THE PANTS LAKE INTRUSIONS, CENTRAL LABRADOR: GEOLOGY, GEOCHEMISTRY AND MAGMATIC Ni-Cu-Co SULPHIDE MINERALIZATION
(PARTS OF NTS 13N/05, 13N/12, 13M/08 AND 13M/09)

A. Kerr

Report 12-02

St. John's, Newfoundland
2012

Newfoundland Labrador

Natural Resources

Geological Survey

COVER

Rhythmically layered fine- to medium-grained olivine gabbro in the North intrusion, NDT lobe; *(Insert)* Layering from the same outcrop. Layering is mostly defined by variations in the amount of olivine. Crossbedding visible in centre of the more detailed view.

Newfoundland Labrador

Natural Resources

Mines

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ABSTRACT

*The *Pants Lake intrusions (PLI) form part of the Mesoproterozoic Nain Plutonic Suite (NPS) in northern Labrador, located some 80 km south of the world-class Voisey's Bay Ni–Cu–Co sulphide deposit. The PLI are dominated by olivine gabbro, with subordinate troctolite, melagabbro, peridotite and leucogabbro. They form several sheet-like bodies that were emplaced into metasedimentary rocks that locally contain sulphides. The largest individual intrusions, termed the North and South intrusions, have been dated by other workers at 1322 ± 2 Ma and 1337 ± 2 Ma, respectively. These results indicate that they formed in two discrete events. The North intrusion is more varied petrologically, and its three units show ambiguous contact relationships, which imply that they partly coexisted as liquids. Disseminated sulphide mineralization is almost ubiquitous near the basal contacts of these intrusions, but massive sulphide mineralization is rare. In the older South intrusion, sulphides 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 sulphides and reacted country-rock fragments. The North intrusion mineralized sequence includes rock types that are strikingly similar to those associated with economically important high-grade sulphide mineralization at Voisey's Bay. A key point of similarity is the evidence for interaction with, and assimilation of, pelitic to psammitic country-rock gneisses, which contain sulphides and graphite.*

Geochemical data demonstrate that the older South intrusion has higher TiO_2, K_2O and incompatible element contents, and steeper REE patterns than the younger North intrusion. The South intrusion closely resembles the Voisey's Bay intrusion (host to the sulphides), whereas the North intrusion has a looser affiliation with the slightly younger and less mineralized Mushuau intrusion of the Voisey's Bay area. Differences in olivine fractionation trends imply that the North and South intrusions, respectively, approached open-system and closed-system evolution. Mineralized rocks within both share all geochemical features of the associated unmineralized rocks, and must be closely related to them. Unmineralized mafic rocks from the PLI almost all have low Ni contents and low Cu/Zr ratios that imply previous extraction of metals by sulphide liquids. Olivines from the PLI mafic rocks have anomalously low Ni contents for their moderate MgO contents. This pervasive depletion signature, coupled with consistent Ni/Cu and Ni/Co, and clustering of sulphide metal contents, suggests that sulphide liquids were developed on an intrusion-wide scale, probably at depth, rather than by local processes. Sulphur isotope data, from other studies, indicate that a significant part of the sulphur now contained in the mineralization was derived from the country-rock paragneisses.

Sulphides in the PLI typically contain less than 2% Ni and 2% Cu (at 100% sulphide), compared to 4% Ni and 2% Cu at Voisey's Bay. The PGE contents are low in PLI sulphides, and generally resemble those reported from Voisey's Bay. These values agree with predictions from the low Ni and Cu contents of silicate rocks that likely equilibrated with the sulphide liquids. These factors imply a low mass ratio (R) of silicate magma to sulphide liquid (R < 300) compared to Voisey's Bay (R = 600 to > 1000). The ubiquitous Ni depletion in the PLI contrasts with the more localized depletion seen at Voisey's Bay. This may indicate that the sulphide liquids formed in the the PLI were not similarly 'upgraded' by later batches of undepleted magma. However, there is evidence for at least two discrete pulses of sulphide-bearing magma in the North intrusion, with increasing metal contents. Simple calculations suggest that > 15 million tonnes of Ni metal are missing in the area of the PLI. Thus, despite apparent limitations on the potential grade of sulphide deposits, there remains considerable incentive for mineral exploration. From the perspective of metallogenesis, data from the PLI support several key concepts proposed in models for the formation of the Voisey's Bay deposit. The evidence suggests that such controls may apply more widely as controls on the formation of magmatic sulphide deposits in broadly gabbroic magma systems. Critical factors at Pants Lake include the presence of sulphide-bearing country rocks, and suitable parental magmas, both of which provide general exploration guides for further work in Labrador. The PLI represent an enormous target area compared to Voisey's Bay, and considerable 'room' remains for exploration in future years.

* See Definitions in Stratigraphic Terminology, page 13.

INTRODUCTION

HISTORICAL BACKGROUND

The discovery of nickel-bearing sulphide mineralization some 40 km south of Nain, by Albert Chislett and Chris Verbiski in 1993, was a turning point for mineral exploration in Labrador, although it was not immediately recognized as such. Late in 1994, drilling at this site, now known as Discovery Hill, provided a 41 m intersection containing almost 3% nickel, and the Voisey's Bay story began to unfold. The discovery and rapid delineation of the high-grade Ovoid deposit over the following months demonstrated that a major mineral discovery had indeed been made, and northern Labrador quickly became the target of a major staking rush.

The four years immediately following the Voisey's Bay discovery saw the highest annual mineral exploration expenditures recorded in the Province prior to 2009, peaking at just over $80 million in 1996 (Figure 1). About half this expenditure was accounted for by the Voisey's Bay project itself, and the rest was spread over close to 50 000 km^2 of wilderness, roughly centred on the Voisey's Bay deposit. Hundreds of junior exploration companies acquired mineral rights in Labrador, and many mounted exploration programs. In 1995, it became apparent that sulphide mineralization was more abundant in the region than previous reconnaissance mapping had suggested. Company press releases referred to 'extensive gossans' and 'widespread mineralization', but most provided little, or no, geological information. In 1996, many of these exploration projects proceeded to more advanced exploration, including ground geophysics and diamond drilling. Some projects inspired great expectations among investors! However, the drilling results in 1996 were disappointing, as the grades reported fell well short of those reported from Voisey's Bay. By 1997, there was a reduction in the number of active areas, although several large projects, where drilling continued, kept overall expenditures in Labrador at over $60 million (including Voisey's Bay). Exploration expenditures fell sharply in 1998, when there were only about 5 active projects outside Voisey's Bay. By 1999, the Voisey's Bay project itself accounted for close to 90% of all exploration expenditures in Labrador, and there was very little activity by junior exploration companies. The summers of 2000, 2001 and 2002 were relatively quiet, although delineation work and related investigations continued at Voisey's Bay. Some activity was recorded elsewhere in Labrador, as ground initially staked in 1995 began to revert to the Government, and there was renewed interest in the Pants Lake area. In 2002, the Government of Newfoundland and Labrador developed a framework agreement with INCO Ltd. for development of the Voisey's Bay deposit. The Voisey's Bay project entered commercial production in 2006, with open-pit mining of the high-grade, near-surface Ovoid zone. In concert with mine development, exploration work has continued to define additional resources amenable to future underground mining.

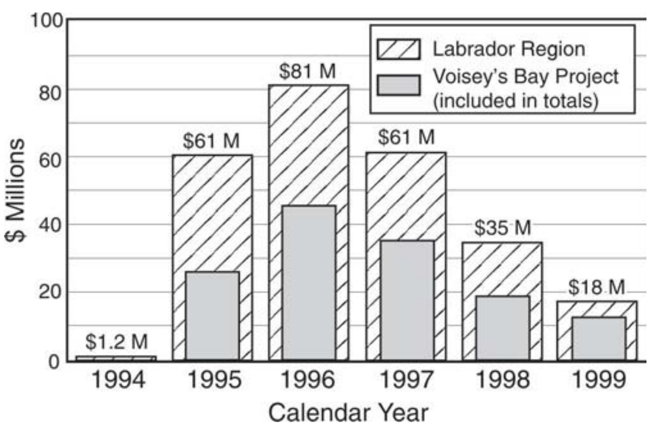


Figure 1. *Mineral exploration expenditures in Labrador between 1994 and 1999. Based on Department of Natural Resources data.*

Although exploration expenditures for nickel in Labrador have indeed been large, it should not be assumed that all areas have been thoroughly assessed. This is a huge and remote region with essentially no infrastructure, and exploration costs are high. A large portion of the expenditure illustrated (Figure 1) was directed toward support and infrastructure, notably aircraft and camp support, and was not spent directly 'on the ground'. Much remains to be explored, and it is hoped that publication of results from Geological Survey projects will aid this future effort.

PROJECT OVERVIEW

The high level of exploration activity between 1995 and 1998 created a need for both regional geological mapping and mineral deposit studies in northern Labrador. The Geological Survey responded by initiating two new projects in 1996. Geological mapping at 1:50 000 and 1:100 000 scales focused in a mountainous region north of Nain, where exploration was particularly active (Ryan *et al.*, 1997, 1998). A coordinated project, directed by this author, set out to document and interpret the numerous new mineralized localities reported by the junior exploration companies. The Labrador Nickel project, as it was known, benefitted greatly from the cooperation of many of these companies. Field work was conducted (Figure 2) for three extended field seasons (1996, 1997 and 1998) over an area stretching from Okak Bay in the north to the Smallwood Reservoir in the southwest. Most of the work in the northern part of the region was carried out from Nain and various field camps operated by the Geological Survey, and by exploration companies.

The Labrador Nickel project was established to meet two principal objectives. The first was to document examples of

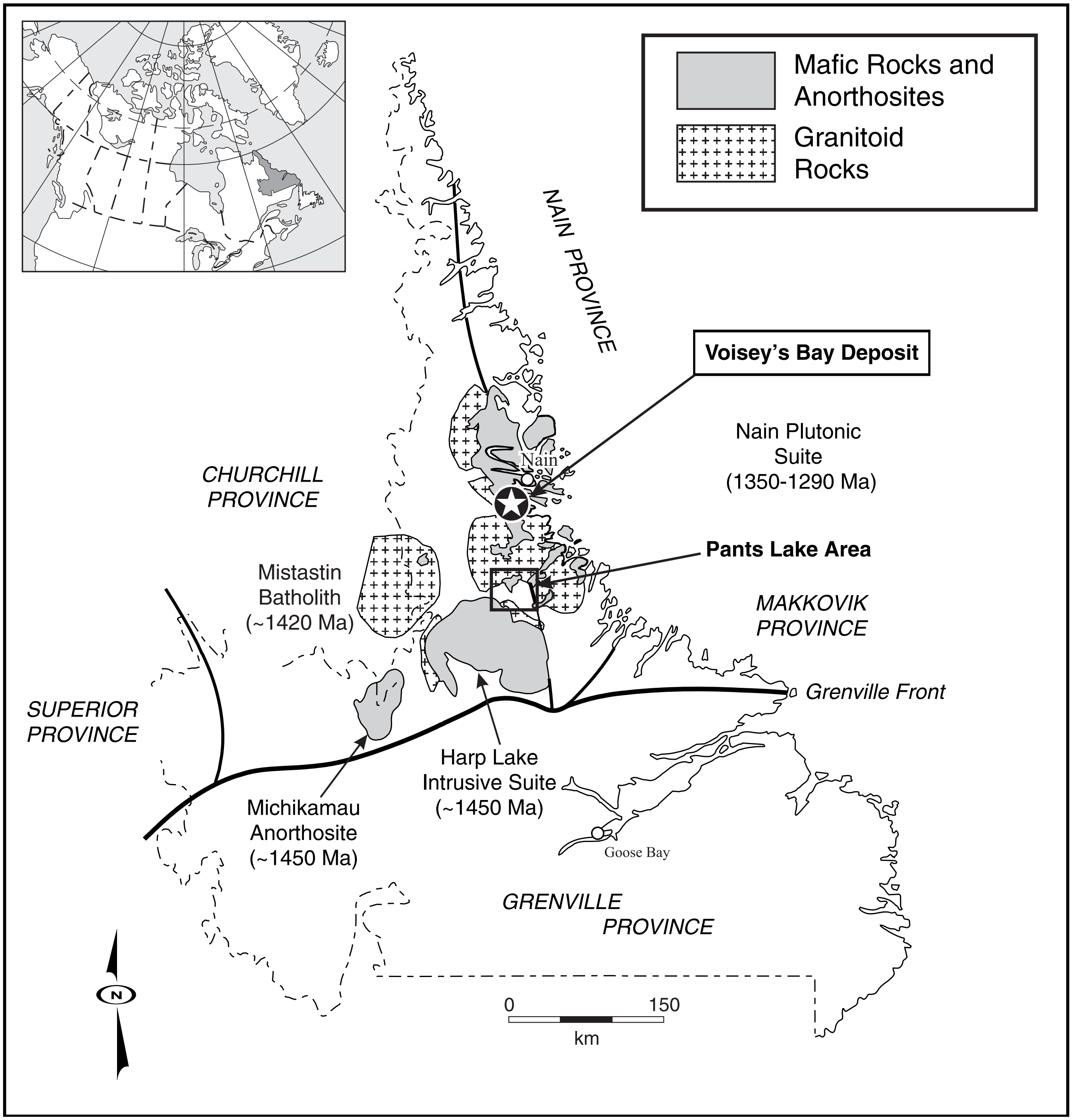


Figure 2. *Locations of structural provinces and major plutonic complexes in north and central Labrador, and areas covered by field work under the Labrador Nickel project (1996–1999). The study area is indicated by the outlined square.*

magmatic sulphide mineralization (outside the immediate Voisey's Bay district) through field work and related laboratory studies, taking advantage of information and material (notably diamond-drill core) obtained through active mineral exploration projects. The second was to understand the controls on such mineralization and genetically associated plutonic suites, to provide a regional context and guidelines for future exploration efforts.

This report is one of several publications that have delivered results from the Labrador Nickel project. It deals with a relatively small area located north of the Adlatok River, in parts of NTS map areas 13N/05, 13N/12, 13M/08 and 13M/09 (Figure 3). This area is treated independently because it is geographically separate from other regions of intense mineral exploration that are mostly located within a 100 km radius of Nain (Figure 2). Also, it was the focus of the largest

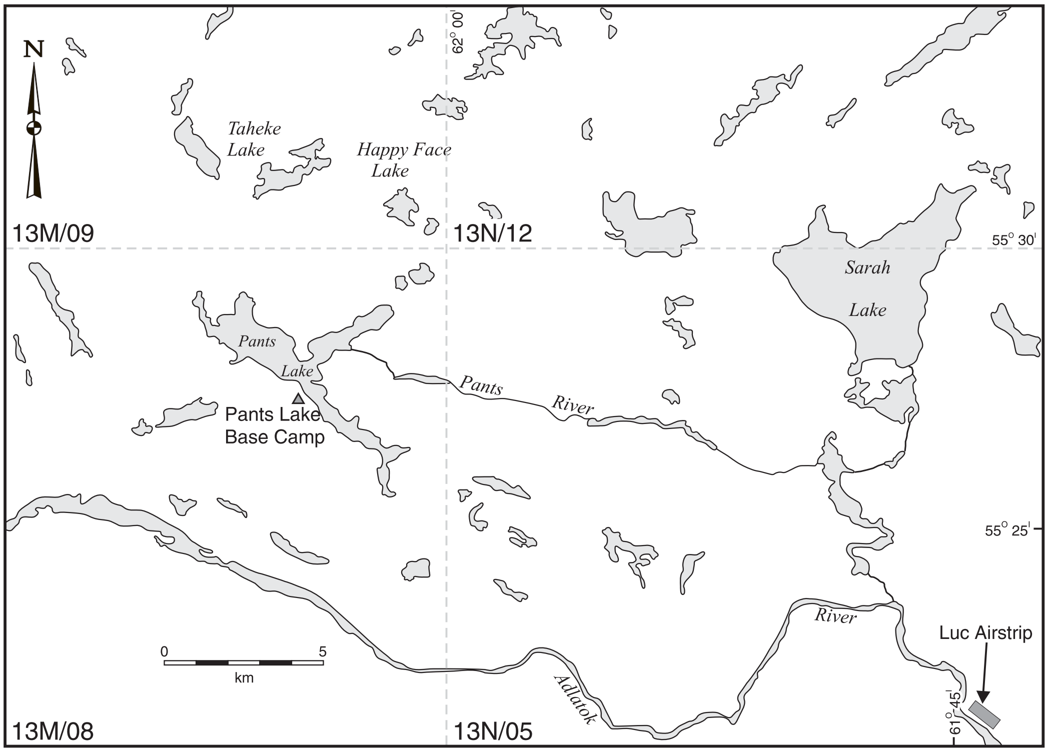


Figure 3. *Summary map of the project area showing the boundaries of NTS 1:50 000-scale map sheets, major physiographic features, location of campsites, Luc airstrip, and other general information.*

drilling in, and around, the Pants Lake intrusions (PLI; *see* below). Field work was conducted in 2001 to define new and refined geophysical targets, and several new drill-holes were completed in 2002. There was little or no activity from 2003 to 2006, but high nickel prices early in 2007 re-awakened interest, and additional electromagnetic (EM) surveys were completed later in 2007.

Several reports published as part of the Geological Survey's Current Research series also provide information on mineralization in the Nain area (*e.g.*, Kerr, 1997, 1998a; Kerr and Smith, 1997; Hinchey *et al.*, 1999; Piercey and Wilton, 1999) and also for the area covered by this report (Kerr, 1999; Kerr *et al.*, 2001). Results from the Harp Lake Intrusive Suite (HLIS) are presented by Kerr and Smith (2000). An article by Kerr and Ryan (2000) provides an overview of magmatic sulphide mineralization throughout the Nain Plutonic Suite (NPS), and its possible origins and controls. Another article by Kerr (2003a) summarizes some of the essential findings of work in the PLI.

and most comprehensive exploration program mounted outside the immediate Voisey's Bay area, with a total expenditure approaching $25 million over four years. This so-called 'South Voisey's Bay' project consisted of a large land package initially held by a Vancouver-based junior exploration company, Donner Minerals, in conjunction with numerous joint venture partners. Expenditure in this area grew progressively over four years following the Voisey's Bay discovery. In 1997 and 1998, the project was operated and managed by Teck Corporation, who acquired both a direct interest in Donner Minerals and options to acquire a portion of their mineral rights. The high level of activity in this area, and the involvement of a major mining company, can be attributed to its geological similarities with the Voisey's Bay district and the presence of a large mafic intrusion containing magmatic sulphide mineralization.

This report sets out to integrate the results of the Geological Survey research project and this comprehensive mineral exploration program, and to provide an information base that will aid in future exploration efforts. Although mineral exploration efforts were mostly suspended in 1999, the area has a high potential for magmatic sulphide mineralization similar to that discovered at Voisey's Bay. In 2001, Donner Minerals entered into a joint venture agreement with major nickel producer Falconbridge Ltd. to continue exploration and

LOCATION, ACCESS AND TOPOGRAPHY

The study area is located in north-central Labrador, about 300 km north-northwest of Goose Bay, and about 100 km due south of the Voisey's Bay deposit. The nearest community is Natuashish, located about 75 km to the northeast. The area includes parts of NTS map areas 13N/05, 13N/12, 13M/08 and 13M/09 (Figures 2 and 3). Access to the area is by air, and several large lakes, including Pants Lake and Sarah Lake (Figure 3), provide access for float-equipped aircraft. In 1997, a bush airstrip was constructed on an alluvial terrace in the Adlatok River valley; it provides access suitable for STOL (Short Takeoff and Landing) aircraft such as the DeHavilland Twin Otter or Cessna Caravan. (The airstrip is known as the Luc airstrip after its discoverer, pilot Luc Gauthier of Canadian Helicopters.)

The area is a dissected portion of the Labrador Plateau physiographic region and has moderate topographic relief compared to the surrounding areas. The maximum elevation is approximately 600 m, north of Pants Lake, and the lowest elevations of about 120 m are in the valley of the Adlatok River. The Adlatok Valley is deeply incised, and runs approximately east–west along the southern edge of the area. The region to the south of the river is dominated by anorthositic and granitic rocks of the HLIS, which form a higher, generally barren region. Tributaries of the Adlatok River drain Sarah and Pants lakes, and most of the drainage within the study area feeds these larger bodies of water. The terrain has moderate relief, has few steep hills, and is variably, but generally thinly, wooded. Forest cover is thick only within stream and river valleys and is sporadic even in these sheltered locations. Alder forests in the river valleys, often combined with large expanses of boulders, present the most significant obstacles to field work. Elevations above 450 m are largely barren. The amount of outcrop is varied, but it is generally good (~20%) at higher elevations and in areas underlain by gabbroic rocks of the PLI. However, lower elevations are mantled by Quaternary deposits, and have much less outcrop. Generally, the terrain is fairly benign for summer field work, particularly if there is a breeze to disperse the ubiquitous and bloodthirsty mosquitoes and blackflies. As is commonly the case in Labrador, these insects are a persistent scourge for field geologists. Field work in the area is possible between June, when the snow cover disappears, to October, when it returns. Geophysical surveys and drilling can be conducted over a longer period, although limited daylight in the depths of winter can be a problem (*e.g.*, air support).

Mineral exploration activity in this area between 1995 and 1998 was conducted from several different sites, but a base camp established in 1996 on the south shore of Pants Lake (Figure 3) was the centre for most activities. A subsidiary camp was established at Taheke Lake (Figure 3) to support extensive diamond-drilling activity. All diamond-drill core from the project, excluding hole SVB-97-67 and some other short, high-grade intersections, are stored at the Pants Lake campsite.

