Al₂O₃, MgO, Fe₂O₃ and SiO₂, which are already abundant in mafic magmas, and vary independently as a function of mineralogy. Thus, the lack of a clear geochemical signature from digested gneiss fragments is not surprising, especially as the data cannot be corrected for sulfides. This feature again implies that reaction and digestion of the gneiss xenoliths was not a purely local process, but rather occurred at greater depths. The contaminants released by the assimilation of the gneisses (for example, SiO₂, K₂O, Na₂O, and various incompatible trace elements) must have been dispersed, and likely contribute to the overall geochemical traits of the North intrusion. The presence of identical reacted gneiss fragments in the South intrusion mineralized sequence implies the operation of similar processes at depth.

Scale and Significance of Metal Depletion Signatures

Virtually all unmineralized gabbros from the Pants Lake intrusions contain < 100 ppm Ni and < 100 ppm Cu, and those that have higher Ni contents are generally olivine-rich, as indicated by MgO-Ni correlations (table 1; fig. 10). Diabases, which provide minimum values for the Ni contents of the parental magmas, generally contain < 50 ppm Ni. Unmineralized rocks virtually all have Cu/Zr < 1, and many are strongly Cu-depleted, suggesting sulfide removal (Lightfoot and others, 1994). Finally, olivines in most gabbros are reported to be depleted in Ni relative to expected fractionation paths for sulfide-free systems, and to the normal range of Ni contents in mafic intrusions (Naldrett, in Fitzpatrick and others, 1999; Li and others, 2001). Collectively, these results indicate that parent magmas for both North and South intrusions interacted with sulfide liquids at some point in their histories, and lost significant amounts of metal.

The scale of this depletion signature in the Pants Lake intrusions is huge, and first-order calculations can place some general constraints on the quantities involved. Morse and others (1991) estimated the bulk Ni content of the Kiglapait Intrusion (also part of the Nain Plutonic Suite; fig. 1) at about 125 ± 25 ppm, and “normal” (that is, unmineralized) troctolite from the Voisey’s Bay Intrusion has an average Ni content of approximately 250 ppm (Li and others, 2000). The latter is influenced by cumulus olivine, but provides a useful upper limit. Thus, an initial value of 150 ppm Ni for the Pants Lake magmas is used here, with 250 ppm Ni as an upper limit.

Reduction in magmatic Ni contents from 150 ppm to 50 ppm indicates that 67 percent of contained Ni was lost; thus, 1 km³ of magma would lose 0.3 million tonnes of Ni metal, assuming a density of 3.0. The present total surface area of the Pants Lake intrusions is about 50 km², and the intrusions are up to several hundred meters thick. Mafic rocks are present widely in the subsurface, and the intrusions have been partly eroded. A first-order estimate of 50 km³ of metal-depleted magma implies that at least 15 million tonnes of Ni metal, and similar amounts of Cu metal, are missing. Using a higher initial magmatic Ni content of 250 ppm doubles this estimate. If mineralization in the Pants Lake area is assumed to cover 50 km², at an average thickness of 10 meters, at an average grade of 0.25 percent Ni, it could account for some 3.75 million tonnes of Ni metal. Thus, a large subeconomic resource of Ni is associated with the Pants Lake intrusions but, more importantly, even larger amounts of Ni remain unaccounted for. These calculations are simplistic, but they certainly provide a rationale for further exploration. Unfortunately, the recognition of missing metal does not provide clues as to its location or physical form (that is, massive or disseminated mineralization).
The pronounced metal depletion in the Pants Lake intrusions also has implications for the potential grade of sulfide deposits. Sulfide liquid / silicate magma partition coefficients for Ni (D_{sulf/mag}) are probably 300 to 600 in basaltic systems (for example, Naldrett, 1989; Barnes and Maier, 1999). Thus, sulfide liquids in equilibrium with a magma containing 50 ppm Ni would thus have Ni contents of 1.5 percent (D_{sulf/mag} = 300) to 3.0 percent Ni (D_{sulf/mag} = 600). These agree well with observational data, which cluster around 2 percent Ni, within an overall range extending from 0.5 percent to greater than 10 percent (Kerr, 1999; Kerr and Ryan, 2000; fig. 7). Pronounced depletion of silicate magmas is characteristic of a low mass ratio of silicate magma to sulfide liquid (R factor). For an initial magmatic Ni content of 150 ppm, the R factor required to produce a sulfide liquid containing 2 percent Ni is between 180 (D_{sul/mag} = 600) and 250 (D_{sul/mag} = 300). To generate a sulfide liquid containing 4 percent Ni (more typical of the Voisey’s Bay deposits) would require significantly higher R factors from 500 (D_{sul/mag} = 600) to almost 2000 (D_{sul/mag} = 300), assuming the same initial magmatic Ni contents. The mineralization in the Pants Lake intrusions thus formed at a relatively low R factor, which imposes limitations upon its grades.