PREVIOUS WORK

The first regional mapping in the area was by the Geological Survey of Canada as part of a large-scale reconnaissance project throughout northern Labrador and adjacent Québec (Taylor, 1979). Subsequently, 1:250 000-scale mapping of the HLIS (Emslie, 1980) covered the southern part of the area (NTS map areas 13N/05 and 13M/08), and indicated some of the areas underlain by the PLI, which, at that time, were grouped with the anorthositic rocks. Hill (1982) mapped the northern part of the area (NTS map areas 13M/09 and 13N/12) at 1:100 000 scale, and also indicated the Pants Lake North intrusion (also called the North intrusion; *see Stratigraphic Terminology*), but did not separate it from other mafic and anorthositic rocks of the NPS. In both cases (Emslie, 1980; Hill, 1982), the Pants Lake area formed the very edge of their study areas, and was not mapped in detail. In order to integrate the results of this earlier mapping, and provide information about the gneisses known to dominate this region, the Geological Survey later mapped the northern parts of map areas 13N/05, 13N/06 and 13M/08 at 1:100 000 scale (Thomas and Morrison, 1991). This work was the first to recognize the gabbroic rocks of the PLI as a separate geological unit, and provided a general outline of the area now termed the Pants Lake South intrusion (also called the South intrusion; *see* section on *Stratigraphic Terminology*), and the northeast-dipping, sheet-like body now known as the Worm intrusion. This mapping also recognized the presence of disseminated sulphide mineralization associated with the basal sections of some of these gabbro bodies; however, the best surface showings lay north of the study area. Thomas and Morrison (1991) also subdivided the gneisses of the Nain and Churchill provinces into several units, and described the characteristics of the Nain–Churchill boundary.

There was essentially no mineral exploration in this area prior to 1995, when junior exploration companies Donner Resources (later Donner Minerals) and Major General Resources both mounted reconnaissance programs. The 'South Voisey's Bay Joint Venture' was established in 1996, and systematic regional mapping was conducted mostly in 1997, under the direction of Teck Corporation, at 1:50 000 scale. Detailed, grid-based mapping of the PLI, at 1:10 000 and 1:20 000 scales, was also conducted in selected areas during 1997 and 1998. This work provides better definition, and subdivision, of the PLI, and also additional information on the distribution of the basement units. The 1:50 000-scale regional maps of Fitzpatrick *et al.* (1998, 1999) are still the most current documents, but their coverage is not systematic, because some claim blocks, not included as part of the joint venture, were not mapped. In addition to mapping, exploration work added a great volume of valuable data through geophysical surveys, geochemical surveys, and diamond drilling. The work carried out as part of these exploration programs is discussed in more detail in later sections of this report.

Two M.Sc. theses were initiated in conjunction with the mineral exploration program. MacDonald (1999) completed a petrological and geochemical study, including an investigation of the olivine geochemistry, and the results of the study are summarized here; Smith (2006) completed a more detailed M.Sc. study of mineralized rocks associated with the basal sections of the North intrusion. This study also resulted in some early abstracts, two of which reported important geochronological data commissioned by Donner Minerals

(Smith *et al.*, 1999, 2001). The final thesis (Smith, 2006) contained these U–Pb geochronological data, and also provided sulphur isotope data that are important in terms of the origins of mineralization. These U–Pb and sulphur isotope data are reported and discussed in the Appendix to this report. Interpretations of the mineralized sequence presented by Smith (2006) are generally similar to those expressed in this report and earlier publications (*e.g.*, Kerr, 1999, 2003a; Kerr *et al.*, 2001) although they differ in some details. Li *et al.* (2001) report some olivine geochemistry and sulphur isotope data from the Pants Lake area, and comment on similarities to, and differences from, the Voisey's Bay area. Previous and current publications from the Labrador Nickel project (Kerr, 1999, 2003a; Kerr and Ryan, 2000; Kerr *et al.*, 2001) have also addressed this topic.

CHARACTERISTICS OF MAGMATIC SULPHIDE DEPOSITS

As this report focusses on magmatic sulphide mineralization and associated rocks, a general overview is provided, drawn mostly from review articles, notably Naldrett (1989, 1997).

Magmatic sulphide deposits are currently the major world sources of Ni, Co and platinum-group-elements (PGE), and are also important sources of copper. An increasing proportion of the world's nickel now comes from laterite deposits in tropical regions but Co and PGEs come, almost exclusively, from magmatic sulphides. These are fundamentally different from most other classes of ore deposits, in that they are formed at high (800° to >1000°C) temperatures in a magmatic environment, and do not directly involve hydrothermal processes. The largest and most productive members of this deposit class are the deposits at Noril'sk, Russia and Sudbury, Canada, which collectively contain close to 50 million tonnes of nickel metal, and huge quantities of Cu, Co and PGEs. These deposits outrank all others in the world by a factor of 10. Other world-class examples include Jinchuan in China, Thompson in Manitoba, the Kambalda district of Western Australia, Pechenga in Russia and Raglan in northern Québec. Voisey's Bay is the most recent world-class magmatic sulphide deposit discovered, and is currently estimated to contain slightly more nickel than the Thompson district (mid-1999 estimates). The reserve and resource figures released by INCO in 2000 indicate that Voisey's Bay contains some 2.2 million tonnes of nickel metal, distributed in about 141 million tonnes of ore. On this basis, it is probably the seventh-largest magmatic sulphide nickel deposit in the world, and the only example in which high-grade sulphide ores presently sit close to the surface and near to tidewater.

Magmatic sulphide deposits are invariably associated with igneous rocks of mafic and ultramafic composition, and these associated igneous rocks represent the magmatic sources or 'reservoirs' from which nickel and other metals were derived. Naldrett (1997) divides deposits into several categories, based on their tectonic setting and character of associated igneous rocks, but this classification is superimposed on a more fundamental division, in which deposits are associated with volcanic and plutonic environments. Deposits hosted by komatiitic or ferropicritic volcanic rocks in Archean to Proterozoic sequences include most of the deposits in Australia, Pechenga, and Raglan, Québec. Most other magmatic sulphide deposits are associated with plutonic environments, although the settings vary widely, and include intracratonic flood-basalt provinces (*e.g.*, Noril'sk), large-scale magmatism induced by meteorite impact (Sudbury), and anorogenic, extensional plutonic suites (*e.g.*, Voisey's Bay).

Regardless of their precise tectonic setting, several common processes occur in the formation of economic magmatic sulphide deposits. The most fundamental is that an immiscible high-temperature sulphide liquid must form at some point during the crystallization of the silicate magma. If such a liquid does form, it must then mix and equilibrate with a much larger volume of silicate magma. During this process, chalcophile elements such as Ni, Cu, Co and PGEs will partition into the sulphide liquid, along with Fe. Clearly, most mafic and ultramafic intrusions contain little or no sulphide, and Ni is normally contained in silicate minerals such as olivine, so unusual circumstances are required for a sulphide liquid to form in this manner. Assuming that it does form, the sulphide liquid must ultimately be concentrated in some way, so that the average metal content of a deposit is of economic interest. This is a crucial step, but it does not happen in all cases. As an example, one of the world's largest inventories of copper and nickel is at Duluth, Minnesota, where there is as much as 4 billion tonnes of disseminated mineralization grading 0.6% Cu and 0.2% Ni. These low grades are uneconomic under present conditions, but the deposit would be of major importance had the sulphides become concentrated. As will be discussed in this report, the PLI also contains a very substantial resource of subeconomic mineralization.

The development of an immiscible sulphide liquid is controlled by the solubility of iron sulphide in the silicate magma. Sulphur normally behaves as an incompatible element because it is not hosted by common silicate minerals, and its concentration will increase in the residual magma as crystallization proceeds. At some point, usually very late in the crystallization process, its concentration will exceed the solubility threshold for the ambient conditions, and it will 'exsolve' as liquid sulphide. This is the normal situation in mafic magmas – sulphides form late, and only in very small quantities. The solubility of sulphur depends on several factors, including magma temperature, ($FeO+TiO_2$) content, oxidation state and the concentrations of SiO_2, Na_2O and K_2O. As crystallization proceeds, the solubility of sulphide in the remaining magma generally declines as a function of normal compositional trends, *e.g.*, silica enrichment and removal of FeO, but it is thought to increase slightly in more fractionated magmas that are crystallizing plagioclase (Naldrett, 1989). Fractional crystallization of mafic magmas normally involves the early removal of olivines and pyroxenes, both of which concentrate Ni in their structures; olivines, in particular, may contain thousands of ppm Ni. Consequently, under normal circumstances, the Ni content of magmas is likely to be low when immiscible sulphide liquids finally form. The development of magmatic sulphide deposits is therefore critically dependent upon early exsolution and segregation of sulphide liquid, so that it has a chance to extract metals from the associated silicate magma. In most of the major Ni-rich magmatic sulphide deposits of the world (with the possible exception of Sudbury), sulphur is thought to have been added from an external source, normally the country rocks to the host intrusions or the substrate to them. Sulphur is presumed to have been added through the assimilation and digestion of such material, and (in conjunction with factors related to magmatic differentiation) this process permits the early development of a sulphide liquid. Magmatic sulphide deposits are most commonly found in the basal sections of host intrusions, which imply that they develop early in the intrusive history, and/or are concentrated, at least partly, by gravitational segregation. There is, however, growing evidence that channels or conduits through which magma has flowed represent very favourable sites for sulphide accumulation. For example, many komatiite-hosted sulphide deposits are now thought to be confined within lava channels (Barnes *et al.*, 1999), and the rich Noril'sk deposits may have developed within magma conduits (Naldrett *et al.*, 1995; Naldrett, 1997). The realization that mineralization at Voisey's Bay is contained within the feeder conduit system of an intrusion has been an important influence on this viewpoint.

Regardless of the details of their formation, all magmatic sulphide deposits have one thing in common – they represent small and difficult exploration targets, particularly in blind settings. Large-scale hydrothermal alteration zones are absent from these deposits, which means that (unlike most other deposit classes) the size of the target and the size of the deposit are roughly equivalent. Magmatic sulphide deposits do have strong anomalous geophysical signatures (notably high conductivity, density and magnetic susceptibility) in near-surface environments, but these are very muted where deposits lie beneath several hundred metres of mafic rocks, as is commonly the case (*e.g.*, Watts, 1997; Balch, 1999). The history of the Voisey's Bay project would likely have been very different if the Ovoid deposit were not located beneath a thin veneer of swamp and gravel, where it was betrayed by loud geophysical anomalies. The magnetic signature of the deeply buried Eastern Deeps deposit is inseparable from regional variations (unless you know where to look) and it had only a very weak response to surface electromagnetic (EM) surveys (*e.g.*, Balch, 1999).

CHARACTERISTICS OF THE VOISEY'S BAY DEPOSIT

Throughout the 1995–1998 Labrador exploration boom, Voisey's Bay provided the dominant exploration model, and it continues to do so. Accordingly, a short review of the essential features of the Voisey's Bay deposit is presented below, drawn from recent articles, notably Naldrett *et al.* (1996, 2000), Li and Naldrett (1999), Lightfoot and Naldrett (1999) and Li *et al.* (2000).

The Voisey's Bay deposits are located about 35 km southwest of Nain (Figure 2), within an area dominated by basement gneisses, and containing the tectonic boundary between the Nain and Churchill provinces. Nickel–copper–cobalt sulphide mineralization at Voisey's Bay is spatially and genetically linked to troctolites and olivine gabbros of the *ca.* 1333 Ma Voisey's Bay intrusion, emplaced as one of the early components of the Mesoproterozoic NPS (Amelin *et al.*, 1999). The Voisey's Bay intrusion consists of three parts (Figure 4; after Li and Naldrett, 1999; Lightfoot and Naldrett, 1999). In the east, the Eastern Deeps subchamber is a 2 by 1 km troctolite body that has a maximum depth of over 1000 m. In the west, scattered enclaves of gabbro and troctolite within younger granitoid rocks form the surface expression of the Western subchamber. Deep drilling in this area shows that troctolitic rocks are more extensive and continuous in the subsurface, extending to depths of at least 1200 m. The Western and Eastern Deeps subchambers are connected by a complex, dyke-like, conduit system, which gradually changes in attitude from south-dipping, through vertical, to north-dipping from west to east (Figure 4). Sulphide mineralization at Voisey's Bay is closely associated with this conduit system, and most of the known massive sulphides are hosted within the conduit or located near to its junctions with the larger subchambers (Figure 4). However, in the Reid Brook zone, massive sulphides occur in the country rocks adjacent to the dyke-like conduit.

From east to west, the major sulphide bodies (November 1999 estimates released by INCO (press release, 2000)) are the Eastern Deeps zone (47 million tonnes at 1.39% Ni, 0.6% Cu and 0.09% Co), the Ovoid zone (32 million tonnes at 2.83% Ni, 1.68% Cu and 0.12% Co), the Discovery Hill zone (13 million tonnes of 1.0% Ni, 0.8% Cu and 0.06% Co) and the Reid Brook zone (17 million tonnes at 1.46% Ni, 0.65% Cu and 0.1% Co). Since 1999, additions to the total resources have mostly been in the Reid Brook zone. The remaining resource is dispersed within several smaller zones, some of which physically link the four major sulphide bodies. The in-

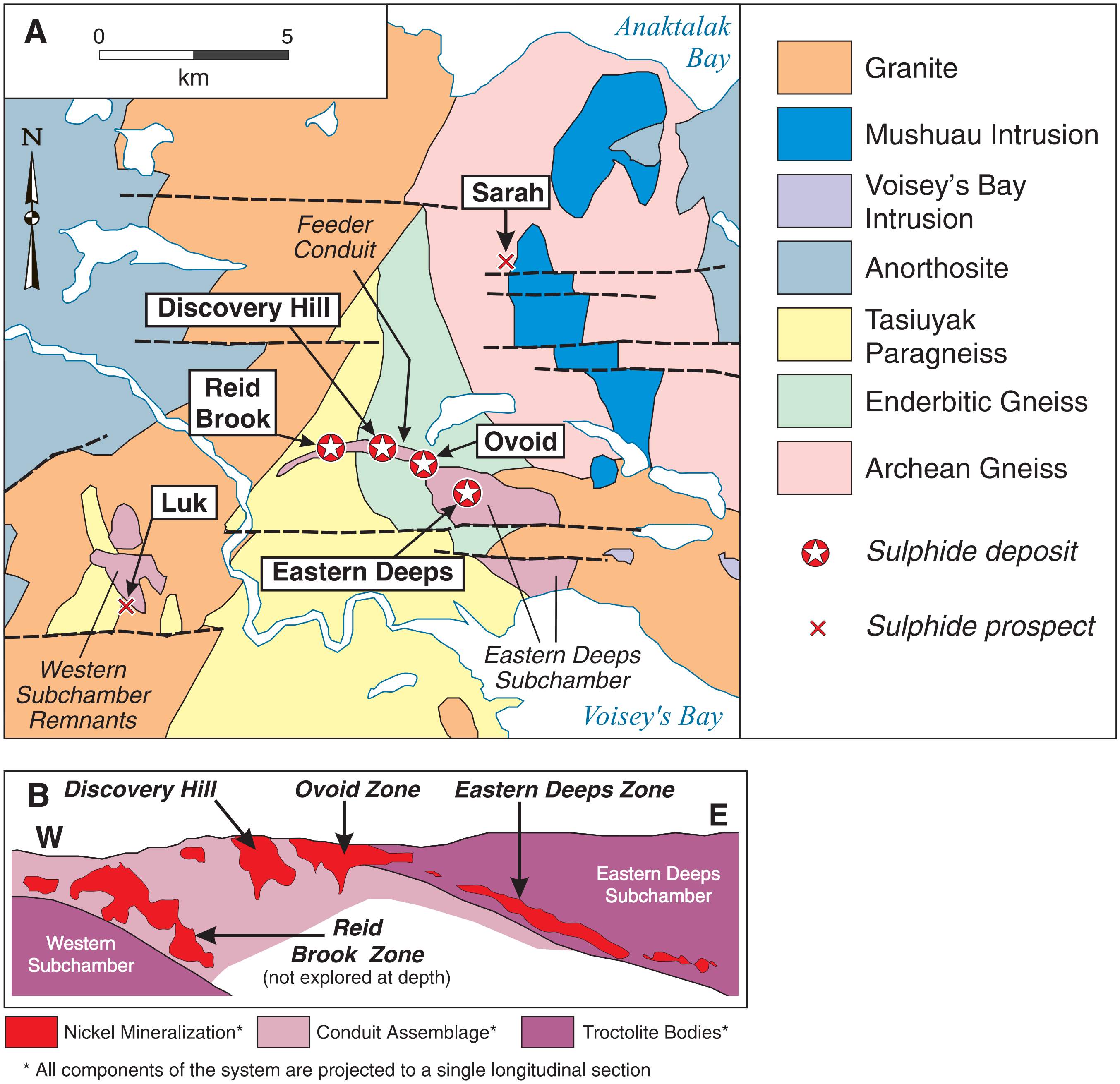


Figure 4. *A. Simplified geology of the area around the Voisey's Bay deposits, showing the location of various parts of the Mushuau and Voisey's Bay intrusions and the major sulphide deposits. B. Schematic longitudinal cross-section through the Voisey's Bay intrusion, roughly east–west in orientation, illustrating the relationship between mineralization and the feeder conduit system. After Li and Naldrett (1999) and Lightfoot and Naldrett (1999).*

dividual sulphide bodies all share a common east-plunging attitude, roughly parallel to the junction line between the feeder conduit and the Eastern Deeps subchamber, and they are locally superimposed in the third dimension, *e.g.*, the deep (eastern) section of the Reid Brook zone lies vertically below the near-surface Discovery Hill zone (Figure 4). Sulphide mineralization in all parts of the Voisey's Bay system is closely similar, consisting mostly of pyrrhotite, pentlandite, chalcopyrite (± cubanite) and variable amounts of magnetite (Naldrett *et al.*, 2000). Mineralized rocks range from coarse-grained, crystalline massive sulphides to disseminated, interstitial sulphides in homogeneous troctolites, to coarse-grained breccia-like sulphides containing troctolitic and reacted country-rock fragments. As in many magmatic sulphide deposits, the effective grade of mineralization at Voisey's Bay is essentially a function of the amount of sulphides, which usually contain between 3 and 5% Ni, and 1.5 and 2.5% Cu. Nickel contents in sulphides, and Ni/Cu ratios, remain generally consistent within individual sulphide bodies, although there is some grade zonation in the Ovoid deposit, and some differences in sulphide metal contents between different parts of the system (Naldrett *et al.*, 2000; Lightfoot *et al.*, 2001). Platinum-group-element contents were not publicly announced, but are reported to be low; typically <0.5 ppm (g/t) combined PGE in massive sulphides (Naldrett *et al.*, 2000). A typical example of mineralized 'basal breccia' analyzed by Kerr (2002a) contained about 100 ppb each of Pt and Pd, and about 20% sulphides.

Massive sulphide mineralization at Voisey's Bay is invariably associated with distinctive sulphide-bearing silicate rocks (Naldrett *et al.*, 1996; Li and Naldrett, 1999). The most characteristic of these is Basal Breccia Sequence or Feeder Breccia, which is a heterogeneous sulphide-bearing troctolite including numerous variably digested gneissic fragments containing unusual anorthite–corundum–spinel mineral assemblages. The fragments are believed to be derived by metasomatic transformation of local country rocks, notably Churchill Province paragneiss (Tasiuyak paragneiss) that contain minor sulphide and graphite. Variable-textured troctolite, common in the Eastern Deeps subchamber, is similar to the basal or feeder breccia in many respects, but is poorer in sulphides and digested fragments. Leopard troctolite, found only in the feeder conduit, consists of clinopyroxene, plagioclase and olivine crystals in a sulphide-rich matrix, and is commonly closely associated with massive sulphides. The textural relationships imply that the sulphides formed a discrete, immiscible liquid, which was transported, in suspension, by associated mafic silicate magmas, from which sulphides extracted their metals. The sulphide liquids appear to have been concentrated and trapped as magma passed through the conduit system enroute to the Eastern Deeps subchamber. The various sulphide bodies are interpreted to represent different structural levels within the system (Figure 5; after Lightfoot and Naldrett, 1999). The Eastern Deeps zone formed at the base of the magma chamber, at the entry point of a flat to gently dipping feeder conduit sheet. The Ovoid zone may have a similar setting, or may have formed in a small 'microchamber' developed within the conduit. The Discovery Hill and Reid Brook zones formed within the conduit system dyke, and are possibly associated with local widening zones or changes in dyke attitude (Figure 5). Changes in the fluid dynamic environment are suspected to control the localization of sulphide zones, but the details of such controls are not always clear, and the development of the conduit system may, in part, be controlled by regional structural patterns (Evans-Lamswood *et al.*, 2000). Similarly, the spatial relationship between the flat-lying feeder at the Eastern Deeps zone and the subvertical feeder associated with the other deposits is not well-known, and they may be discrete conduit systems (Evans-Lamswood *et al.*, 2000).