**Comparisons Between the Pants Lake and Voisey’s Bay Areas**

Exploration efforts in the Pants Lake area are predicated largely on the idea that the mafic host rocks and sulfide mineralization represent close analogues to those at Voisey’s Bay (for example, Kerr and Smith, 1997). This section of the paper further evaluates parallels and divergences between the two areas, and their significance in terms of genetic models for such deposits.

**Regional Geological Settings**

Both areas contain relatively primitive mafic magmas that intruded into the sulfide- and graphite-bearing Tasiuyak Gneiss (fig. 1). The reacted gneiss fragments associated with mineralization in the Voisey’s Bay Intrusion attest to physical and chemical interaction between magmas and these country rocks (for example, Li and Naldrett, 1999, 2000). Identical reacted gneiss fragments are present in both the South and North intrusions at Pants Lake, and indicate closely similar processes. Naldrett and others (1996) further suggested that the Nain - Churchill tectonic boundary was a conduit that facilitated ascent of the Voisey’s Bay Intrusion, but no such case can be made for the Pants Lake intrusions, which lie some 20 kilometers west of the equivalent structure (figs. 1 and 2). However, the exact position of the Nain - Churchill boundary near Voisey’s Bay was also questioned by Ryan (2000), and may lie several kilometers to the east. Thus, although there may be a general role for the boundary or associated structures as channels for magma ascent in both areas, caution is dictated in using it as a direct exploration guide.

Nain Plutonic Suite mafic intrusions that were emplaced into Archean gneisses of the Nain Province lack significant sulfide mineralization (Kerr and Ryan, 2000). The mineralized Pants Lake and Voisey’s Bay Intrusions are the only examples emplaced into the Tasiuyak Gneiss of the Churchill Province. Data from Pants Lake thus strongly support a critical role for the Tasiuyak Gneiss in metallogenesis, either as a source of sulfur, a contaminant that promoted sulfide exsolution, or via both processes (Naldrett and others, 1996; Li and Naldrett, 1999; Kerr and Ryan, 2000). Sulfides in the Pants Lake intrusions have δ^{34}S values from 0 to −5 per mil, compared to local paragneiss values of −1 to −5 per mil (Li and others, 2001; Smith and others, 2001). These results indicate a significant contribution of sulfur from the country rocks, and are less equivocal than data from Voisey’s Bay, where interpretation is complicated by the very wide range of δ^{34}S values (−1 to −17 per mil) reported from the Tasiuyak Gneiss in that area. However, the δ^{34}S values of the sulfide deposits (0 to −4 per mil) are similar to those from the Pants Lake data (Ripley and others, 1999, 2000; Li and others, 2001).
Timing of Mafic Magmatism

The ages of 1337 ± 2 Ma and 1322 ± 2 Ma reported for the Pants Lake South and North intrusions respectively (Smith and others, 1999, 2001) resemble ages of 1333 ± 1 Ma and 1313 ± 1 Ma reported from the Voisey’s Bay and Mushuau Intrusions (Amelin and others, 1999; Li and others, 2000). The South and North intrusions are also geochemically similar to the Voisey’s Bay and Mushuau Intrusions respectively. However, the Pants Lake North intrusion is extensively mineralized, whereas the Mushuau Intrusion to date is known to contain only limited basal mineralization. The Mushuau Intrusion also differs from the Pants Lake North intrusion in that it was emplaced into Archean orthogneisses of the Nain Province, rather than Tasiuyak Gneiss. Amelin and others (2000) suggested that the chronological position of the Voisey’s Bay Intrusion, as one of the oldest mafic plutons in the Nain Plutonic Suite, was an important factor in the genesis of the sulfide mineralization. The presence of similar mineralization in both older and younger intrusions at Pants Lake indicates that age by itself is not critical. It seems more likely that geological location and the nature of subjacent country rocks are ultimately more important controls upon mineralization (Kerr and Ryan, 2000).

Nature and Anatomy of “Mineralized Sequences”

The composite gabbro and leopard-textured gabbro of the Pants Lake North intrusion are clearly akin to the “feeder breccia” and “leopard troctolite” at Voisey’s Bay (Kerr and Smith, 1997; Kerr, 1999). However, there are important differences in the anatomy and internal relationships of the “mineralized sequences” at Pants Lake and Voisey’s Bay.

Most sulfide mineralization at Voisey’s Bay is hosted by (or associated with) feeder conduit systems, such as the dike-like body that hosts the Ovoid, Discovery Hill and Reid Brook Zones (Naldrett and others, 1996; Li and Naldrett, 1999; Evans-Lamswood and others, 2000). Widespread disseminated sulfide mineralization exists near the base of the Eastern Deeps troctolite body (Naldrett and others, 1996; Evans-Lamswood and others, 2000). The mineralized sequence of the Pants Lake North intrusion resembles this dispersed basal sulfide accumulation, which is interpreted to be the distal manifestation of an influx of sulfide- and fragment-charged magma (Li and Naldrett, 1999), similar to that invoked here. No discrete feeder conduit systems associated with the North intrusion have yet been identified. Thin gabbro intersections noted around and below the body are probably older dikes, as they are hornblende- and biotite-rich, and are geochemically distinct (A. Kerr, unpublished data). The location of any feeder conduit system beneath the North intrusion remains a mystery, but it is a riddle that explorationists would love to solve, as comparisons with Voisey’s Bay imply that it should be the prime site for significant sulfide accumulation. However, feeder conduits are small drilling targets (the dike connected to the Ovoid deposit at Voisey’s Bay is in places less than 50 m thick), and most exploration drilling was terminated just a few meters below the basal contact. Thus, this is a case where absence of evidence does not (yet) equate to evidence of absence.

The spatial relationship between composite gabbro (= feeder breccia) and leopard gabbro (= leopard troctolite) is also different at Voisey’s Bay and Pants Lake. At Voisey’s Bay, the feeder breccia forms the lower part of the feeder sheet, and the leopard troctolite the upper part (Naldrett and others, 1996; Li and Naldrett, 1999). The Pants Lake North intrusion mineralized sequence has the opposite stratigraphy (fig. 6). However, there are complex vertical and lateral facies variations in the Voisey’s Bay feeder system, likely related to changes in the fluid-dynamic environment (Evans-Lamswood and others, 2000). The leopard troctolite is interpreted to reflect a relatively tranquil magmatic environment, as suggested here for the leopard gabbro at Pants Lake. It is probably naive to expect that the distribution of “facies” within two
dynamic magma systems would be identical, and a better knowledge of the environments represented by these unusual rocks is required to further evaluate such differences.

Finally, the Pants Lake South intrusion mineralized sequence has no clear equivalent at Voisey’s Bay, although such rocks may occur at depth. Ultramafic inclusions in “feeder breccias” at Voisey’s Bay locally contain sulfide mineralization, and have been interpreted as disrupted cumulates transported by later magmas (Li and others, 2000). These probably formed in much the same way as the mineralized melagabbro of the South intrusion.

**Geochemistry of Magmatic Sulfide Mineralization**

Sulfide mineralization at Pants Lake has lower Ni/Cu (~1.1) and Ni/Co (~7) compared to that of Voisey’s Bay, in which Ni/Cu averages ~2 and Ni/Co ranges from 15 to 30 (Kerr, 1999; Lightfoot and others, 2001). Differences in Ni/Cu likely reflect differing silicate magma compositions, but Ni/Co ratios are significantly affected by sulfide segregation processes, due to differences in $D_{sulf/mag}$ values for Ni and Co. Lower Ni/Co in the Pants Lake mineralization thus in part may reflect lower R factors, which depress Ni contents to a greater extent than Co contents. Significantly, the lowest Ni/Co ratios at Voisey’s Bay are in the Reid Brook deposit, which also has lower sulfide Ni contents and interpreted lower R factors (Lightfoot and others, 2001).