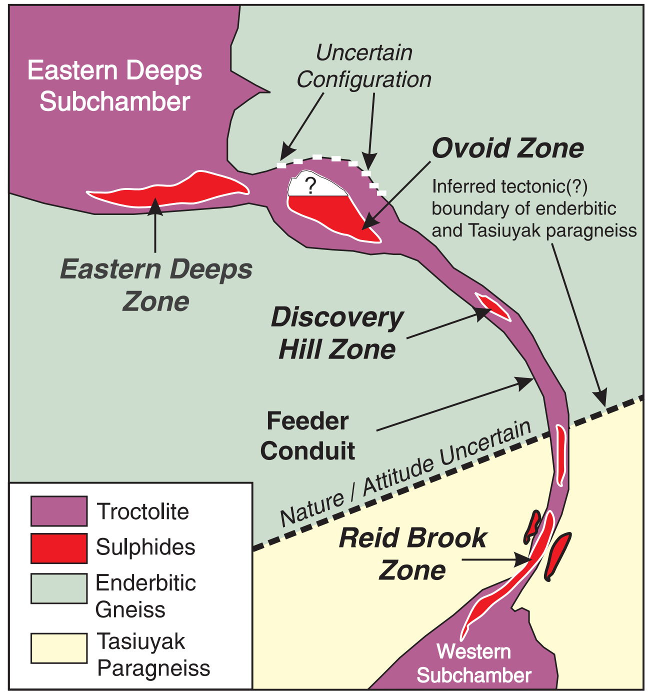


Figure 5. *Schematic cross-section illustrating the inferred settings of major massive sulphide deposits within the feeder conduit and associated magma chambers of the Voisey's Bay intrusion. The nature of the enderbite–Tasiuyak gneiss boundary is uncertain. After Li and Naldrett (1999), and Lightfoot and Naldrett (1999).*

Current thought on the genesis of the Voisey's Bay deposits suggests that several critical factors were important (Naldrett, 1997; Li and Naldrett, 1999; Li *et al.*, 2000). The tectonic boundary between the Nain and Churchill provinces, which lies close to the deposits, may have acted as a zone of weakness that facilitated rapid ascent of the mafic magmas. These original magmas are believed to have reacted extensively with the sulphide-bearing Tasiuyak paragneiss below the present level of exposure, and to have exsolved an immiscible sulphide liquid as a consequence of direct sulphur addition and/or felsification effects. These early sulphide liquids were relatively metal-poor (<1.5% Ni), but were progressively upgraded by interaction with fresh mafic magma batches that had not previously surrendered their metals to sulphides. The immiscible sulphide liquids were eventually forced through the conduit system toward the Eastern Deeps subchamber, where they became trapped in various settings, as indicated in Figure 5. The associated sulphide-bearing silicate rocks record the contamination of magmas by the Tasiuyak paragneiss, and the subsequent interaction between different batches of magma and sulphides. From an exploration perspective, the key factors at Voisey's Bay appear to be a sufficiently primitive original magma composition (*i.e.*, nickel was not completely removed by olivine fractionation), contamination by the Tasiuyak paragneiss (possibly involving sulphur addition), and the fortuitous preservation of the feeder conduit system close to the present erosion level. There have been few publications on the Voisey's Bay deposit since 2000, although ideas concerning its genesis have continued to evolve. The development of various magma batches, and the eventual 'pumping' of sulphide-rich magmas from a deep chamber into the overlying conduit system, are now seen as part of a wider process of magma-chamber development, in which there is progressive collapse of the magma chamber, akin to processes of caldera development and subsidence (*e.g.*, Cruden, 2008; Lesher *et al.*, 2008).

OBJECTIVES

The objectives of this report are to describe and interpret the mafic rocks and magmatic sulphide mineralization of the PLI, and to present and synthesize relevant information from the mineral exploration programs. The latter includes huge amounts of geophysical data, and also assay data from surface and drillcore samples. No attempt is made here to discuss the geophysical data, to tabulate all these geochemical data, or to provide detailed logs of individual drillholes. These results may be found in a series of comprehensive assessment reports, discussed and referenced in subsequent chapters.

This report is divided into seven sections. The section entitled *'Regional Geological Framework'* provides an account of the regional geology, the general geology of the study area, and the principal results of the exploration programs. The section *'Country Rocks'* describes the metamorphic rocks of the area, and also igneous rocks assigned to older members of the Nain and Harp Lake intrusive suites. The section *'Geology and Petrology'* deals with the rock types; the section *'Geometry and Stratigraphy'* deals with the 3-D arrangement of rock types and their relationships, and the section *'Magmatic Sulphide Mineralization'* discusses areas of economic interest. The section *'Geochemistry'* details the geochemical trends of both unmineralized and mineralized rocks. The final section of the manuscript, *'Summary, Discussion and Conclusions'*, synthesizes and expands previous discussions, with an emphasis upon comparisons between the Pants Lake and Voisey's Bay areas.

The map that accompanies this report (Map 2012-18) is a 1:50 000-scale compilation that includes the results of mapping conducted by the Geological Survey of Newfoundland and Labrador. This mapping was not systematic; thus, the map also draws extensively from mapping conducted by exploration programs in the area.

REGIONAL GEOLOGICAL FRAMEWORK

GEOLOGY OF NORTH-CENTRAL LABRADOR

Labrador is truly a microcosm of the Canadian Shield, containing parts of Archean high- and low-grade cratonic regions, several orogenic belts of Paleoproterozoic to Mesoproterozoic age, and large Mesoproterozoic 'anorogenic' plutonic complexes. The region of most interest, in terms of exploration for magmatic sulphide deposits, is north-central Labrador, situated north of the Grenville Front tectonic zone (Figures 2 and 6).

North-central Labrador and adjacent Québec (Figure 2) include parts of two contrasting Precambrian structural provinces (Hoffman, 1988). The coastal region is part of the Archean Nain Province (*e.g.*, Bridgwater and Schiøtte, 1991), whereas the hinterland forms part of the Churchill Province, consisting of Archean and Paleoproterozoic rocks that were reworked within the 1.85 Ga Torngat Orogen (Wardle *et al.*, 1990; Bertrand *et al.*, 1993). A belt of granulite-facies pelitic paragneiss (the Tasiuyak paragneiss) lies to the west of the Nain–Churchill boundary along much of its length (Figure 6) and partly coincides with the 1.85–1.82 Ga Abloviak shear zone (Bertrand *et al.*, 1993). The Abloviak shear zone is a major high-strain zone along which sinistral motion occurred in the closing stages of the Torngat Orogeny. The Nain–Churchill boundary is inferred to be a crustal-scale discontinuity, possibly a suture, marking the line along which the Nain Province craton collided with the interior Churchill Province (Bertrand *et al.*, 1993). 'Anorogenic' plutonic suites, including the *ca.* 1450 Ma HLIS and the 1350 to 1290 Ma NPS were emplaced across this boundary zone (*e.g.*, Emslie, 1980; Emslie *et al.*, 1994; Ryan, 1998), and were essentially unaffected by later tectonic events. Major east–west faults were last active during the Cretaceous rifting of the Labrador Sea, but some of these may be reactivated Precambrian structures. Northern Labrador lay beyond the realm affected by later Mesoproterozoic events (*e.g.*, Grenvillian Orogeny).

OVERVIEW OF THE NAIN PLUTONIC SUITE

The NPS is perhaps the classic undeformed Mesoproterozoic anorogenic plutonic terrane, and it has been studied for over 50 years, starting with the pioneering work of E.P. Wheeler (1942). As outlined in a review by Ryan (1998), the NPS includes four major compositional subdivisions, *i.e.*, anorthositic rocks, granitoid rocks, gabbroic to troctolitic rocks, and iron-rich intermediate rocks.

The anorthositic and granitoid rocks make up over 80% of the NPS on surface, in roughly equal amounts, but these proportions may be an artifact of erosion level, as granitic rocks are less extensive in the HLIS, which is considered to

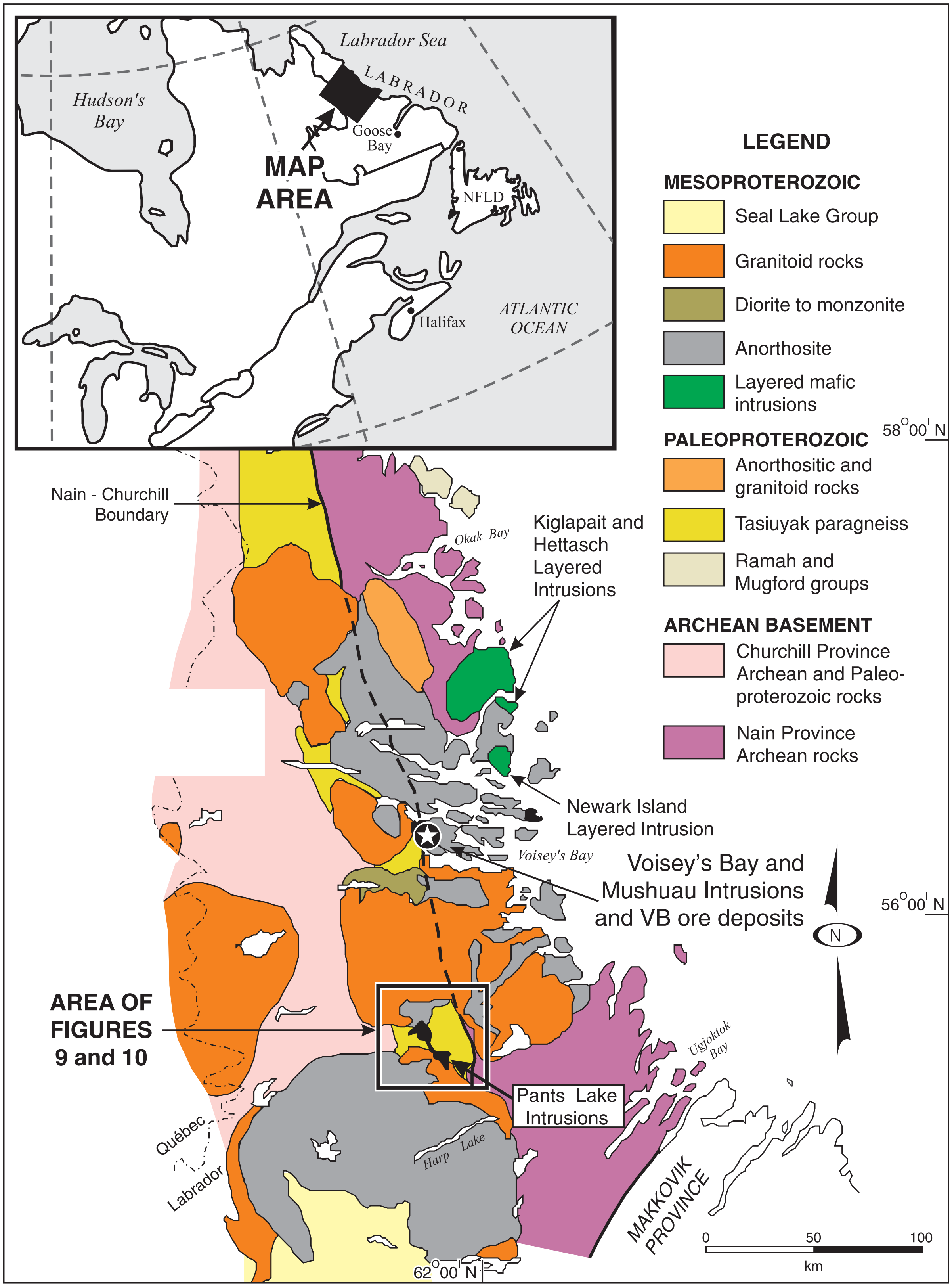


Figure 6. *Simplified geology of north-central Labrador, showing basement rocks, major Mesoproterozoic intrusive complexes and the location of the Voisey's Bay deposits. The study area is indicated by the outlined square, corresponding to Figures 9 and 10, and the 1:50 000-scale map accompanying this report.*

be more deeply eroded (Ryan, 1991; Kerr and Smith, 2000). The rocks within each compositional subdivision are not synchronous, and the NPS consists of myriad, overlapping plutons intruded over at least 60 m.y. Details of typical NPS rock types are provided elsewhere (Ryan *et al.*, 1995; Ryan, 1998). Figure 7 illustrates the general geology of the NPS (after Ryan, 1998; Kerr and Ryan, 2000). The anorthosite and gabbro–troctolite subdivisions have received the most exploration attention, and the best-known examples of the latter are indicated. Mapping north of Nain (Ryan, 1998; Ryan *et al.*, 1997) has also delineated older, variably foliated and metamorphosed plutonic rocks that are compositionally akin to the NPS, but are of *ca.* 2100 Ma age (Hamilton *et al.*, 1998). The full extent of these Paleoproterozoic plutonic rocks in Labrador is unclear, but there are certainly examples in the immediate Nain area (Ashwal *et al.*, 1992). This adds some complications to both regional and metallogenic syntheses, as discussed below.

Several models have been proposed for the genesis of anorthosite-dominated plutonic suites (*see* Weibe, 1992), but the most popular is that of Emslie *et al.* (1994). In this model, magmatism is initiated by thermal plumes sourced in the mantle, coupled with thermal blanketing from stable continental crust (Figure 8). Mafic magmas are ponded at, or near, the base of the crust, and induce anatexis of lower crustal rocks, producing the granitic magmas of the NPS. The plagioclase-rich restite is then assimilated by the mafic magma, driving it to Al-rich compositions. From this magma, plagioclase accumulates by flotation. The 'anorthosite magmas' thus produced are 'mushes' of plagioclase and residual mafic liquid, which separate and ascend buoyantly, utilizing pathways prepared by earlier granitoid magmas. Depending upon the proportions of crystals and magma, and the degree of heat loss during ascent, they may behave either as crystal-rich diapirs (generally early anorthositic intrusions in the NPS sequence) or liquid-dominated intrusions (generally late anorthositic intrusions). Both of these end-member types, and intermediate varieties, are recognized in the Labrador area (Emslie *et al.*, 1994; Ryan, 1998). The subordinate gabbro–troctolite and ferrodiorite subdivisions represent, respectively, samples of little-modified mafic magmas, and late-stage residual intermediate magmas, both derived from the deep magma chambers. This is viewed as a long-term, repetitive process in which the subcrustal mafic magma is periodically replenished, and the thermal flux is maintained for periods in excess of 100 Ma. The complex, 'nested pluton' architecture of the NPS indicates that magmatism was episodic, and that its geographic focus changed with time. Thus, the actual intrusive relationships between the individual member plutons of different compositional subdivisions are complex.

REGIONAL GEOLOGY

The study area lies at the southern extremity of the NPS, in a region dominated by basement rocks that lie immediately north of the older HLIS. The area can be divided into several 'packages' of rocks, as shown in Figure 9. In the east of the area, gneisses form part of the Archean Nain Province. These are in presumed tectonic contact with Paleoproterozoic gneissic rocks that are assigned to the Churchill Province. However, the actual contact region is unexposed. Churchill Province gneisses include both paragneiss and granitic orthogneiss, commonly mixed on an outcrop scale. This package of rocks strikes north-northwest–south-southeast through the area, but exhibits considerable local structural complexity. Undeformed Mesoproterozoic plutonic rocks intrude both the Archean and Paleoproterozoic gneisses in the northwest and northeast corners of the area, and also in a large area straddling the Adlatok River. Those in the north are assigned to the NPS, whereas those in the south are assigned to the HLIS; rock types include anorthosite, diorite and quartz monzonite to granite. The youngest rocks are the PLI, which form an elongated belt of mafic plutonic rocks running northwest–southeast through the central area; on the basis of their age and composition, the PLI are grouped as part of the NPS, rather than with the older HLIS (Kerr, 1999; Smith *et al.*, 1999, 2001).

The Archean Nain Province gneisses form the western extremity of the Hopedale Block. The Hopedale Block is complex, and includes ancient gneisses up to 3200 Ma in age, extensive tonalitic to granodioritic plutonic rocks and their gneissic equivalents (*ca.* 2800 Ma), and remnants of greenstone belts. The nature of the Archean gneisses is poorly known, and it is not certain which of these components they represent. Compositionally, they are dominated by banded granodioritic gneiss, but also include units of mafic (amphibolitic) composition. Gneisses of the Churchill Province are significantly more varied in composition than the Nain Province gneisses, and are very complex. In the study area, the dominant Churchill Province rock types are paragneisses of pelitic to psammitic composition, rich in biotite and other aluminous minerals, and commonly contain minor graphite and sulphide. In almost every outcrop, there are zones of granite and pegmatite, and several map-scale units of granitoid gneiss can be defined. These contain relict igneous textures, and are younger than the paragneisses, which they locally intrude. However, they are undated. In the west, the paragneisses give way to quartzofeldspathic gneisses of uncertain, but probably igneous, origin.

The HLIS and NPS consist of essentially undeformed, Mesoproterozoic massive igneous rocks. The HLIS is domi-

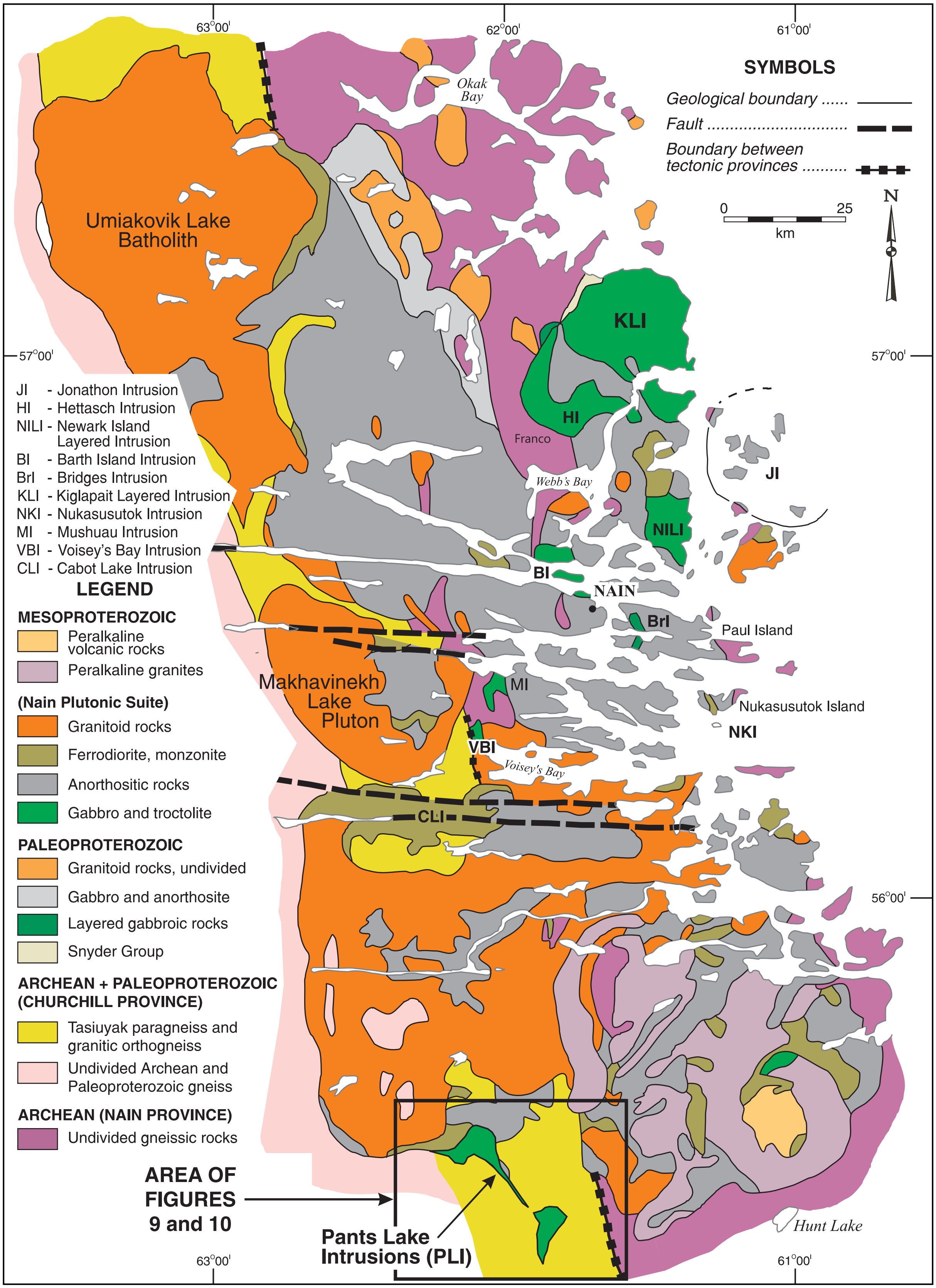


Figure 7. *Simplified geology of the Nain Plutonic Suite between Okak Bay and Harp Lake. After Ryan (1998) and Kerr and Ryan (2000). Note that the geology in the study area is simplified, and thus does not correspond exactly to that presented in subsequent figures.*

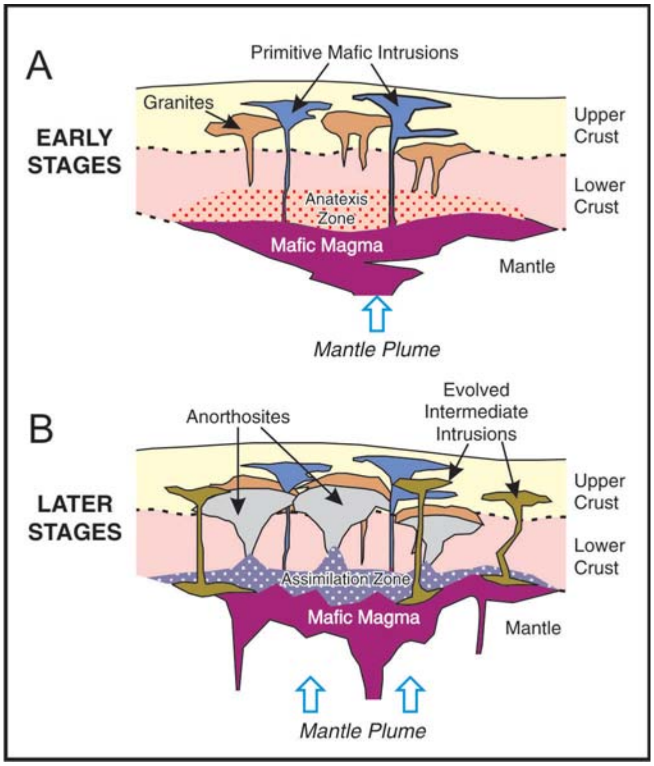


Figure 8. *Schematic illustration of the model proposed for the development of 'anorogenic' anorthosite–mangerite–charnockite–granite (AMCG) suites such as the Nain Plutonic Suite, based on the suggestions of Emslie* et al. *(1994). A. 'Early' stages, in which mantle-derived mafic magma causes anatectic melting of the lower crust and generation of granitic magmas; mafic magmas are emplaced where structural weaknesses permit their ascent. B. 'Later' stages, in which plagioclase-rich restite from the lower crust is assimilated by mafic magmas to generate A1-rich parental magmas for anorthosites; fractionation of the deep-seated mafic magmas leads to the generation of relatively evolved mafic and intermediate magmas that produce the ferrodiorite suite. Note that 'early' and 'late' stages have different absolute timing in different parts of Labrador, thus creating a complex set of intrusive relationships.*

nated by granitoid rocks, which occupy a large area stretching from Pants Lake to south of the Adlatok River, and some minor anorthositic rocks (Figure 9). The NPS is dominated by anorthositic rocks, with lesser amounts of granitoid rocks. Intermediate plutonic rocks, broadly included with the 'ferrodiorite' clan, occur in the northwest corner. None of the Mesoproterozoic plutonic rocks have been dated (aside from the PLI) and thus assignment as HLIS or NPS largely reflects their location. The most important components of the NPS are the PLI. These were originally considered to be a single entity, but geochronology now shows that the North intrusion was emplaced at 1322 ± 2 Ma (Smith *et al.*, 1999; Smith, 2006; *see* appendix), whereas the South intrusion was emplaced at 1338 ± 2 Ma (Smith *et al.*, 2001; Smith, 2006; *see* appendix). This age range generally corresponds to that of mafic rocks in the Voisey's Bay area. The PLI consist of troctolite, olivine gabbro and gabbro. Despite the age difference, rocks from the South and North intrusions are essentially identical. The PLI are also divided into four main lithological units based on field relationships, petrology and geochemistry, but some areas currently remain undivided. On the basis of the geochemical data, most of the smaller gabbroic bodies indicated in Figure 9 are considered to be correlative with the North intrusion.