The most important difference between Pants Lake and Voisey’s Bay lies in sulfide metal contents. Most Pants Lake sulfides contain about 2 percent Ni and 2 percent Cu, or less (fig. 7) compared to 3.5 to 5 percent Ni and about 2 percent Cu at Voisey’s Bay (Naldrett and others, 1996; Lightfoot and others, 2001). As discussed above, this implies low R-factors (<350) during sulfide segregation, compared to values up to 2000 at Voisey’s Bay. Thus, the per-tonne value of sulfide “ore” at Pants Lake (if such is ultimately defined) would only be about half that of typical Voisey’s Bay material. There are, however, a few exceptions; some sulfides from the South intrusion have high Ni and high Ni/Cu, and the Taheke Lake lobe of the North intrusion also locally contains metal-rich sulfides (fig. 7).

In their model for the Voisey’s Bay deposit, Li and Naldrett (1999) proposed that an early low-grade sulfide liquid was subsequently upgraded by continued interaction with fresh magma. This is supported by the relative abundance of mafic rocks that show little or no Ni depletion within the Voisey’s Bay Intrusion, which are interpreted to represent products of this continued magmatic flux. The proposed early sulfide liquid at Voisey’s Bay had Ni contents akin to those of the Pants Lake sulfides, and olivines in Ni-depleted rocks at Voisey’s Bay have similar Ni contents to those from Pants Lake (Li and Naldrett, 1999; Naldrett, in Fitzpatrick and others, 1999). These observations led Kerr and Ryan (2000) and Li and others (2001) to suggest that sulfide liquids at Pants Lake were not upgraded to the same extent by later magmas.

The contrasting sulfide metal contents of the lower (early ?) and upper (late ?) Sections of the North intrusion mineralized sequence provide limited evidence for multistage processes at Pants Lake. Similarly, variations in sulfide Ni content and Ni/Cu ratios in the South intrusion mineralization may suggest interaction with different magma batches, or changes in R factors. However, the existing data strongly suggest that multistage upgrading processes at Pants Lake were far less efficient than at Voisey’s Bay.

**AN INTEGRATED MODEL**

The South intrusion was emplaced at about 1337 ± 2 Ma (Smith and others, 2001). It is suspected to have developed in two stages, with the upper part (above about 250 m depth in fig. 3) emplaced first. Abundant diabase sheets and dikes that cut this material are believed to be derived from the underlying (slightly later) main magma chamber. The parental magmas experienced significant country-rock contamination
at depth, leading to their steep REE patterns, although this feature may in part be source-related. Reacted gneiss fragments within the South intrusion mineralized sequence attest to this crustal interaction. This was an important factor in the development of sulfide liquids, probably accomplished by simple bulk addition of sulfur, selective addition through hydrothermal transfer, and contamination-related changes in sulfur solubility (compare Li and Naldrett, 2000; Ryan, 2000). Initial development of sulfide liquids took place at deeper levels, as did much of the crustal contamination. Following emplacement, the magma crystallized under an approach to closed-system conditions, without large influxes of new mafic magma (MacDonald, ms, 1999). The sulfides, and reacted gneissic fragments brought up from depth, settled with cumulus olivine to form mineralized melagabbro. Sulfide metal contents at the very base of the intrusion are low (~1% Ni), but increase to values of around 4 percent Ni in the upper part of the mineralized sequence. This pattern is believed to record the increasing residence time of sulfides within the chamber, and perhaps increased settling distances within the magma column, leading to higher R factors.

The North intrusion represents a separate magmatic event at around 1322 ± 2 Ma (Smith and others, 1999), which involved discrete magma batches. The first to be emplaced was the parent to (at least part of) the layered gabbro unit, although this is difficult to prove (see below). The chamber appears to have been a relatively dynamic environment, which was tapped, and replenished with progressively less fractionated magma (MacDonald, ms, 1999). A chilled rind developed at the base of the magma chamber, later to be preserved as the barren unit that sits at the base of the mineralized sequence. Ni depletion in the layered gabbro indicates that it had already interacted with sulfide liquids at greater depths, but little or no sulfide was carried upward in the early stages. The magma had been contaminated by assimilation of metasedimentary gneiss, and probably had significant amounts of sulfur added to it, but this must also have occurred at greater depth. The feeder conduit system is suspected to lie in the north of the body, as the most magnesian layered gabbros are found in the Taheke Lake lobe. Conversely, the gabbro outliers of the Mineral Hill area contain the most evolved examples of this unit. This pattern is consistent with increasing fractionation of the magma as it moved laterally through tens of kilometers.

Sulfide- and fragment-charged magmas arrived soon after this initial magma influx, associated with the parent magma to the black olivine gabbro. The latter is restricted to the northern part of the body, again suggesting that the conduit entry point is in this region. There were at least two discrete pulses of sulfide-charged magma. The first carried a low-grade sulfide liquid and relatively few gneissic fragments, perhaps because the deeper source magma chamber had already developed gravity stratification. It had only limited interaction with the resident magma, and began to crystallize under relatively tranquil conditions. This influx penetrated as far south as the Mineral Hill area, where metal-poor sulfides are dominant, but did not penetrate extensively into the NDT lobe of the present North intrusion. It was followed by a second (and more voluminous ?) influx, which carried more abundant gneissic debris and higher-tenor sulfide liquids. This pulse interacted extensively with the partly crystallized resident mafic magma, which froze upon contact, developing the distinctive composite gabbro. This second pulse penetrated into the NDT lobe, but it apparently did not reach the Mineral Hill area in significant amounts. The mineralized sequence is thickest in the Taheke Lake lobe, probably because the conduit system lies in this area. Sulfide liquids and reacted fragments “rained down” into previously unmineralized magma and/or into the earlier sulfide-bearing unit, but contrasts in sulfide metal contents between the two influxes were preserved. These sulfide- and fragment-bearing magma influxes were displaced from a deeper magma chamber by the parent magma to the black olivine gabbro unit, and eventually gave way to more homogeneous and sulfide-free material. The development of composite-gabbro-like
rocks along the upper boundary of the black olivine gabbro in the Taheke Lake lobe implies that this eventually spread out beneath the parent to the layered gabbro unit, but this is debatable (see below).

The age relationships between the layered gabbro, black olivine gabbro and the mineralized sequence remain inherently ambiguous. An alternative interpretation is that formation of the mineralized sequence and black olivine gabbro are early, and entirely predate the arrival of the parent to the fine-grained olivine gabbro unit. However, there must have been some magma resident in the chamber when the sulfide-charged influxes arrived, in order to generate the ubiquitous inclusions in composite gabbros.

The final stage in development was the emplacement of the parent magma to the massive leucogabbro unit. This is unmineralized, but its low Ni contents and Cu/Zr ratios again imply a previous encounter with sulfide liquids. The massive leucogabbro forms veins that apparently cross-cut the layered gabbro unit, and the other units were probably largely solidified at the time of its emplacement. The massive leucogabbro is suggested to represent a plagioclase cumulate developed within the deeper magma chamber, following expulsion of the sulfide-rich material. This was subsequently emplaced as a mixture of phenocrysts and interstitial liquid, that is, a crystal mush. Finally, post-1322 Ma gentle folding created the present geometric pattern of the North intrusion, and presumably affected other areas also, although its effects are less obvious.

CONCLUDING REMARKS

The recognition of widespread mineralization in the Pants Lake intrusions adds to the economic potential of Labrador. It also allows assessment of concepts developed from the Voisey’s Bay deposits and, by inference, models for magmatic sulfide mineralization in broadly mafic systems. This paper outlines many striking similarities between the mafic intrusions of the Pants Lake and Voisey’s Bay areas and their associated sulfide mineralization, and it is clear that similar ore-forming processes were in operation. The total amount of contained Ni metal at Pants Lake likely equals or exceeds the 2 million tonnes now known at Voisey’s Bay. Metal depletion in the Pants Lake intrusions suggests that much larger amounts of Ni and Cu remain unaccounted for, which is a powerful incentive for continued exploration. Despite these compelling statistics, deposits at Pants Lake are presently uneconomic, due to their disseminated nature and lower sulfide metal contents. Just as the similarities between Voisey’s Bay and Pants Lake allow assessment of genetic models, the differences provide clues to the most critical factors in such models.