The dominant structural grain throughout the area is northwest–southeast to north-northwest–south-southeast, as indicated by the pattern of units in the Churchill Province gneisses, and dips are steep to vertical. In detail, however, this structural grain was developed *via* several episodes of deformation, and there are local domains where fabrics show an east–west orientation. The HLIS and NPS igneous rocks appear undeformed in outcrop, and are viewed as posttectonic; however, the 3-D pattern of the PLI may indicate some very gentle post-NPS warping or flexing. The continuity of basement units and elongate sections of the PLI argues against east–west faults with significant displacements, although some small fault zones were defined by detailed mapping conducted by exploration companies.

STRATIGRAPHIC TERMINOLOGY

Several terms have been used for the mafic igneous rocks that are the principal subject of this report. The units were not named by Hill (1982) or by Thomas and Morrison (1991). Wares (1997) used the general term Pants Lake gabbro, and Fitzpatrick *et al.* (1998) used the term Pants Lake Intrusive Suite. The terminology was amended to Pants Lake intrusion in a later descriptive account (Kerr, 1999) because the initial U–Pb age of 1322 ± 2 Ma (Smith *et al.*, 1999; Smith, 2006) suggested that these rocks should be included in the NPS, which precluded the use of the term 'suite' in a formal manner. Prior to this determination, there had been some informal speculation that the mafic rocks might be significantly younger, and possibly equivalent to the 1274 Ma Harp dyke swarm. Due to the strong petrological and geochemical similarities amongst the mafic rocks, it was tacitly assumed that all were of essentially identical age, although MacDonald (1999) and Kerr *et al.* (2001) highlighted some geochemical contrasts between the Pants Lake North and South intrusions (*see* below).

The subsequent recognition that some of these mafic rocks are significantly older at 1338 ± 2 Ma (Smith *et al.*, 2001; Smith, 2006) complicates stratigraphic nomenclature, because it illustrates that they cannot all be part of a single intrusion. Ultimately, the solution to this dilemma lies in ad-

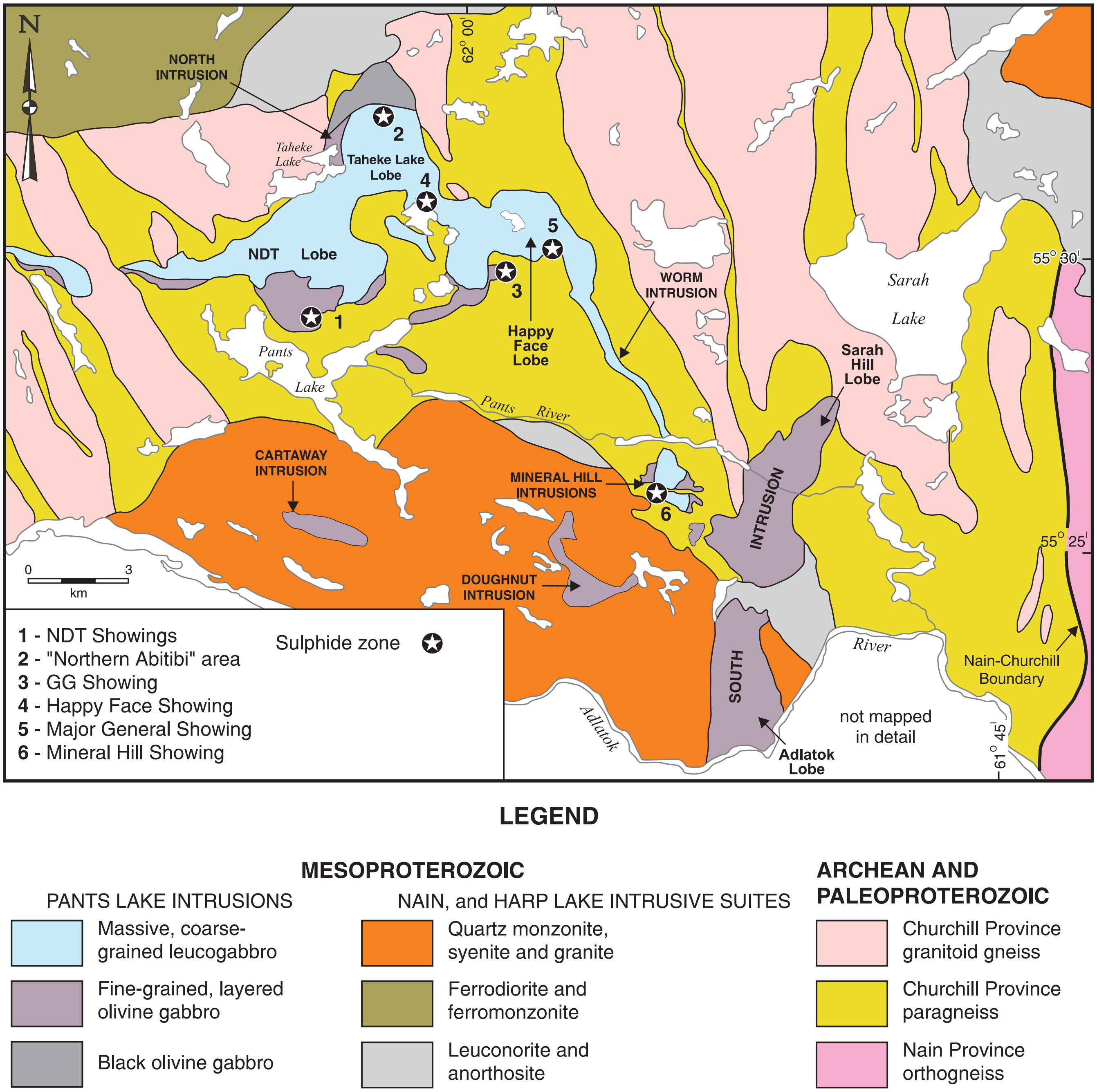


Figure 9. *Simplified geology of the study area. After Kerr (1999), but mostly based on work conducted by Thomas and Morrison (1991), Hill (1982) and Fitzpatrick* et al. *(1998).* See *1:50 000-scale map for additional detail.*

ditional geochronology, followed by renaming of one or both age groupings. This would resemble the redefinition of the original Reid Brook intrusion in the Voisey's Bay area to the Mushuau intrusion and Voisey's Bay intrusion (*e.g.*, Ryan, 2000; Li *et al.*, 2000). For the purposes of this report, an interim solution is used. The mafic rocks are referred to collectively as the Pants Lake intrusions, within which the terms Pants Lake North intrusion and Pants Lake South intrusion are used to refer to the 1322 and 1338 Ma components, respectively. These two subdivisions include most of the rocks within the PLI. Other minor mafic bodies currently included within the PLI are named informally (*e.g.*, Worm intrusion). For reasons of geological continuity and geochemical affinities, most of these smaller mafic bodies are believed to correlate with the Pants Lake north intrusion. This system conforms to the nomenclature employed by Kerr (2003a).

MINERAL EXPLORATION WORK AND RESULTS

Magmatic sulphide mineralization associated with gabbroic rocks in the Pants Lake area was initially recognized by Thomas and Morrison (1991), but received no exploration attention until 1995, when Donner Minerals and Major General Resources conducted reconnaissance work. The 'South Voisey's Bay' joint venture was then established, and extensive exploration work was conducted from 1996 to 1998. Exploration expenditures grew steadily over this period, peaking at over $10 million in 1998. A more modest exploration program was proposed for 1999, but was deferred. The results of the exploration work are contained within several comprehensive assessment reports (notably Wares, 1997, and Fitzpatrick *et al.*, 1998, 1999). In this report, some information from the exploration program has been integrated with the work conducted by the Geological Survey. However, the assessment reports listed above also contain a large amount of other information, notably detailed geophysical data, which is beyond the scope of this report. This section summarizes the major components of the exploration program, and the principal results. Exploration work resumed in the area under a new joint venture with Falconbridge Ltd. in 2001, and these results are summarized by more recent assessment reports.

1995 Program

The 1995 exploration program is detailed by von Einsiedel and St. Hilaire (1996), and summarized also by Wares (1997). The area was targeted initially for exploration because it showed broad geological similarities to the Voisey's Bay district, *i.e.*, it lies close to the Nain–Churchill boundary zone and includes mafic rocks noted to contain sulphides. The lake-sediment geochemical data for the area are weakly anomalous, showing Ni concentrations similar to those in the area around the Voisey's Bay deposit. Ground exploration work started late in 1995, and initial prospecting efforts were based on LANDSAT TM satellite imagery processed to reveal red or brown anomalies indicative of gossan zones. Hundreds of colour anomalies were defined, and several proved to be weathered sulphide-bearing gossans. The GG, NDT, Major General and Mineral Hill showings (Figure 9) were all defined at this stage. Thomas and Morrison (1991) had previously noted the Mineral Hill locality during mapping. Initial prospecting also indicated that disseminated mineralization had interesting whole-rock metal contents, up to 0.53% Ni and 0.45% Cu (von Einsiedel and St. Hilaire, 1996). A stream-sediment sampling program was carried out in conjunction with prospecting. This work confirmed the surficial anomalies indicated by regional lake-sediment data, and indicated broad Ni and Cu anomalies, notably north of Pants Lake. Airborne total field magnetic and electromagnetic (EM) surveys were completed in 1995. The results showed an irregular northwest–southeast-trending magnetic high, partially coincident with known gabbroic rocks, and locally associated with zones of anomalous conductivity. A short diamond-drill program mounted in late 1995 was targeted on the strongest conductors, but these proved to be graphitic zones in the paragneisses, rather than magmatic sulphides.

1996 Program

Based on results from 1995, Donner Minerals acquired interests in many surrounding claim blocks, and the 'South Voisey's Bay joint venture' was established. The 1996 exploration program, detailed by Wares (1997), was much more ambitious. It involved additional prospecting, reconnaissance geological mapping, airborne and ground geophysical surveys, and a diamond-drill program.

Prospecting resulted in discovery of the Happy Face showing, and several smaller sulphide-bearing zones, all associated with the basal contacts of gabbroic units (Figure 9). Geological mapping confirmed the basic distribution of gabbroic rocks outlined by Thomas and Morrison (1991) in the south, and identified several new areas of gabbroic rocks. In the north, mapping suggested that areas included with NPS anorthosites by Hill (1982) were actually coarse-grained gabbro, similar to rocks seen in the south. The North intrusion was broadly defined by this work, as was its basic subdivision into a lower fine-grained unit and an upper, coarse-grained, leucocratic unit. The South intrusion was examined, but in lesser detail. Regional geophysical surveys suggested that many areas of anomalous conductivity represented concentrations of graphite and/or sulphides hosted by paragneiss, but several were associated with gabbroic rocks and positive magnetic anomalies. Coincident conductivity and magnetic anomalies were prioritized for further investigation. More detailed ground geophysical surveys included total-field magnetic surveys, horizontal-loop EM surveys (HLEM) and induced polarization (IP) surveys, mostly focused around the areas of known mineralization (Figure 9).

With the combined geological and geophysical information as a guide, a diamond-drill program was undertaken. A total of 53 holes were completed, mostly in 1996, and most of these were located at, or adjacent to, the main mineralized showings and sulphide zones indicated in Figure 9. No stratigraphic drilling was undertaken. All of the holes were short (<165 m), and most were less than 100 m in length. With a few exceptions, all intersected disseminated magmatic sulphide mineralization. This mineralization was located at, or near, the basal contacts of gabbroic units, and locally ranged up to over 20 m in thickness. The mineralization was found to be extensive, but grades were generally subeconomic (<0.8% combined Ni and Cu). No significant massive-sulphide mineralization was found, but the proportion of sulphides in mineralized rocks was generally low, implying that the sulphides themselves might contain interesting metal values. The textures of the mineralized rocks were of particular interest, because they resembled textures reported from sulphide-bearing troctolites at the Voisey's Bay deposit (Naldrett *et al.*, 1996). Li (1996) completed a petrographic study of mineralized gabbro, and concluded that it was closely similar to the sulphide-bearing leopard troctolite of the Voisey's Bay deposit. Complex, breccia-like rocks containing inclusions of gneissic material in a sulphide-bearing matrix were also considered to be analogous to the 'basal breccias' and 'feeder breccias' at Voisey's Bay. Estimates of sulphide metal contents in disseminated mineralization suggested potential for up to 5% combined Ni and Cu in massive sulphide zones. During a 1996 visit to the area, Bruce Ryan (GSNL) and the author were also impressed by these distinctive rock types, and also by the many similarities in the geology of the two areas, as outlined by Kerr and Smith (1997). In late 1996, Donner Minerals and Teck Corporation entered into an agreement whereby Teck could acquire up to 50% of the mineral rights by funding exploration work. Teck Corporation managed the exploration program over the next two years. The involvement of Teck Corporation, which had acquired an early interest in the Voisey's Bay project, was seen as a significant development, and the area around the South Voisey's Bay began to attract wider exploration interest.

1997 Program

The 1997 exploration program, detailed by Fitzpatrick *et al.* (1998), marked another significant expansion of effort. Work from the previous two years was reviewed and compiled, and the 1996 drillholes were relogged. New exploration work was divided into two components. On a regional scale, a large tract of territory was mapped at 1:50 000 scale, and prospected. This area included the Churchill and Nain provinces' gneisses, and parts of the adjoining NPS and HLIS. A more detailed component, focused on the PLI, consisted of detailed, grid-based mapping (1:20 000 and larger scales), coupled with ground geophysical surveys. In addition to increasing ground magnetic and EM coverage, a gravity survey was initiated to provide 3-D constraints on the geometry and thickness of the PLI in various areas. Downhole EM surveys were also employed extensively.

The 1997 drill program also marked a departure from previous efforts in that it moved away from known surface showings, which were now established as subeconomic, and toward investigation of blind geophysical anomalies and stratigraphic drilling. Over 12 000 m of drilling was completed in 44 holes, with the deepest holes exceeding 750 m. The results showed that the PLI define a major mafic igneous complex, not just near-surface sheet-like bodies, and demonstrated that their stratigraphy and geometry are complex. Virtually every hole that penetrated basal contact regions encountered some sulphide mineralization, although the thickness of the 'mineralized sequence' and the amounts of sulphide varied considerably. The most interesting results were obtained to the north of the North intrusion, where the 'Northern Abitibi' area was defined during follow-up of EM anomalies. Thin massive sulphide intersections at the base of a dark, massive gabbro unit contained 1.35 to 1.93% Ni, 0.84 to 1.64% Cu and 0.17 to 0.26% Co, and were associated with thick zones of disseminated mineralization. A later hole, in a nearby location, intersected a 1.1-m massive-sulphide zone below the basal gabbro contact, which contained remarkable grades of 11.9% Ni, 9.6% Cu, 0.43% Co and 54 g/t Ag, with enrichment in Au (170 ppb), Pt (109 ppb) and Pd (794 ppb). However, attempts to trace and extend this zone were unsuccessful. Exploration work in the South intrusion showed that disseminated sulphides also occurred near its basal contact, but the target areas were near the depth limits of drilling capability at the time.

At the very end of the 1997 program, a drillhole in the same area as the high-grade intersection noted above penetrated 15.6 m of semi-massive to massive sulphide at the base of the gabbro, with an average grade of 1.13% Ni, 0.78% Cu and 0.20% Co. Although such grades fell well short of those reported from Voisey's Bay, the 1997 program ended on an optimistic note.

1998 Program

The 1998 exploration program, detailed by Fitzpatrick *et al.* (1999), was viewed with much anticipation. It was an advanced program dominated by detailed geophysical surveys and diamond drilling. The gravity survey from 1997 was extended, and an attempt was made to use a new 'airborne gravity' technique to provide regional coverage aimed at detection of buried gabbro units. This was only partially successful, and regional coverage was eventually obtained through ground methods. The central area of the project, around the main zone of the PLI, was covered by in-loop pulse EM (time-domain) surveys. Additional geological mapping defined new areas of gabbro in the southern part of the project area.

Over 15 000 m of drilling was completed in 1998, representing 40 new drillholes and the extension of 5 holes from the 1997 season. The initial work set out to follow up the 15.6-m-thick sulphide intersection in the Northern Abitibi area (Figure 9). The survey proved that the massive sulphides are thinner in the surrounding area, implying that overall size is too small to be of economic interest. However, drilling in the surrounding area continued to intersect basal sulphide mineralization, which locally contained up to 4.5% Ni and 2.6% Cu over narrow widths. Drilling in the South intrusion confirmed that the gabbro extended to depths of 800 m, and established the widespread presence of basal, disseminated sulphide mineralization in ultramafic cumulates. Finally, drilling well outside the known area of the PLI established that the gabbroic rocks are locally present at depth beneath the Churchill Province gneisses. This recognition increased the size of the target area significantly.

The 1998 season also saw the initiation of research studies aimed at evaluating the potential of the area, and its similarities to Voisey's Bay. MacDonald (1999) examined the whole-rock and olivine geochemistry of key drillholes, and provided evidence for contrasting fractionation trends. Depletion of nickel in olivines, and depletion of chalcophile elements in most gabbros were also recognized at this stage, although the results were not included in the study. The olivine geochemistry study was extended to other parts of the area (Naldrett, 1999), with similar conclusions. The North intrusion was dated at 1322 ± 2 Ma by G.R. Dunning (Department of Earth Sciences, Memorial University) and the results were reported by Smith *et al.* (1999). A thesis study (Smith, 2006) examined the mineralized sequence of the PLI in more detail, and also the sulphur isotope variation patterns.

A smaller scale, but focussed exploration program was proposed for 1999. This was to include deep-seeking EM surveys, extension of gravity surveys, and diamond drilling. The target areas included those identified by previous work (*e.g.*, the Northern Abitibi area and South intrusion) and also areas where PLI mafic rocks were suspected to lie in the subsurface, below Churchill Province gneisses; however, this exploration program was deferred to a later date.

2000 Program

A short field program was mounted by Major General Resources in 2000, using the Pants Lake base camp. This consisted largely of diamond drilling to test gravity anomalies located northeast of the North intrusion (Figure 9). Drilling intersected mafic rocks at depth, which were, at the time, considered to be related to the PLI. However, examination of this drillcore in the summer of 2002 suggests that these rocks are more likely iron-rich intermediate rocks of the NPS (ferrodiorites) (A. Kerr, unpublished data, 2003).

Donner Minerals conducted some compilation and geochemical analysis work. J.N. Connelly (of the University of Texas in Austin) obtained the 1338 ± 2 Ma age from gabbros in the South intrusion (hole SVB-97-79); results were reported by Smith *et al.* (2001) and Smith (2006). For further discussion of geochronological data, *see* the Appendix.

2001 and 2002 Programs

A new agreement between Donner Minerals and Falconbridge Canada allowed for renewed exploration of the PLI in 2001 and 2002. Work in 2001 consisted of mapping and ground geophysics. Work in 2002 included additional geophysical surveys and the completion of 5 new drillholes in the South intrusion. The results from this work (summarized in Kerr, 2002b) confirmed the continuity of stratigraphic units defined by previous interpretation (Kerr, 1999) and that sulphide mineralization was similar in character to that previously observed elsewhere in the body.

OVERVIEW OF GEOLOGICAL SURVEY PROGRAM

The Pants Lake area was first visited by the author in 1996, as were numerous other exploration projects in Labrador, which were then in their early stages. Drillcore and surface samples were examined, and preliminary descriptions were published in a review article (Kerr and Smith, 1997). During the 1997 and 1998 seasons, several weeks were spent in the project area, working from the Teck Corporation–Donner Minerals base camp at Pants Lake.

The work conducted by the Geological Survey under this project is largely thematic, and is aimed at documenting and describing the mineralization, and understanding its relationship to the regional geology. Systematic geological mapping was not part of the mandate, although work of this type was completed by the exploration program. Geological Survey activities involved examination of field relationships and surface mineralization, and systematic examination and sampling of diamond-drill core. The latter was emphasized strongly, because it allows an understanding of 3-D relationships and the geometry of the PLI, insights that would be difficult to obtain through surface mapping alone. Petrographic and geochemical studies of both mineralized and unmineralized rocks were conducted from 1996 to 1999.

Some initial results from field work and petrographic studies were reported by Kerr (1998a, b), and a more comprehensive account of the geology of the PLI and its mineralization was published in the following year (Kerr, 1999). An initial description and discussion of the lithogeochemistry of the PLI was presented by Kerr *et al.* (2001). Externally published papers by Kerr and Ryan (2000) and Kerr (2003a) provide summaries of much of this work.

COUNTRY ROCKS

The PLI have been studied in far greater detail than any of the surrounding rocks, and are therefore described and discussed in separate chapters. This section summarizes more limited observations concerning country rocks, *i.e.*, gneisses of the Nain and Churchill provinces, and Mesoproterozoic plutonic rocks that are not included with the PLI. This summary is based on limited field observations, coupled with observations of 'footwall gneiss' intersections from diamond-drill programs, and integrates these data with previous accounts by Hill (1982) and Thomas and Morrison (1991). Mesoproterozoic plutonic rock types are assigned to the NPS in the north and to the HLIS to the south, but this subdivision cannot be substantiated on the basis of field characteristics alone.

NAIN PROVINCE BASEMENT ROCKS (UNITS 1 and 2)

Gneisses of the Nain Province form a thin strip along the eastern boundary of the study area, and they have been examined by the author only adjacent to their boundary with the Churchill Province. However, they were examined on a much wider scale by Thomas and Morrison (1991), and divided into two units, *i.e.*, a tonalitic orthogneiss and a mylonitized variant. Regional mapping by Teck Corporation (Fitzpatrick *et al.*, 1998) grouped these units together and outlined several areas of more mafic composition as a discrete unit. The geological map (Map 2012-18) appended to this report follows this subdivision.

Outcrops near the Nain–Churchill boundary consist of a variably banded, grey, orthogneiss of broadly tonalite–granodiorite composition (Unit 1), in which the banding partly reflects transposed compositional variation and partly migmatization. Some outcrops show a chaotic, agmatitic or nebulitic texture suggestive of *in-situ* melting, or voluminous injection of externally derived melt. According to Thomas and Morrison (1991), the gneiss consists of quartz, plagioclase, K-feldspar, two pyroxenes, hornblende and biotite, and fine-grained garnet locally present in the matrix; the banding is defined primarily by variations in the biotite and amphibole contents. Concordant bands of dark-grey to black amphibolite are common in most outcrops, and represent either supracrustal remnants or transposed mafic dykes. Several areas dominated by amphibolite, with lesser amounts of tonalitic gneiss, were distinguished as a separate unit (Unit 2; Fitzpatrick *et al.*, 1998), but the boundaries of these two units are not sharp, and amphibolite is present to some extent in virtually all outcrops.

Thomas and Morrison (1991) suggested that the Archean gneisses correlate with the ancient (*ca.* 3100 Ma) Maggo gneiss, one of the oldest components of the Hopedale Block (Ermanovics, 1993). It is abundantly clear that they have a long and largely unresolved geological history, and only the latest deformational events can be confidently recognized. Adjacent to the Nain–Churchill boundary, there is evidence of at least two ‘late’ episodes of deformation, the younger of which resulted in northwest–southeast-striking mylonite zones, which reoriented an earlier fabric oriented in a general east–west direction. The same pattern is seen in paragneisses of the adjacent Churchill Province (*see* below), where it is reported to be widespread (Fitzpatrick *et al.*, 1998; K. Emon, personal communication, 1998); the patterns suggest that both deformational episodes are Proterozoic.

No pervasive intense straightening or mylonitization was observed in Archean gneisses adjacent to the Nain–Churchill boundary, but the distribution of localized mylonitic zones coincides generally with the outcrop area of Unit 1b of Thomas and Morrison (1991). However, much more intense deformation is observed in paragneisses west of the inferred position of the boundary (*see* below).

CHURCHILL PROVINCE BASEMENT ROCKS (UNITS 3 to 6)

Previous mapping (Thomas and Morrison, 1991; Hill, 1982) indicated that amphibolite-facies pelitic to psammitic paragneiss forms the dominant unit within the Churchill Province basement rocks throughout the area. Subsequent mapping during the exploration program (Fitzpatrick *et al.*, 1998) confirmed this pattern, but these rocks remained undivided because they are highly variable on an outcrop scale, and it is very difficult to define mappable compositional variants. In addition, paragneiss outcrops invariably contain leucocratic granitoid gneiss and pegmatite, and the proportions of metasedimentary versus metaigneous material are commonly subequal. Conversely, granitoid gneiss outcrops invariably contain screens and zones of paragneiss. Thus, any delineation of paragneiss and granitoid gneiss units is inherently subjective, and different workers have outlined different boundaries. The pattern illustrated in the accompanying map (Map 2012-18) is derived largely from mapping by Teck Corporation (Fitzpatrick *et al.*, 1998), and is modified from Thomas and Morrison (1991) in areas outside the exploration project. Hill (1982) and Thomas and Morrison (1991) recognized two types of granitoid orthogneiss (*see* below) within the Churchill Province, and the exploration-company mapping also confirms this subdivision. The unit distributions differ slightly from earlier patterns.

Pelitic and Psammitic Paragneiss (Unit 3)

The paragneiss unit is commonly white to pale grey or rusty-weathering (depending on how much granite is present in a given outcrop), and generally well banded. Banding is defined primarily by alternation of quartz- and feldspar-rich layers, which are essentially granitic, with more biotite-rich bands; it records repeated migmatization, associated with deformation and transposition (Plate 1). In some areas, well-banded gneiss passes along strike into nebulitic material indicating late, static, *in-situ* migmatization. Elsewhere, granitic leucosome forms concordant bands and seams, and may, in part, be injected from deeper levels. Thomas and Morrison (1991) noted that granitic layers tend to be thicker than

Plate 1. *Highly deformed pelitic to psammitic paragneisses adjacent to the Nain Province–Churchill Province tectonic boundary. Dark areas are biotite-rich paragneiss; light bands are leucocratic granitoid gneiss.*

biotite-rich restitic zones, implying that many of them were actually injected as sheets, rather than formed *in-situ*.

The darker, restitic material consists essentially of quartz, plagioclase, K-feldspar, biotite, muscovite, garnet and sillimanite. It is medium to coarse grained, and commonly displays a well-developed polygonal to granular texture. Cordierite is locally prominent, and is likely present as a cryptic phase in most outcrops. Coarse, prismatic, sillimanite occurs locally. Leucocratic zones commonly contain large garnets up to 2 cm in diameter, and have a 'spotty' appearance (Plate 2). Graphite is locally abundant in the restite, and many outcrops are rusty-weathering, suggesting that disseminated sulphide is also present. The latter has been entirely oxidized in many outcrops, but is present widely in diamond-drill core, where it occurs as very fine-grained disseminated pyrrhotite in biotite-rich areas, and as thin massive pyrrhotite seams, which are probably derived from metamorphic remobilization (Plate 3). Most drillcore intersections of the paragneiss unit represent material immediately beneath gabbroic rocks of the PLI, and these exhibit signs of contact metamorphism. Petrographic studies conducted on field and drillcore samples (the latter by Hearn, 2001) suggest that the original protolith compositions were pelitic, arkosic and quartzitic. Pelitic gneisses consist of quartz, K-feldspar, plagioclase and biotite, along with abundant garnet, sillimanite and cordierite. Sillimanite commonly forms inclusions in garnet and cordierite, suggesting that these larger porphyroblasts formed relatively late (Hearn, 2001). The metamorphic assemblages in pelitic gneisses were interpreted to indicate upper amphibolite- to granulite-facies regional conditions where pressure was 4 to 7 kbars and temperature was 650 to 825°C (Hearn, 2001). Arkosic rocks contain similar mineral assemblages, but are dominated by quartz and K-feldspar, and only small amounts of other minerals. Some develop spectacular quartz ribbons,

Plate 2. *Typical intersection of 'footwall gneiss' below the base of the Pants Lake North intrusion. Most of this drillcore consists of white granitoid gneiss containing relict garnets (now partially retrogressed to cordierite); banded biotite-rich paragneiss visible at top right. Drillcore is approximately 4 cm in diameter.*

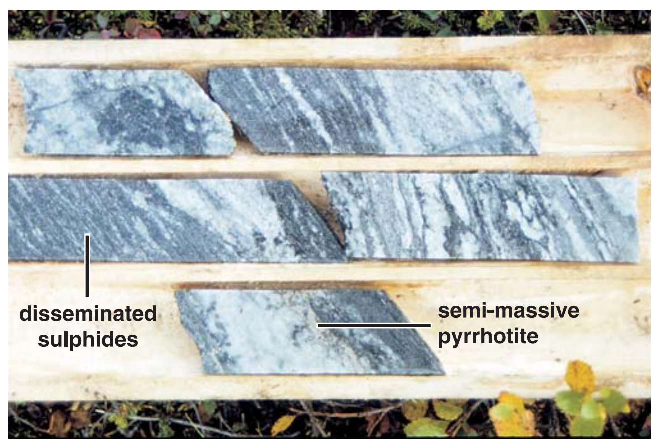


Plate 3. *Pelitic paragneiss containing disseminated sulphides and thin bands of semi-massive pyrrhotite in lower core sample. Drillcore approximately 4 cm in width.*

and are gradational with impure quartzites. Hearn (2001) reported the presence of relict sedimentary textures in paragneiss samples including load casts and flame structures.

The structural pattern in the paragneiss unit is invariably complex on a local scale, with well-developed rootless and interference-type folds, indicative of polyphase deformation.

Thomas and Morrison (1991) noted that the intensity of deformation decreases from west to east, and that fabric orientations are more variable in the central part of the study area, surrounding the PLI (Figure 9). Narrow mylonitic zones having a northwest–southeast trend (*i.e.*, parallel to regional trends) are common in some outcrops, and locally achieve widths of 1 m or more; in most examples, these zones deflect an earlier mineral fabric. The sense of deflection is sinistral, and these effects produce spectacular crenulated outcrops (Plates 4 and 5). The folds thus produced affect early migmatite layers in the gneisses, but the mylonite zones themselves were subsequently intruded by late, undeformed pegmatitic granite (Plates 4 and 5). These relationships are only a single snapshot of the structural and metamorphic evolution of the paragneisses, but they illustrate its probable complexity.

Regional mapping by both Thomas and Morrison (1991) and Fitzpatrick *et al.* (1998), and observations by the author, suggest that the regional structural pattern may mirror the outcrop-scale relationships discussed above. Foliation directions in the paragneiss unit fall into two groups, with broadly northwest–southeast and east–west attitudes, respectively. K. Emon (personal communication, 1998) suggests that the reorientation of earlier east–west fabrics by later northwest–southeast fabrics is widespread on a regional scale. The same pattern was also observed in the Nain Province gneisses immediately east of the Nain–Churchill boundary (*see* above). The paragneisses immediately west of the inferred position of the boundary contain a strong, mylonitic fabric having a north–south orientation, and no sign of earlier fabrics remains in them. This observation implies that deformation along the Nain–Churchill boundary was preferentially accommodated within the paragneiss unit, rather than in orthogneisses to the east.

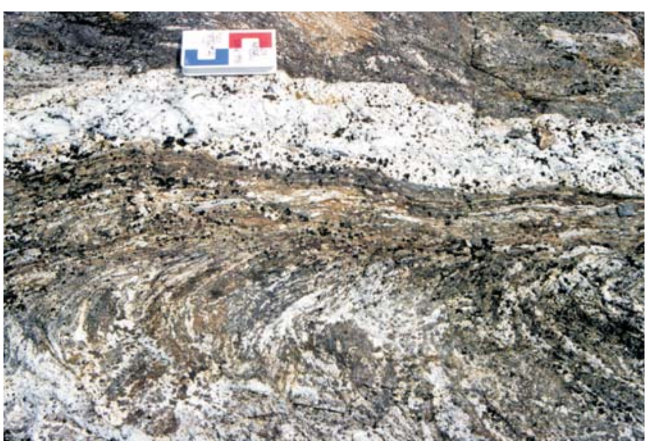


Plate 4. *Reorientation of early fabric in pelitic paragneisses into the dominant northwest–southeast fabric observed throughout the Pants Lake area. The high-strain zone that resulted developed during reorientation has been exploited by a younger granitic pegmatite.*

'Charnockitic' Granitoid Gneiss (Unit 5)

This 'charnockitic' granitoid gneiss (Unit 5) unit, equivalent to Unit 4 of Thomas and Morrison (1991) and Unit 12 of Hill (1982) forms several bodies west of, and adjacent to, the Nain–Churchill boundary, north and south of Sarah Lake (Figure 9, and accompanying Map 2012-18). Although contact positions vary, these same bodies were outlined by Fitzpatrick *et al.* (1998) and described as 'granodiorite to granite'. The rock type consists of medium- to locally coarse-grained, granoblastic gneiss composed of quartz, plagioclase, orthopyroxene and hornblende, and lesser biotite and opaques. Primary igneous textures are generally not well-preserved in outcrop, although Thomas and Morrison (1991) suggest their presence in the cores of larger bodies. Generally, the rock type is akin to 'charnockite' or 'enderbite' gneiss reported from equivalent regions of the Churchill Province to the north (*e.g.*,

Plate 5. *Folding of early fabric in pelitic paragneiss to produce a 'crenulated' outcrop; late pegmatitic vein has subsequently been emplaced parallel to the axial planes of the folds, which are parallel to the dominant northwest–southeast structural grain of the area.*

Ryan, 1996). Although local zones (inclusions?) of paragneiss occur, these rocks are, in general, far more homogeneous than the garnetiferous granitoid gneiss unit (*see* below, Unit 6). None of these bodies were examined in detail during the current project.

Megacrystic Garnetiferous Granitoid Gneiss (Unit 6)

As discussed above, almost every outcrop of pelitic to psammitic paragneiss (Unit 3) contains at least some coarse-grained, variably foliated, garnetiferous leucogranite (Unit 6). This material is texturally variable, and much of it represents *in-situ* or injected anatectic segregations of local origin. Much of the paragneiss unit could be properly described as a diatexite.

In addition to this omnipresent local material, there are several mappable units dominated by gneiss of granodioritic to granitic composition (Unit 6), equivalent to Unit 5 of Thomas and Morrison (1991) in the south, and Unit 9 of Hill (1982) in the north. The unit distribution defined by more recent exploration-company mapping is generally similar, although contacts may be positioned differently. The dominant rock type is a white, coarse-grained, variably K-feldspar porphyritic granitoid gneiss, containing prominent garnet. The less porphyritic to equigranular varieties resemble the garnetiferous pegmatites within adjoining paragneiss units. The porphyritic to megacrystic varieties are more homogeneous metaplutonic rocks. The igneous texture ranges from exceptionally well-preserved to strongly cataclastic or mylonitic, and the margins of larger mappable granitoid gneiss units are commonly marked by zones of strong deformation (Plate 6). Enclaves of psammitic paragneiss, commonly with diffuse boundaries, are common within mappable units of granitoid gneiss.

In thin section, the granitoid gneisses generally consist of subequal amounts of quartz, K-feldspar and plagioclase. This assemblage suggests a general correspondence to minimum-melt compositions in the quartz–albite–anorthite–orthoclase system. The K-feldspar is the most common relict phenocryst phase, and biotite is the dominant ferromagnesian species. Garnet is common, and forms rounded clots; some examples contain up to 15% garnet. Garnets are typically red and poikiloblastic, and contain numerous quartz inclusions. Orthopyroxene and amphibole, commonly relict, were reported by Thomas and Morrison (1991). Orthopyroxene-rich coronas on garnets were interpreted by Hearn (2001) to reflect contact metamorphism adjacent to the PLI. Other minerals thought to develop *via* contact metamorphism include cordierite and spinel, which are commonly intergrown with orthopyroxene and biotite (Hearn, 2001). These textures are also seen locally in areas distal to the PLI, but it should be remembered that other (older) NPS and HLIS intrusions could also contribute, regionally, to such affects. Graphic quartz-feldspar intergrowths observed in samples immediately adjacent to the contacts of the PLI were interpreted as evidence of local fusion of the gneisses. The primary metamorphic assemblages are less informative in terms of facies conditions than those of the paragneisses (*see* above). Contact metamorphic reactions imply high temperatures (760 to 900°C, and possibly higher where fusion occurred) and moderate pressures of 2 to 6 kbars (Hearn, 2001).

The contacts between granitoid gneiss units and the surrounding paragneisses are commonly concordant with regional fabrics, and locally marked by stronger-than-normal deformation (Plate 6). Such features imply that they are at least locally zones of transposition. Outcrop-scale relationships are more widely preserved within the paragneiss unit, and indicate that the granitoid gneisses intruded it.

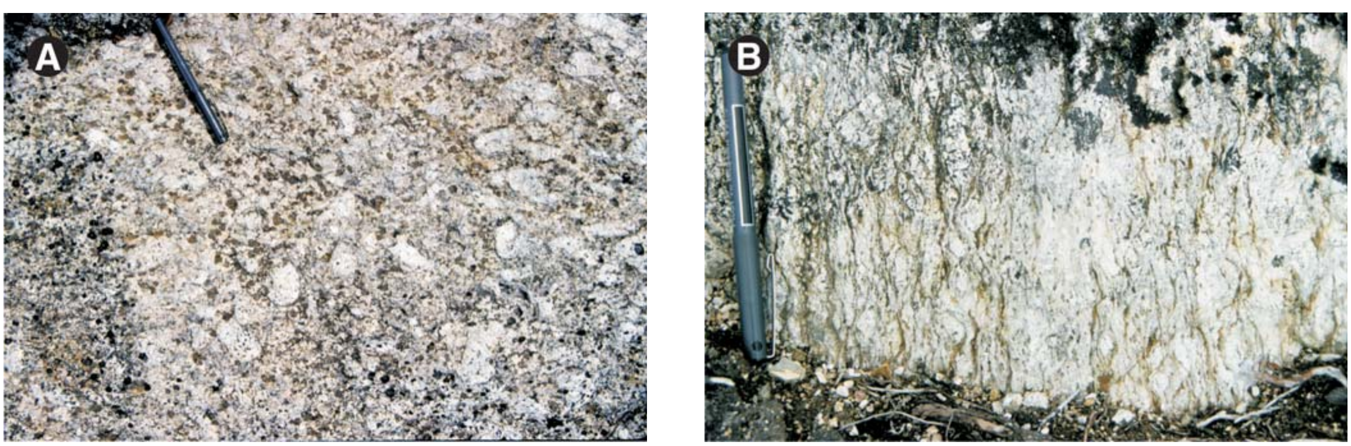


Plate 6. *A. Well-preserved garnetiferous granitoid orthogneiss, showing relick K-feldspar porphyritic texture. B. Ductile to cataclastic fabric developed in a closely adjacent outcrop closer to the contact between the orthogneiss and surrounding paragneisses.*

HARP LAKE INTRUSIVE SUITE (UNITS 10 and 11)

Units 10 and 11 in the south are here assigned to the *ca.* 1450 Ma HLIS (Emslie, 1980). The most abundant, at surface, is the Arc Lake granite, exposed south of Pants Lake. Anorthosite occurs along the northern edge of this body, and was also intersected in deep drillholes in the southern part of the area. This suggests that it is more abundant in the subsurface. Similar anorthositic rocks intersected in deep drillholes east of the North intrusion (Figure 9) may also be part of the HLIS, but could also be pre-PLI members of the NPS. There is no age information to clarify this, and assignment has been based purely on geographic location.

Anorthositic Rocks (Unit 10)

The anorthositic rocks of Unit 10 outcrop along the northern edge of the Arc Lake granite, south of the Pants River, and north of the prominent bend in the Adlatok River (Figure 9). The western unit is a coarse-grained, grey-weathering plagioclase cumulate containing a brown-yellow interstitial mafic mineral, probably altered iron-rich olivine, and scattered plagioclase megacrysts (Plate 7). Outcrops near the Adlatok River are similar, but appear more altered. At one locality, anorthosite contains gneissic inclusions, and is cut by mafic dykes; the latter are rarely seen in the PLI gabbros, and may provide useful criteria for distinction. A deep drillhole collared near the centre of the South intrusion (SVB-97-89) intersected about 1200 m of coarse leucogabbro to anorthosite that was originally interpreted as part of the PLI, because it was superficially similar to coarse-grained leucogabbro common in the north. However, it was later realized that these rocks were more likely part of the Harp Lake anorthosites because they are closely similar to material seen in surface outcrops of this unit (Plate 7). The Harp Lake anorthosites contain interstitial iron-rich olivine, and clinopyroxene, both of which are extensively altered to aggregates of serpentine, fine-grained amphibole and carbonate.