Many key features of the Pants Lake intrusions support genetic models proposed by others (for example, Li and Naldrett, 1999) for Voisey’s Bay. The most important conclusion is that there must be a critical role for sulfide-bearing country rocks of the Tasiuyak Gneiss in developing sulfide liquids. The exact nature of this role remains debatable, but the physical evidence and sulfur isotope data from Pants Lake (Smith and others, 2001; Li and others, 2001) are compelling. This conclusion has clear exploration implications in Labrador, and in a more general sense elsewhere. An important further test of this link will come from ongoing radiogenic isotope studies at Pants Lake, and comparison with the data of Amelin and others (2000) from Voisey’s Bay.

A second important conclusion comes from the differences in sulfide metal contents and metal ratios, and the contrasts between pervasive and more localized metal depletion signatures. As pointed out elsewhere (Kerr, 1999; Li and others, 2001), this is a critical difference. The initial sulfide liquids formed at Pants Lake and Voisey’s Bay were probably very similar, but those at Voisey’s Bay were significantly upgraded by interaction with later silicate magmas, which doubled or tripled their metal contents. There is some evidence for increases in sulfide metal contents at Pants
Lake, but it is clear that the process was less effective, perhaps because later magmas encountered sulfides at depth, and lost their metals. A more general conclusion is that multistage processes, involving dynamic magmatic systems, may be essential to generate high-grade sulfide liquids in basaltic systems, where lower magmatic Ni contents and mass-balance effects limit the tenor of any liquid developed by closed-system “batch” processes. Simple segregation may be effective in the context of Ni-rich ultramafic magmas (for example, komatiites) but is likely inadequate in these more evolved systems.

The absence of discrete feeder conduit systems that acted to concentrate magmatic sulfides has also been cited as an important difference (Kerr, 1999; Li and others, 2001), and it is certainly true that large-scale sulfide segregation processes did not lead to significant massive sulfide accumulations in either the South or North intrusion. I believe that mineralized conduit systems remain to be discovered in the North intrusion, likely under the Taheke Lake lobe, and it is to be hoped that they will contain at least some of the missing metals. This paper provides a comprehensive statement of current knowledge about the mineralized intrusions at Pants Lake, but I doubt very much that it represents the final chapter in its history.

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APPENDIX I
Calculation of Sulfide Metal Contents
The sulfide assemblage is considered to consist of pyrrhotite, chalcopyrite and pentlandite, and it is assumed that samples consisting entirely of sulfides would contain 35 wt % sulfur. Calculations use a normalization factor of \([35/S]\), where S indicates the analyzed sulfur content in %. Corrections for metals in silicates (principally Ni in olivine) are performed by mass-balance methods assuming that silicate material has similar metal contents to unmineralized (sulfide-free) rocks. Estimates of 50 ppm Co, 100 ppm Ni and 100 ppm Cu were used for bulk silicates, and Ni estimates were doubled for melagabbro. Corrections are usually trivial, unless the amount of sulfide is very small (<1% S), or the metal content of the sulfides is very low. A more detailed discussion of the method is provided by Kerr (2003).

APPENDIX II
Analytical Techniques
A summary of analytical methods was given by Kerr and others (2001). Most major and trace element data in this paper were acquired at the Department of Mines and Energy laboratory in St. John’s, Newfoundland. With the exception of Rb, determined by atomic absorption spectrometry, all elements were determined by inductively-coupled plasma emission spectrometry (ICP-ES). Major elements have detection limits of 0.01% or better, and trace elements have detection limits of 1 ppm or better (0.1 ppm for Be, Li, Sc, and Dy). Accuracy and precision of analyses are monitored by use of international standards, internal standards and regular analytical duplicates; precision for most elements is ± 3% or better, with some degradation close to detection limits. A statistical treatment of data from the laboratory, including data on international standards, is provided by Finch (1998). REE data were acquired at Memorial University of Newfoundland by inductively-coupled plasma mass spectrometry (ICP-MS). Samples were processed using Na₂O₂ fusion techniques to eliminate problems due to accessory phases. Detection limits are 0.1 ppm or
better for all REE. S analyses were completed by external laboratories (Leco furnace method), with a detection limit of 0.01% and precision of ± 4% or better. Data in figure 7 also incorporate results from exploration programs (Fitpatrick and others, 1998); as Cu, Ni and S contents of these samples are generally high, precision is good.

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