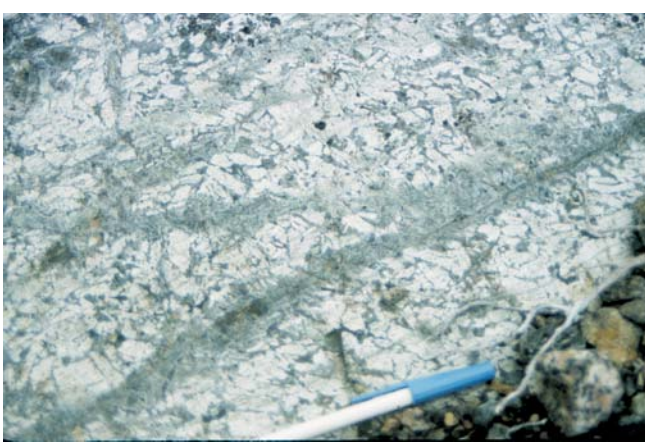


Plate 7. *Coarse-grained anorthosite assigned to the Harp Lake Intrusive Suite.*

Ferrodioritic Rocks (Subsurface Only)

Ferrodioritic rocks are not known in surface exposures in the south of the area, but occur in deep drillholes, notably hole SVB-97-91. The rocks consist of plagioclase, orthopyroxene, clinopyroxene and fayalitic olivine. Apatite is a prominent minor phase. They closely resemble dioritic rocks in the north of the area (*see* below), which are assigned to the NPS.

Quartz Monzonite, Syenite and Granite (Arc Lake Granite; Unit 11)

Granitoid rocks (Unit 11) assigned to the HLIS are situated in the south of the area, and form part of the Arc Lake granite (Emslie, 1980; Thomas and Morrison, 1991). These rocks are of varied composition, but are dominated by massive syenite and granite, commonly K-feldspar porphyritic, with variably developed mantled-feldspar (rapakivi) textures (Plate 8). Mafic minerals include orthopyroxene and clinopyroxene, and rare fayalitic olivine; the latter is associated with rusty weathering of surface outcrops. Amphibole and biotite occur locally, but may not be part of the primary assemblage. Anorthositic rafts are locally observed in granite outcrops, and gneissic inclusions are also present, particularly near the northern contact, where rapakivi-textured granite appears to be finer grained adjacent to the anorthosite. The Arc Lake granite is intruded by the South intrusion, and by smaller bodies assigned to the PLI, notably the 'Doughnut intrusion', located southeast of Pants Lake (Figures 9 and 10).

Plate 8. *Rapakivi texture, defined by rounded K-feldspar phenocrysts with plagioclase mantles, developed in the Arc Lake granite (Harp Lake Intrusive Suite) south of Pants Lake.*

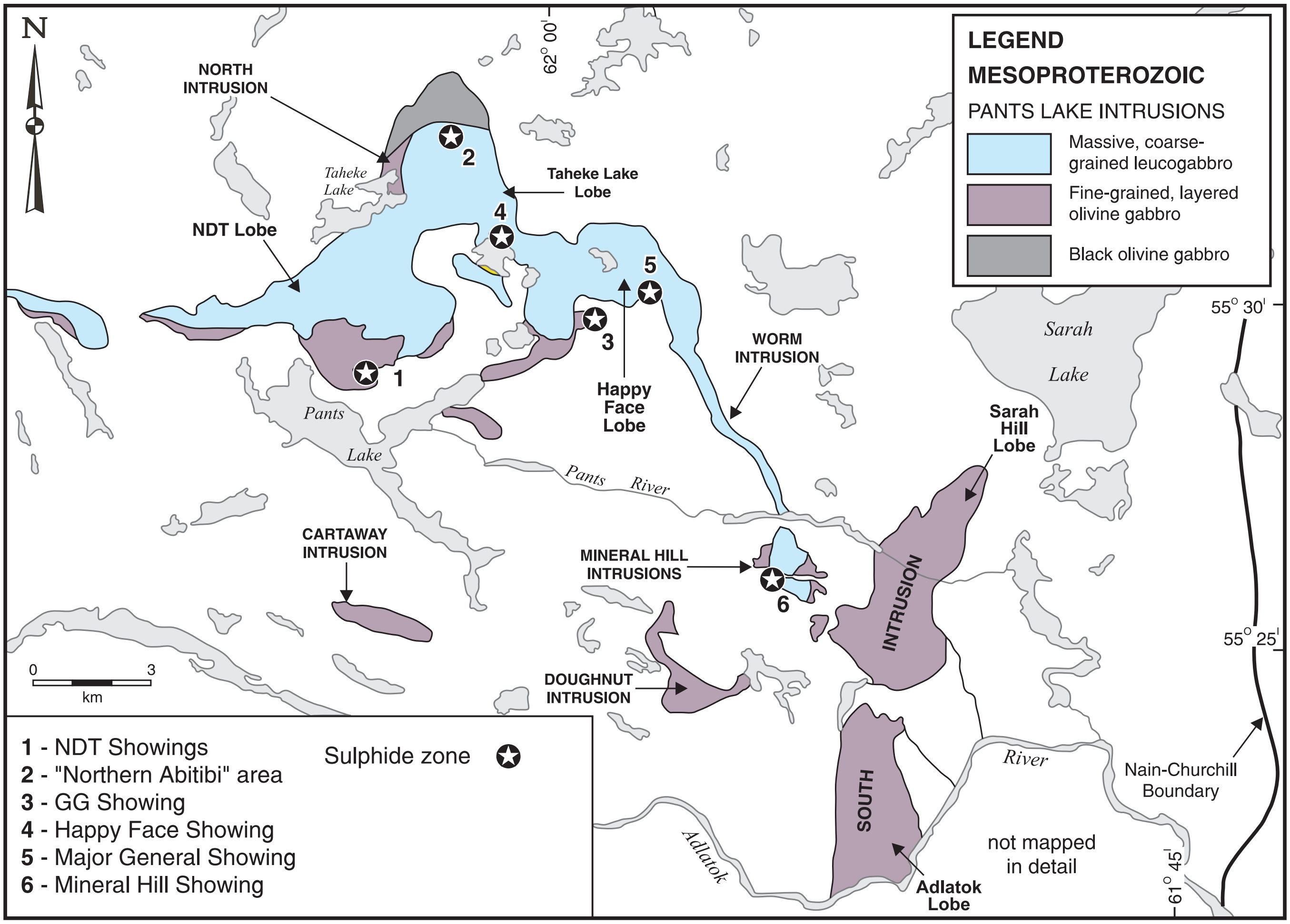


Figure 10. *Locations and outlines of the various component bodies assigned to the Pants Lake intrusions, as discussed in this and subsequent sections. For locations of all drillholes,* see *Figures 11 and 15, and assessment reports.*

NAIN PLUTONIC SUITE

Anorthositic Rocks (Unit 12)

In the northern part of the area, large areas of anorthosite (Unit 12) were mapped by Hill (1982) as his Unit 14c. This unit also included much of the North intrusion, which is dominated on surface by coarse-grained, leucocratic mafic rocks that are superficially similar to anorthosites. Exploration company and Geological Survey mapping suggests that the anorthosites and North intrusion leucogabbro are actually separated by a thin screen of dioritic rocks and paragneisses north of Taheke Lake (Figure 9) and their contact relationships are not observed. The anorthosites are coarse-grained plagioclase cumulates containing interstitial clinopyroxene and olivine, which show brown to yellow weathering similar to that seen in HLIS anorthosites. Blocks of white-weathering, monomineralic anorthosite are contained within this dominant phase (Plate 9). Anorthositic rocks also occur northeast of Sarah Lake, where they were initially mapped by the author, assisting Hill (1982). They have not been examined as part of this study, but include typical coarse-grained cumulate rocks that have a finer grained border phase of gabbroic composition.

Drillhole SVB-97-92, located east of the North intrusion, penetrated several hundred metres of coarse-grained anorthosite vertically below the basal contact of the intrusion, but similar anorthosites were absent from the inclined drillholes completed at the same location. The anorthosite in this hole resembles the anorthosites encountered in deep drillholes to the south, and its affinity (HLIS or NPS) is unclear. The drillhole also penetrated more mafic rocks correlated with surface outcrops of iron-rich intermediate rocks.

Ferrodioritic and Dioritic Rocks (Unit 13)

Ferrodioritic rocks (Unit 13) occur in the northwest only, where they were mapped by Hill (1982), and by more recent company mapping. They also form a thin unit along the eastern side of a larger anorthositic body located north of the

Plate 9. *Block of white-weathering monomineralic anorthosite, enclosed by leuconorite to anorthosite assigned to the Nain Plutonic Suite.*

North intrusion. These iron-rich rocks show deep, crumbly weathering, which is a function of high magnetite content and Fe-rich (fayalitic) olivines; where fresh, they are typically grey-green. Plagioclase-rich variants are similar to many of the anorthosites. Clinopyroxene, hornblende and olivine are the most common mafic minerals, and few biotite crystals are present locally. Dykes of medium-grained diorite intrude the neighbouring anorthosites in the north, and rafts of anorthosite are present in the diorites. Both relationships indicate that the intermediate rocks are younger than adjacent anorthosites, which is a common pattern. Hill (1982) suggested that many of the intermediate plutons have a broad sheet-like geometry, and this pattern is also known from the Nain area (Ryan, 1990). In thin section, the ferrodiorites commonly contain both orthopyroxene and clinopyroxene, and prominent fayalitic olivine. Brown hornblende and biotite are also commonly present, and appear to be part of the primary assemblage. Apatite and iron oxides form prominent accessory phases. Some samples contain mostly plagioclase feldspar, whereas others contain both quartz and K-feldspar, and are transitional to monzonite and quartz monzonite.

Pyroxene–olivine diorites, similar to those seen at the surface, also occur in the middle section of deep drillhole SVB-97-92 above coarse-grained anorthosites. The diorites typically contain inclusions of anorthosite and scattered phenocrysts of plagioclase. This relationship is consistent with the age relationship inferred from surface outcrops, and these dioritic rocks are considered to be subsurface equivalents of the diorite unit exposed to the north.

Granitoid Rocks (Unit 14)

Nain Plutonic Suite granitoid rocks (Unit 14) occur in the northwest and northeast corners. The unit in the northwest is typical crumbly weathering 'rapakivi-type' granite, and forms part of a more extensive body mapped by Hill (1982) commonly termed the Notokwanon batholith. In addition to quartz and K-feldspar, the batholith contains hornblende, orthopyroxene, clinopyroxene, and relict fayalite olivine. In many respects, this mineral assemblage resembles that seen in the dioritic and monzonitic rocks, but the granite is considerably more leucocratic. Regional map patterns to the north imply that the granitoid rocks sit above anorthositic plutons over wide areas. Granitoid rocks occur to the northeast.

Mafic Dykes

Small mafic dykes, generally less than 1 m wide, are common in massive plutonic rocks assigned to the NPS and HLIS. They rarely occur in the basement gneisses on surface, but have been found in some drillholes. At least some dykes have the east-northeast trend typical of the Harp dykes (Emslie, 1980), but there is likely more than one generation present. The 1274 Ma age for Harp dykes (Cadman *et al.*, 1993) implies that they should also cut the PLI, but they have so far not been observed in the field.

Hornblende-rich mafic rocks in which primary mineral assemblages are partly or completely retrogressed were encountered in some diamond-drill holes that penetrated beneath the basal contacts of the PLI. These rocks were in many cases initially grouped with the intrusion by exploration companies and by the author. However, thin section and geochemical studies show that these are different, and probably unrelated to the PLI. The age of these rocks is unknown, but they cut the paragneiss and orthogneiss units, and locally display well-developed chilled margins. They are interpreted as dyke- or sill-like, and are provisionally grouped as part of the NPS, perhaps equivalent to parts of the ferrodiorite unit (*see* above, Unit 13).

GEOLOGY AND PETROLOGY

INTRODUCTION

The PLI (Units 20–23) are the main foci of mineral exploration, and of this study. Most of the area underlain by the PLI has now been mapped, in detail, on surveyed grids, by exploration companies, and most of the more than 130 diamond-drill holes completed since 1996 intersect the PLI. The GSNL has examined field relationships throughout the area, and logged most of this drillcore. This work has generated much information about the petrology, stratigraphy and 3-D geometry of the PLIS, which this and the following sections summarize and synthesize. The complex, sulphide-bearing rocks (informally termed the mineralized sequences) are discussed in the section entitled, '*Magmatic Sulphide Mineralization*'.

The PLI consist of olivine gabbro, gabbro, leucogabbro and peridotite, and are associated with widespread Ni–Cu sulphide mineralization. The North intrusion (Units 20a, 21 and 22) was grouped, by Hill (1982), with anorthositic rocks of the NPS because the coarse-grained leucogabbro of the surface outcrops resembles an anorthosite. The Worm intrusion and the South intrusion formed Unit 19 of Thomas and Morrison (1991), described as gabbro, diabase and fragmental rocks. Thomas and Morrison (1991) interpreted these rocks to be subhorizontal and sill-like in geometry. These rocks were later denoted as a separate unit by Wardle (1993), and not included with NPS or HLIS plutonic rocks. The southernmost extremity of the South intrusion near the Adlatok River, was mapped by Emslie (1980) as anorthosite and leuconorite and grouped with the HLIS.

GEOGRAPHICAL AND PETROLOGICAL SUBDIVISIONS OF THE PANTS LAKE INTRUSIONS

The PLI include several discrete intrusive bodies (Figures 9 and 10). Despite the age contrasts between the North and South intrusions, closely similar rock types are observed in these bodies. Many intrusions also appear to have a similar igneous 'stratigraphy', but there are equally important variations in their character and anatomy. From south to north, the main subdivisions are here informally termed the South intrusion, the Mineral Hill intrusion(s), the Worm intrusion and the North intrusion. There are also two smaller intrusions within the Arc Lake granite, informally termed the Doughnut intrusion and the Cartaway intrusion. In exploration-company reports (*e.g.*, Fitzpatrick *et al.*, 1999) the Doughnut intrusion was renamed the Slingshot intrusion, following its redefinition by mapping, and the southern lobe of the South intrusion is referred to as the Tongue intrusion. For simplicity and consistency, the terminology used by Kerr (1999, 2003a) is retained in this report. The North and South intrusions are here divided into 'lobes' for the purpose of description. Most of the smaller bodies are believed to correlate with the North intrusion, because they all contain coarse-grained massive leucogabbro and exhibit geochemical similarities (*see* later discussion).

From the perspective of petrology, the PLI are divided into several component rock types, but these are not necessarily all present in each of the geographical subdivisions listed above. The two most abundant rock types are layered, fine-grained olivine gabbro and massive coarse-grained leucogabbro. The layered olivine gabbro is the most abundant in the South intrusion, but essentially identical rocks also occur in the lowermost parts of the North intrusion. The rock types are very similar in both areas, although there is a significant difference in age. The massive leucogabbro is the dominant unit in surface outcrops of the North intrusion, but does not occur in the South intrusion. It also dominates the Mineral Hill and Worm intrusions. Melagabbro and peridotite forms a minor (but important) unit. The unit has so far been encountered mostly in deep drillholes in the South intrusion, but is also seen very locally in the North intrusion. In both cases, it appears to be associated with the layered, fine-grained olivine gabbro; melagabbro and peridotite are not denoted on the maps. Black olivine gabbro (Unit 22; commonly abbreviated to 'black gabbro') occurs in parts of the North intrusion. This unit was previously labelled as troctolitic (Fitzpatrick *et al.*, 1998), but is of gabbroic composition. In the field, this rock type is difficult to distinguish from texturally similar massive leucogabbro, and the distribution pattern on the geological maps largely reflects drillhole information. Two other rock types are present, but only in small quantities, near the external contacts of the PLI. Diabase is locally seen at the lower and upper contacts, where it records chilling effects and provides important information about parental magma compositions. Intrusive breccia occurs in several areas at the contacts, and consists of angular to locally resorbed gneissic fragments in a fine-grained mafic matrix.

In addition to the above, several distinctive and unusual rock types occur within a thin sequence of rocks at, or just above, basal contact zones, particularly in the North intrusion. These rocks are invariably associated with sulphide mineralization, and in this report are collectively informally termed, the mineralized sequence. A mineralized sequence is also present in the South intrusion, where it is associated with melagabbro and peridotite. These rocks are discussed separately, in conjunction with mineralization, in the section entitled, *Magmatic Sulphide Mineralization*. The scattered geography, common rock types, and complex 3-D geometry of the PLI require that the description be broken into two parts. The characteristics of the various rock types, excluding the mineralized sequences, are presented first. This is followed, in the section entitled, *Geometry and Stratigraphy*, by a discussion of the relationships and geometry of the component intrusions, as currently understood, and the possible links among them. The described presentation of the units in the following sections does not imply any order of intrusion.

FINE-GRAINED, LAYERED OLIVINE GABBRO (UNIT 20)

This unit is probably the most abundant rock type within the PLI (in terms of volume). It dominates the South intrusion, and forms the lower section of the North intrusion, where it achieves thicknesses of up to 400 m. It also forms thinner sequences in the lower sections of the Doughnut, Cartaway, Mineral Hill and Worm intrusions. In the latter intrusions, and throughout much of the North intrusion, the fine-grained, layered olivine gabbro unit is spatially associated with sulphide-bearing rocks of the mineralized sequence, and its characteristics are locally obscured by gossan development and deep weathering.

South Intrusion

The area of the South intrusion is rugged but has few outcrops. The limited surface exposures mostly consist of a brown-weathering, fine- to medium-grained granular mafic rock containing obvious plagioclase and olivine in fresh samples. In the field, this rock type is homogeneous, and primary compositional layering was not observed. Drilling within this area (Figure 10), and also to the west of the exposed part of the South intrusion, demonstrates that the fine-grained gabbro extends to depths of several hundred metres, and passes downward into mafic cumulate rocks containing sulphide mineralization (*see* below). Most of the following description is based on examination of diamond-drill core, notably from deep holes SVB-97-79, 97-86 and 97-94; hole SVB-97-79 was also examined in detail by MacDonald (1999).

These drillholes reveal a monotonous sequence of fine- to medium-grained, pale to dark-grey, equigranular to slightly porphyritic gabbro (Plate 10). The porphyritic variants have a ‘speckly’ texture in which small plagioclase laths, up to 4 mm in length, are set within a finer grained groundmass (Plate 10A). Alignment of plagioclase laths is visible in many samples, and is probably a primary magmatic fabric, developed parallel to compositional layering. Colour and grain-size variations are subtle, but a regular pattern observed in some intervals suggests that primary layering is present, although generally without large variations in cumulus mineral proportions (Plate 10B). As noted by Kerr (1999), the gabbro in the longest hole (SVB-97-79) appears to consist of two discrete parts. There is an upper part that contains some minor sulphide mineralization located just above a thin (<5 m) zone of partially digested gneissic material at its base, and a lower part that appears to be finer grained at the top along its upper zone, and may therefore be chilled against the gneiss interval and/or the upper unit. The transition is located some 258 m below the surface. There is no clear contact zone within nearby drillhole SVB-97-86, but the upper approximately 200 m of the hole contain abundant diabase-like, fine-grained intervals, some of which exhibit sharp but uninformative contacts. Drillhole SVB-97-94 contains two discrete mafic units separated by approximately 40 m of gneisses. In all these drillholes, the rock types in the upper and lower units appear identical and are very similar in thin section (*see* below). However, the overall pattern and relationships imply that the South intrusion may have formed from more than one batch of mafic magma, emplaced at slightly different times.

In thin section, the fine-grained olivine gabbro is generally fresh and preserves superb primary igneous textures (Plate 11A). The gabbro consists of olivine (30 to 60%), plagioclase (40 to 60%; typically An50–An65) and clinopyroxene (up to 30%), with minor red biotite, magnetite, and serpentine (after olivine). The amount of olivine versus clinopyroxene is variable, and some samples are troctolites, at least on the scale of a thin section. Plagioclase is lath-like, and locally shows a well-developed alignment. Clinopyroxene is purple-grey, and probably titaniferous. Red biotite, magnetite and apatite are all part of the primary assemblage; amphibole, serpentine and chlorite are locally present as alteration minerals. Olivine occurs generally as granular crystals and aggregates, but is locally prismatic, in which case it is aligned with the magmatic foliation. Olivine locally contains small euhedral plagioclase grains, but is more commonly inclusion-free. More commonly, small grains of olivine are included in larger plagioclase laths, and the textural relationships imply that both minerals were cumulus

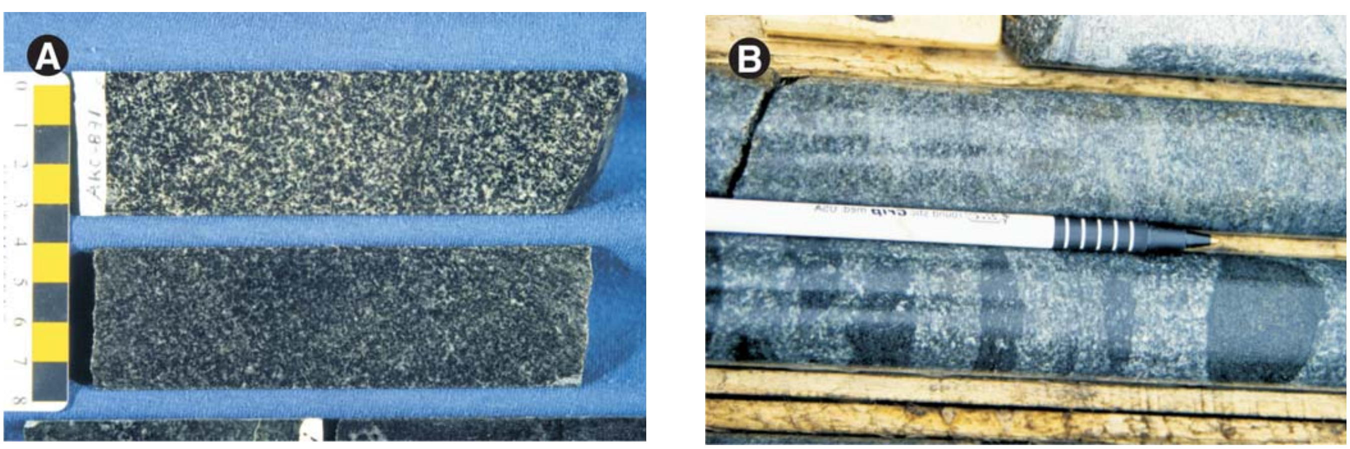


Plate 10. *A. Typical fine- to medium-grained olivine gabbro from the South intrusion; upper sample shows a typical ‘speckly’ plagioclase–porphyritic variety, scale in cm. B. Drillcore from fine- to medium-grained gabbro of the South intrusion. The upper part of the picture shows subtle colour variations indicative of variations in mafic mineral content due to magmatic layering. The dark patches in the lower part of the picture are inclusions of melagabbro, probably derived from disrupted cumulate units.*

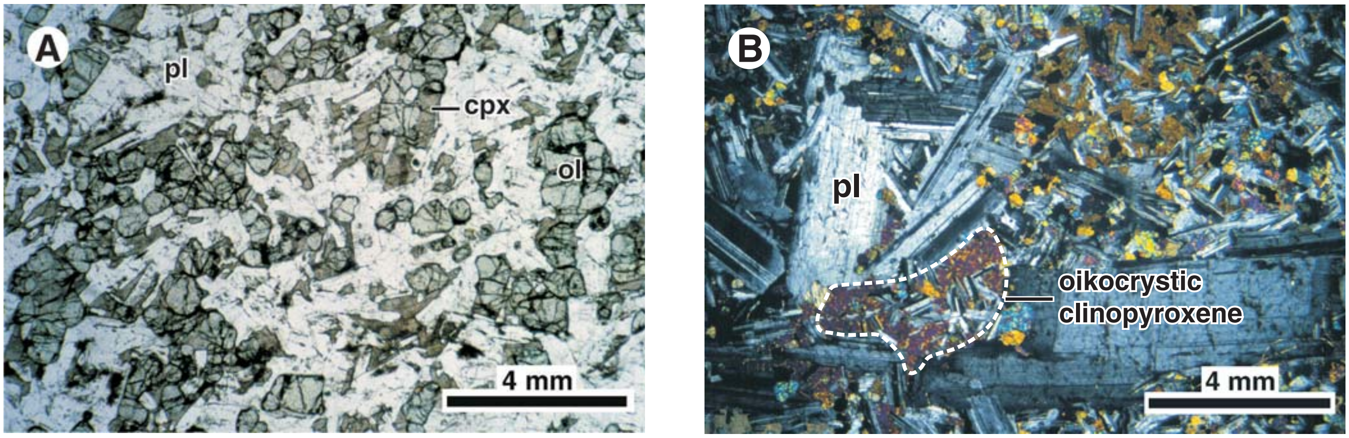


Plate 11. *A. Thin-section texture (PPL) of typical fine- to medium-grained olivine gabbro unit, showing early granular olivine and late interstitial clinopyroxene. These textures are typical of both the South and North intrusions. B. Plagioclase–porphyritic variant (XP), also showing outlines of oikocrystic clinopyroxenes (PPL–plane polarized light, XP–crossed polarizers, cpx–clinopyroxene, ol–olivine).*

phases, with olivine crystallization initiated prior to plagioclase crystallization. Clinopyroxene is interstitial and late in all samples, and it contains inclusions of both plagioclase and olivine. Clinopyroxene commonly forms large, optically continuous oikocrystic (interstitial) crystals. Cumulus apatite was observed in a few samples.

North Intrusion

In the North intrusion, fine-grained, layered olivine gabbro (Unit 20) occurs in all areas, but its thickness and stratigraphic position within the body vary. It is most abundant in the NDT lobe (Figure 10) where it is up to 400 m thick in the lower section of the intrusion, and forms extensive surface outcrops in the area north of the NDT sulphide showings. To the east, in the Happy Face lobe (Figure 9), it is reduced to a thin sequence at the base of the body, closely associated with the unusual rocks of the mineralized sequence. In the Taheke Lake lobe, the fine-grained, layered olivine gabbro is locally up to 200 m thick; however, it is not found at the base of the intrusion, as it is generally underlain by the black olivine gabbro unit (*see* below; also section entitled *Geometry and Stratigraphy*).

The area north and west of the NDT showings contains the best exposure. In outcrop, the unit displays the yellow-orange-red weathering typical of olivine-rich rocks (Plate 12A, B). On fresh surfaces, it is a grey-green to dark grey, fine- to medium-grained (1 to 4 mm) rock having a granular appearance. Olivine and plagioclase are readily recognized, and are accompanied by subophitic clinopyroxene, and minor magnetite and biotite. Layering is easily observed on some cliff faces (Plate 13), and can be seen in hand samples, but it is commonly difficult to discern on flat outcrop surfaces, as it is subhorizontal to gently dipping. The layering is defined primarily by variations in olivine:plagioclase ratios, and locally by grain-size contrasts (Plate 13B). The best examples of layering are seen on the high hilltops about 1 km north of the NDT showings (Figure 9; Plate 13). Elsewhere in the North intrusion, the fine-grained, layered olivine gabbro is rarely seen on the surface, as it is thin, and generally sits beneath the coarse-grained massive leucogabbro unit. However, it also outcrops in the area of the GG showing (Figure 9), and around the northeast arm of Pants Lake.

The best information on the fine-grained, layered olivine gabbro unit comes from several relatively deep drillholes in the NDT lobe, notably SVB-97-59, 97-63, 97-77 and 97-82 (*see* Figure 15); hole SVB-97-77 was also studied in detail by MacDonald (1999). Holes SVB-97-83 and 97-93, and also SVB-98-105, 98-106, and 98-108 also intersected substantial thicknesses of this unit within the Taheke Lake lobe. In all of these areas, and also in the thin sequences intersected in the Happy Face lobe, the fine-grained, layered olivine gabbro is essentially identical in appearance and petrology. In drillcore, it is a monotonous pale to dark-grey rock with a granular, homogeneous appearance, and looks exactly the same as the material in the South intrusion. Layering is very subtle, and appears in drillcore as slight variations in colour and grain size. A single 5 m interval of olivine-rich melagabbro and peridotite is present in hole SVB-97-59, but does not appear to have any wide lateral extent. In some areas, the fine-grained, layered olivine gabbro develops a characteristic ‘speckly’ texture due to the presence of small (2 to 4 mm) plagioclase phenocrysts, but these zones cannot be correlated between widely spaced holes.

In thin section, the fine-grained, layered olivine gabbro consists of olivine (30 to 60%), plagioclase (40 to 60%; typically An50–An65) and clinopyroxene (5 to 30%), with minor

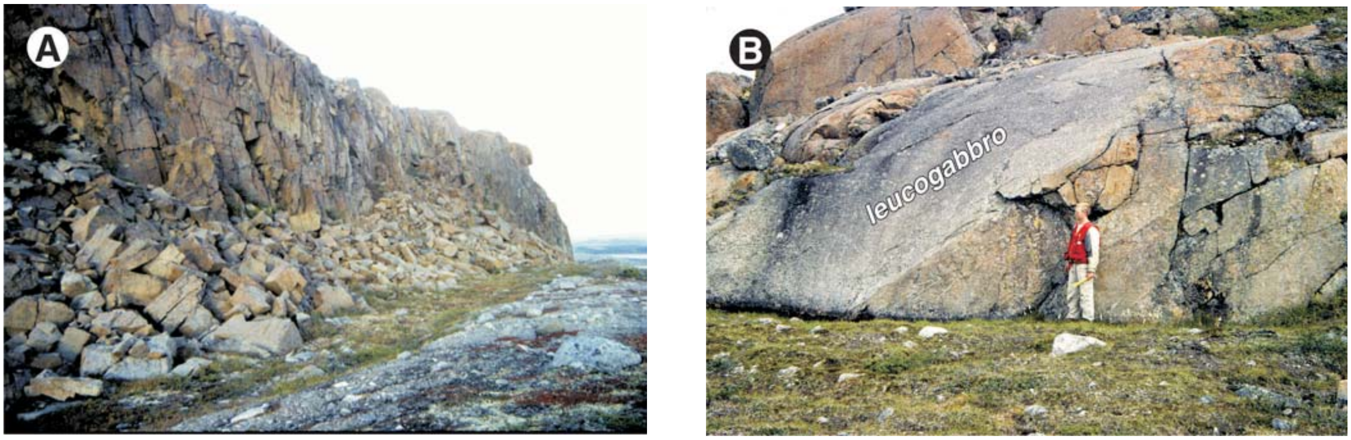


Plate 12. *A. Cliffs of typical red-weathering, fine-grained olivine gabbro west of the NDT showings, NDT lobe, North intrusion. Cliffs are 10-15 m high. B. Contrast between red-weathering, fine- to medium-grained olivine gabbro and grey-weathering massive leucogabbro unit. The field relationships are uncertain at this locality, but the leucogabbro is interpreted as a discontinuous vein or sheet, rather than an inclusion or raft.*

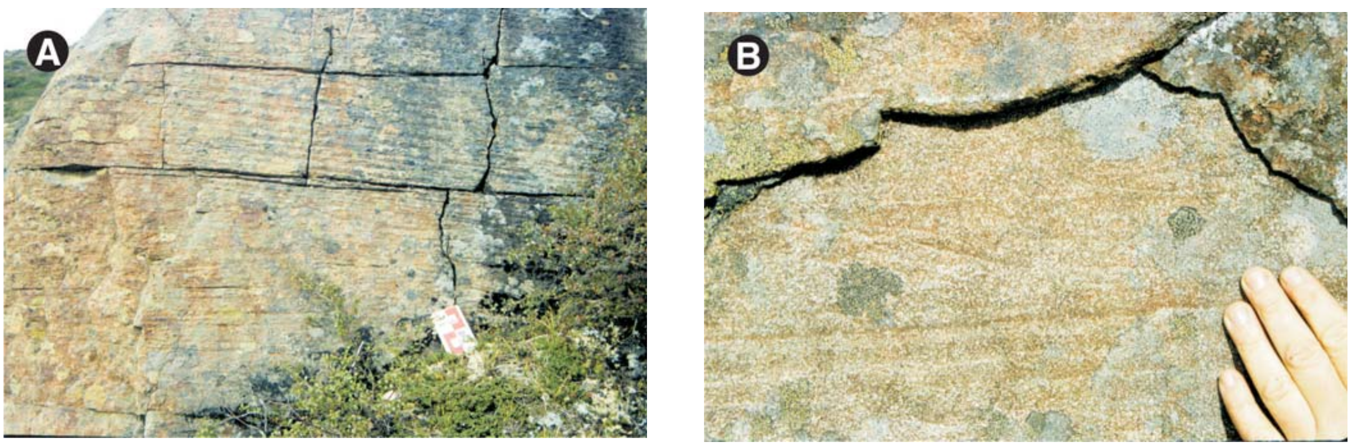
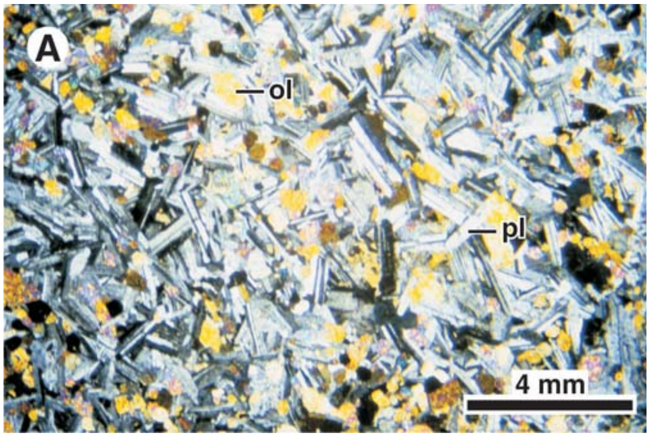


Plate 13. *A. Rhythmically layered fine- to medium-grained olivine gabbro in the North intrusion, NDT lobe. B. More detailed view of layering from the same outcrop. Layering is mostly defined by variations in the amount of olivine. Crossbedding visible in centre of more detailed view.*

red biotite, magnetite, and serpentine (after olivine). Orthopyroxene is present only rarely, as thin rims on scattered olivine grains. A few examples (*e.g.*, Plate 14A) are truly troctolitic (*i.e.*, <10% pyroxene), but most are classified as olivine gabbro; however, all are olivine-rich. Variations in the amount of olivine are apparent even on the crude scale of sampling in this study, and presumably reflect modal layering. MacDonald (1999) sampled hole SVB-97-77 at 10 m intervals and noted numerous sample-to-sample variations in the proportions of olivine and pyroxene relative to plagioclase. The unit displays a uniform texture, in which olivine is granular, plagioclase is lath-like, and clinopyroxene is interstitial, subophitic or (more rarely) poikilitic (Plates 11A and 14B). Small olivine grains are typically included in plagioclase laths. The texture indicates that olivine crystallized first, followed by plagioclase, and finally clinopyroxene. Magnetite and biotite are also late-crystallizing phases, and commonly have an interstitial habit. The textures are identical to those described above from the South intrusion, but plagioclase laminations (magmatic fabrics) are less commonly observed. The crystallization sequence indicates that many of these rocks are essentially plagioclase–olivine cumulates, containing variable amounts of late clinopyroxene.

Other Areas

The Worm intrusion has a ‘stratigraphy’ that is very similar to that of the Happy Face lobe of the North intrusion, of which it may be a continuation. The fine-grained olivine gabbro is closely associated with the mineralized sequence in the Worm intrusion. A similar situation exists in the Mineral Hill intrusions, where fine-grained olivine gabbro is also closely



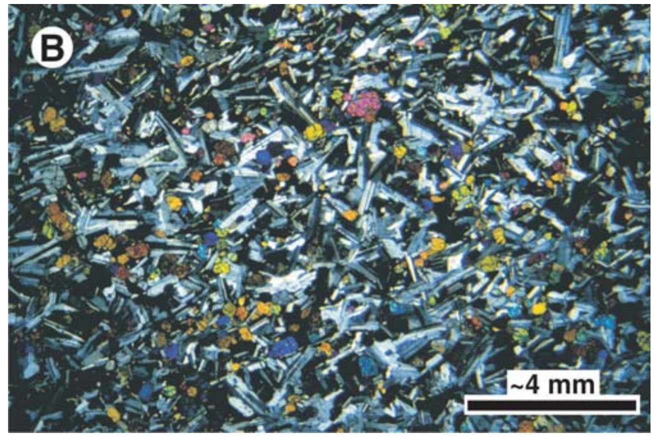


Plate 14. *A. Troctolitic variant of the fine- to medium-grained olivine gabbro, showing lath-like plagioclase and granular olivine (XP). B. Typical example of fine-grained olivine gabbro, showing lath-like plagioclase and generally homogeneous texture (XP–crossed polarizers, ol–olivine, pl–plagioclase).*

associated with the mineralized sequence. In both of these areas, samples of unmineralized rocks overlying mineralized gabbros are texturally and mineralogically identical to the rocks described above from the North intrusion, *i.e.*, they contain granular, early olivine, and late interstitial clinopyroxene. Fine-grained gabbro from the base of the Doughnut and Cartaway intrusions is similar in field appearance, but has not been examined in thin section.

In these smaller, thinner intrusions, the fine-grained gabbro unit locally displays a knobbly weathering texture in surface outcrops (Plate 15). This texture is imparted by large (up to 2 cm in diameter) poikilitic clinopyroxenes, which are set in an olivine-rich groundmass, which weathers recessively. Poikilitic clinopyroxene is also present in samples from the North and South intrusions, but the individual crystals are normally much smaller, and less obvious. This texture is similar to that of 'leopard gabbro', which is a distinctive component of the mineralized sequence, in which the olivine-rich matrix also contains magmatic sulphides (*see* section entitled '*Magmatic Sulphide Mineralization*'). The development of large poikilitic clinopyroxenes is probably favoured by relatively rapid cooling and solidification in thinner, sill-like bodies of the PLI, compared to the larger bodies of the North and South intrusions.

Plate 15. *Typical 'knobbly weathering' texture of fine-grained olivine gabbro that contains large clinopyroxene oikocrysts in an olivine-rich matrix. This example is from the Mineral Hill intrusions, but similar rocks are also common within the North intrusion. Field book is approximately 15 cm wide.*

MELAGABBRO AND PERIDOTITE

South Intrusion

These important and distinctive rock types (melagabbro and peridotite) are mostly known from drillcore. They are best represented in three drillholes (SVB-97-79, 97-86 and 98-100) from the South intrusion, in which they appear to form part of a mafic cumulate sequence that sits just above its basal contact (*see* section entitled, '*Geometry and Stratigraphy*)'. In drillcore, they are dark-green, variably serpentinized, medium- to coarse-grained rocks consisting mainly of olivine and plagioclase, with lesser pyroxene (Plate 16A, B). In thin section, the olivine is seen to be granular and rounded, and is contained within large, optically continuous plagioclase and clinopyroxene crystals, which are of intercumulus origin. Red mica, possibly Mg-rich phlogopite, is a prominent minor phase. Serpentinization ranges from moderate to pervasive, and serpentine veinlets are present in all samples. The most melanocratic samples approach a dunite or peridotite in composition, but the rocks typically contain 10 to 20% plagioclase, and are probably best described as melatroctolite or melagabbro. The contacts between these rock types and associated fine-grained layered olivine gabbro are abrupt but gradational, and the rocks are probably related. Melagabbro is also locally interlayered with fine-grained olivine gabbro.

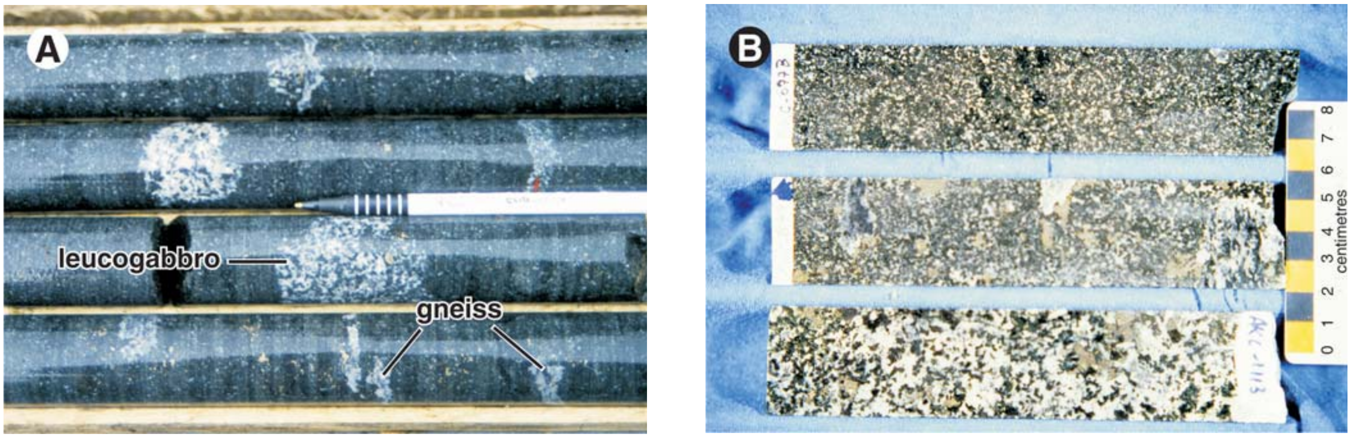


Plate 16. *A. Drillcore of typical sulphide-bearing melagabbro to peridotite from the South intrusion, containing inclusions of more leucocratic gabbro in the upper part of the photo, and digested gneissic fragments, mostly in lower part of photo. The gabbroic inclusions are probably equivalents of the basal unit in the South intrusion. B. Upper core samples are two typical examples of melagabbro, showing digested gneissic fragments and interstitial sulphides, which appear yellow; the lower core sample represents the basal gabbroic unit, also containing sulphides. Scale in cm.*

In the South intrusion, parts of the melagabbro and peridotite unit contain disseminated, interstitial, magmatic sulphides, commonly associated with late-crystallizing biotite. The unit also contains scattered and variably digested gneissic fragments, and fragments of more leucocratic gabbro similar to an underlying unit in the South intrusion (Plate 16A, B). The mineralization is discussed separately in the section entitled, '*Magmatic Sulphide Mineralization*'.

North Intrusion

Only one example of melatroctolite is known in the North intrusion, where it forms a 4-m-thick layer located 286 m below surface in hole SVB-97-59. This rock type is identical to olivine-rich examples observed in the South intrusion, but lacks sulphide mineralization. Fine-grained, layered olivine gabbro located above this unit is also anomalously olivine-rich, and both may be part of a broader zone of mineral accumulation.

MASSIVE COARSE-GRAINED LEUCOGABBRO (UNIT 21)

In terms of areal extent on surface, massive coarse-grained leucogabbro (Unit 21) is the most abundant unit in the PLI. It dominates the North intrusion and most of the smaller component bodies. It does not occur within the South intrusion, but thin drillhole intersections of similar coarse-grained material, probably representing crosscutting veins, suggest that offshoots of this unit from the North intrusion cut the South intrusion.

The best exposures of Unit 21 are on the hills between Pants Lake and Taheke Lake, in the North intrusion, and within the Worm intrusion. In these areas, it is a coarse-grained and homogeneous rock having a characteristic pale-grey to white-weathering colour, and a variably developed seriate to porphyritic texture (Plate 17A). Plagioclase crystals are commonly in the 1 to 2 cm range, and form stubby prisms, but the unit locally becomes extremely coarse grained (crystals up to 5 cm in diameter), particularly in the Worm intrusion. The mafic minerals invariably show an interstitial to subophitic habit, and contrasting green- and brown-weathering colours, with variable alteration to chlorite and amphibole, respectively (Plate 17B). The more leucocratic variants of the unit are superficially very similar to typical Nain or HLIS anorthosites, although somewhat richer in mafic minerals. The author initially recorded many outcrops as gabbronorite, as the contrasting mafic minerals were assumed to be ortho- and clinopyroxenes on the basis of their habit. However, the brown-weathering 'orthopyroxene' noted in the field proved to be olivine, and most examples are now classified as olivine gabbro. Outcrops and drillcore intersections of the unit appear identical in all of the areas where it occurs, aside from variations in grain size and secondary alteration.

In thin section, the freshest examples consist of plagioclase (60 to 80%; typically <An55), olivine (5 to 20%) and clinopyroxene (10 to 20%), with lesser amounts of biotite and magnetite. The coarse grain-size (up to 1 to 2 cm) makes modal analysis very difficult, and the mafic minerals commonly form large, single, optically continuous crystals (oikocrysts) that are commonly larger than a typical thin section. Consequently, individual thin sections may appear either troctolitic, or completely olivine-free. Drillcore examination suggests that olivine is slightly less abundant than clinopyroxene, and most rocks are olivine gabbros. The larger plagioclase crystals show prominent zoning, and the overall

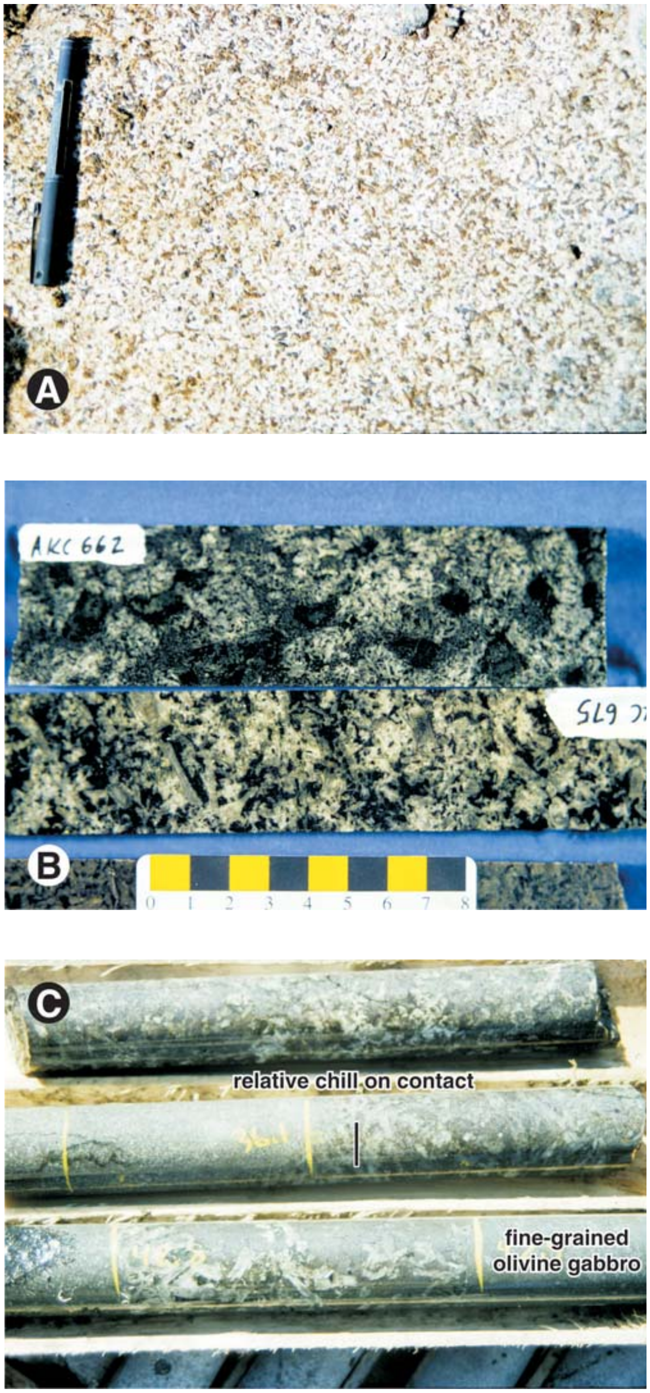


Plate 17. *A. Typical field appearance of the coarse-grained massive leucogabbro unit, showing the interstitial habits of olivine and pyroxene, which cannot easily be distinguished. B. Typical drillcore appearance of the massive leucogabbro unit; upper sample shows secondary alteration related to proximity to the upper contact of the North intrusion. Scale in cm. C. Veins of coarse-grained leucogabbro cutting fine- to medium-grained olivine gabbro in hole SVB-98-112; note marginal chill near centre of the photo.*

texture ranges from seriate to porphyritic. Plagioclase compositions are difficult to determine due to zoning, but are more variable than in the fine-grained gabbro, with a maximum of around An55. Olivine locally has an unusual pale-grey colour, probably caused by fine iron-oxide dust, and clinopyroxenes are commonly purplish and weakly pleochroic. This suggests that they are titaniferous. Thin reaction and/or alteration rims of orthopyroxene, surrounded by amphibole, are seen around olivines in some samples. Both olivine and clinopyroxene are interstitial to subophitic in habit (Plate 18). This indicates that they crystallized late, in contrast to those in the fine-grained, layered olivine gabbro of Unit 20.

Massive leucogabbro showing strong secondary alteration is observed locally in the field, but is more commonly noted in drillholes that penetrate an upper cap of gneissic country rocks, above the gabbro. In the gabbro beneath this upper contact, clinopyroxene and olivine are altered to secondary amphibole, serpentine and iron oxide, but this retrogression diminishes downhole from the upper contact region, normally within 50 m. The upper regions of the massive leucogabbro unit also contain rounded, very-fine-grained inclusions of unknown origin; in thin section, these consist of extremely fine-grained amphibole-rich material surrounded by coarser hornblende. Grain-size variations are also common within drillhole intersections of massive leucogabbro, and localized pegmatitic zones contain extremely coarse olivine and pyroxene. These pegmatites show no recognizable systematic pattern in the North intrusion, and are presumed to be local in scale, analogous to coarse-grained pockets of pegmatite noted in some outcrops. However, the massive leucogabbro of the Worm intrusion appears to be consistently coarser grained than in most of the other PLI component intrusions.

Coarse-grained massive leucogabbro was observed locally on surface within the South intrusion, and also forms a 20-m-thick unit in the upper part of hole SVB-97-79. This unit is interpreted as an intrusive sheet or vein, although there is no unequivocal evidence for the sense of emplacement. A similar leucogabbro sheet observed in hole SVB-02-137 appears to be slightly chilled against fine-grained olivine gabbro of the South intrusion, implying that it is indeed younger (Plate 19). These rocks are identical in thin section to massive leucogabbro from the North intrusion and associated bodies, and are viewed as younger intrusive veins, rather than as part of the South intrusion *ss*.

BLACK OLIVINE GABBRO (UNIT 22)

The black olivine gabbro (Unit 22), is best exposed in the northern part of the North intrusion (termed the Taheke Lake lobe), in the vicinity of the so-called Northern Abitibi

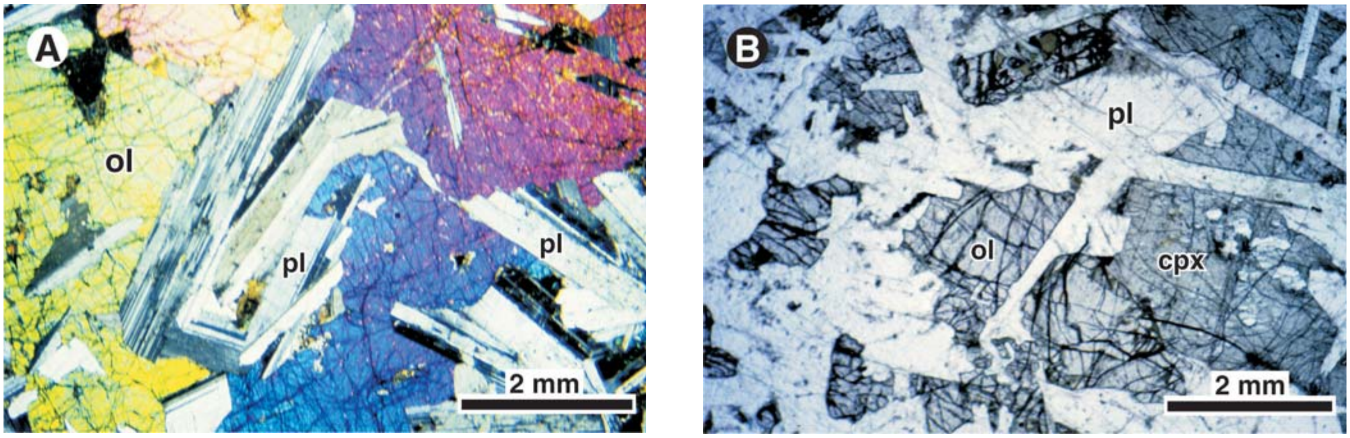


Plate 18. *A. Spectacular interstitial olivine crystals and lath-like plagioclase in coarse-grained massive leucogabbro (XP). B. Typical texture of coarse-grained massive leucogabbro, showing interstitial olivine and clinopyroxene (PPL) (XP–crossed polarizers, PPL–plane polarized light, ol–olivine, pl–plagioclase, cpx–clinopyroxene).*

Plate 19. *Coarse-grained massive leucogabbro in contact with fine-grained olivine gabbro in the South intrusion. Note relative chill developed on coarse-grained unit adjacent to contact, left of the pen.*

area (Figures 9 and 10). Over much of this area, black gabbro is very hard to distinguish in the field from the coarse-grained leucogabbro to the south. However, the black gabbro appears distinctly different from the coarse-grained leucogabbro in drillcore. In the west part of the Taheke Lake lobe, it does not outcrop, but forms a thick sequence toward the base of the intrusion, best seen in SVB holes 97-93, and 98-105, 106 and 108. In this area, the black gabbro sits beneath the fine-grained, layered olivine gabbro, whereas the massive coarse-grained leucogabbro sits above the fine-grained unit in hole SVB-98-108. In conjunction with some differences in their mutual contact relationships (*see* section entitled '*Geometry and Stratigraphy*'), these relationships indicate that the black gabbro is indeed a distinct unit, despite a common textural similarity to the coarse-grained massive leucogabbro.

There has been considerable debate about the status of the black gabbro, particularly as it is spatially associated with some of the most interesting sulphide mineralization. The author initially suggested that black gabbro represents a lateral variant of the coarse-grained leucogabbro unit (Kerr, 1998a), but the present information supports the views of Fitzpatrick *et al.* (1998), *i.e.*, that the black gabbro is a discrete unit. The possible relationships between the black olivine gabbro and some of the rocks in the mineralized sequence are discussed in the following section.

Black gabbro is generally absent from the NDT and Happy Face lobes of the North intrusion, although the Mineralized sequence in these areas may contain thin units that represent its lateral equivalent. In one area of the Happy Face lobe, a few metres of black gabbro sit beneath the fine-grained, layered olivine gabbro and above the mineralized sequence, *i.e.*, in exactly the same stratigraphic position as in the Taheke Lake lobe. Black olivine gabbro has not been recognized in the South intrusion, or in smaller component bodies of the PLI.

The characteristics of the black olivine gabbro are best known from drillcore. It is a medium- to coarse-grained, homogeneous, dark-grey to black rock, which superficially appears almost ultramafic in composition (Plate 20). It is generally inclusion-free. It was initially described as troctolitic (Fitzpatrick *et al.*, 1998), but most examples actually contain subequal amounts of olivine and clinopyroxene. The dark appearance is deceptive, as it commonly contains 60 to 75% dark-grey plagioclase, with the remainder consisting mostly of olivine and purple-bronze clinopyroxene. Plagioclase crystals are commonly prismatic and well-twinned, in contrast to the more equant habit of the plagioclase, typical of the massive leucogabbro. A 'stellate' texture is locally seen,

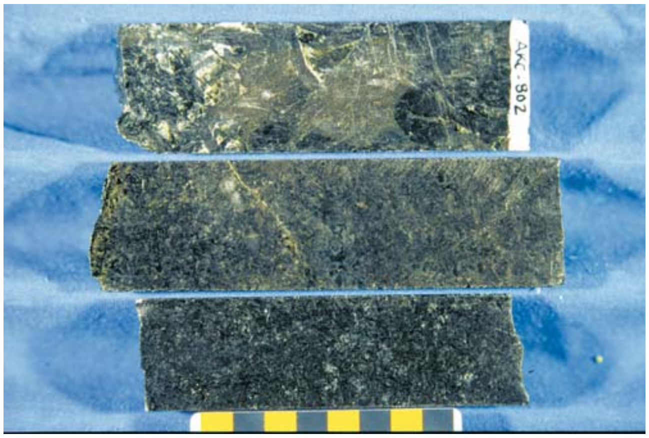


Plate 20. *Typical drillcore examples of the black olivine gabbro unit from the Taheke Lake lobe of the North intrusion. Scale in cm.*

and the mafic minerals almost always appear to have an interstitial habit (Plate 21). There are broad grain-size variations within this unit, and finer grained examples are black diabase-like rocks that contain large poikilitic olivines and pyroxenes. The term 'poikilitic olivine diabase' is used here for these fine-grained variants of the black gabbro. The black gabbro also contains coarse- to very coarse-grained pegmatitic zones in which individual pyroxene crystals may be several centimetres in size. In drillcore, black gabbro locally displays a blotchy appearance, probably indicating variable secondary effects, and the lighter coloured regions are superficially similar to the massive grey leucogabbro.

The black olivine gabbro displays some petrographic and textural variation related to geographic and/or stratigraphic position. The lower sections of the unit are similar in many respects to the massive leucogabbro in that purple-brown

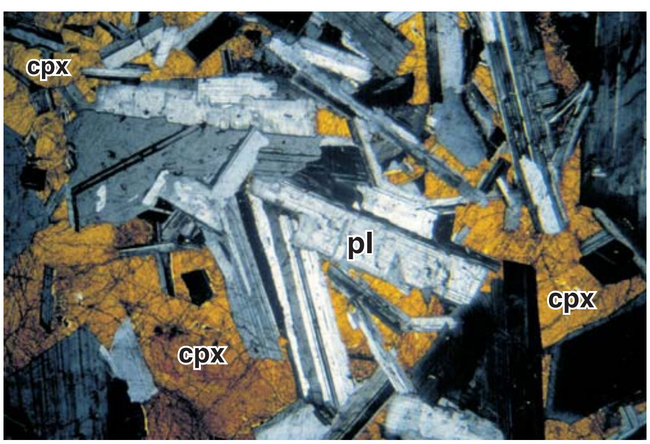


Plate 21. *Thin-section texture of black olivine gabbro (XP), showing interstitial clinopyroxene and elongated plagioclase crystals (XP–crossed polarizers, cpx–clinopyroxene, pl– plagioclase).*

clinopyroxene and grey-green olivine are both late-formed, interstitial to oikocrystic, mineral phases. Biotite, iron-oxides and apatite are also part of the primary assemblage, but most of the amphibole appears to be an alteration product of pyroxene. Plagioclase commonly shows a mottled, pale-grey colour in thin section, which is caused by numerous opaque inclusions, visible only under high magnification. These inclusions were originally suggested to be graphitic (A.J. Naldrett, personal communication, 1998), and were later investigated using the scanning electron microscope; results indicated that they were iron-rich, and probably represent iron oxides exsolved from the feldspar structure (MacDonald, 1999). The oxide inclusions are undoubtedly responsible for the dark colour of the plagioclase. In the upper part of the black gabbro unit, the textures are subtly different, because the habit of the olivine grains is more varied. Here, olivine forms interstitial to poikilitic late crystals (including plagioclase), but it also occurs as euhedral to rounded grains, which are themselves enclosed in the large, interstitial to poikilitic clinopyroxene crystals. Olivine is only rarely seen as inclusions in plagioclase crystals. These textural relationships imply that both mafic minerals crystallized after plagioclase, but that olivine started to form before clinopyroxene, and was able to grow for a while without impinging on other grains. Later formed olivine formed interstitial to poikilitic crystals similar to those developed by clinopyroxene. This downward change in olivine habit and texture is best seen in the western part of the Taheke Lake lobe, notably in holes SVB-98-106 and 108 (*see* Figure 15). The thickness of material with entirely interstitial olivine is greatest in the Northern Abitibi area, located in the east-central part of the North intrusion.

Poikilitic olivine diabase (the fine-grained variant of the black gabbro) is mostly present toward the base of the unit, although it is locally observed in the west adjacent to its upper contact with the fine-grained, layered olivine gabbro. In thin section, this is a spectacular rock in which both olivine and clinopyroxene form large poikilitic crystals enclosing innumerable plagioclase laths, less than 1 mm in length. Their texture resembles that of a coarse diabase. Fine-grained, sulphide-bearing rocks that exhibit an identical texture occur within the mineralized sequence and may also be related to the black gabbro.

DIABASE

North Intrusion

Fine-grained, dark-grey to black diabase is found close to the lower (footwall) contacts of the North intrusion in several drillholes, and is less commonly seen at upper contacts. Diabase is developed against the contact, and is a chilled version of overlying fine-grained gabbro within the mineralized sequence, with which it is gradational. Although most of these chilled zones are close to, or within, the mineralized sequence, the spatially associated gabbro is normally sulphide-free, and is most commonly akin to the layered olivine gabbro, *i.e.*, it contains early formed granular olivine. However, some examples of associated gabbro contain large poikilitic olivines akin to those seen in fine-grained variants of the black olivine gabbro. In many cases, turbidity and alteration of diabases makes it hard to distinguish olivine and clinopyroxene and their respective textural habits.

Chilled upper contacts of diabase are less common, partly because the upper contact is only rarely seen in drillcore. In hole SVB-97-56 (in the Happy Face lobe, Figure 15), a similar diabase unit is developed at the upper contact of the massive leucogabbro unit, and grades downward into it.

South Intrusion

Disrupted chill zones are present at the top of hole SVB-97-79 in the South intrusion, and there are several intervals of diabase and very fine-grained gabbro in the upper part of this hole and the adjacent hole SVB-97-86. These diabase intervals appear to have sharp contacts, implying that they post-date the dominant layered olivine gabbro in this area. They commonly have a very turbid appearance due to dispersed iron oxide and alteration. Olivine is usually present in these fine-grained rocks, but it is difficult to estimate its abundance or determine its texture. Diabase also occurs at the base of holes SVB-97-79 and 97-86, below the melagabbro and peridotite sequence described above. In thin section, all of these rocks are typical diabases, consisting of finely intergrown plagioclase, clinopyroxene and olivine.

Other Areas

The only other area where chilled rocks, including diabase, have been observed is in the Mineral Hill intrusions, notably hole SVB-96-36. These rocks are indistinguishable from diabases in the North and South intrusions.

INTRUSIVE BRECCIAS

Locally, spectacular intrusive breccias consisting of gneiss fragments in a gabbroic matrix are developed in several places around the North intrusion, and also in some gabbro outliers near the South intrusion. These units are not depicted on Figure 9. Typical examples contain angular to rounded country-rock blocks, dominated by orthogneiss and quartz-rich gneiss, with lesser metasedimentary gneiss (Plate 22). Fragments range in size from a few cm to about 1 m. The matrix to the blocks may contain minor sulphide, and in one of the southern examples appears vesicular, and was suggested to be subvolcanic by Thomas and Morrison (1991). Inclusions of graphite are also recorded at this, and other

Plate 22. *Intrusive breccia consisting of angular fragments of country-rock gneisses in a grey gabbroic matrix, locally developed at the base of the North intrusion.*

localities. In the North intrusion, intrusive breccias are developed locally at the external contacts of both layered olivine gabbro and massive leucogabbro, representing lower and upper contacts, respectively (Fitzpatrick *et al.*, 1998). Although there is local assimilation of fragments and contamination of gabbroic matrix in these breccia units, the gneiss fragments do not show the strong resorption and reaction textures observed in drillcore from the mineralized sequence (*see* later discussion). Most of the intrusive breccias recognized outside the mineralized sequence are sulphide-poor. The xenolith population appears to be mostly of local origin, with only a short 'residence time' in the mafic magma.

The mineralized sequence in the North intrusion also includes complex, breccia-like composite rocks that contain abundant gneissic material, and sulphides, but these are viewed as distinctly different rock types and are described separately, in conjunction with mineralization, in the section entitled '*Magmatic Sulphide Mineralization*'.

GEOMETRY AND STRATIGRAPHY

INTRODUCTION

Thomas and Morrison (1991) recognized that the rocks here assigned to the Pants Lake intrusions form two or more sill-like bodies, which, in part, dip gently eastward. Exploration work indicates that the 3-D shapes of these mafic intrusions are complex, and not all of the subtle details are yet fully resolved. This work has also shown that consistent stratigraphic patterns exist in different intrusions, and parts thereof. This section details the geometric and plutonic stratigraphic information provided by the existing database, and outlines the significant problems that remain to be addressed. The representation of drillhole data and surface relationships are illustrated using traditional summary maps, numerous cross-sections, and surface contour (isopach) maps. Note that cross-sections all incorporate a 2:1 vertical exaggeration to adequately represent the geology, and that true thicknesses and dip angles are thus distorted.

The cross-sections indicate the four principal petrological units described in the preceding chapter:

1) Fine-grained, layered olivine-gabbro
2) Peridotite and melagabbro
3) Coarse-grained, massive leucogabbro, and
4) Black olivine gabbro

In this section, the mineralized sequences of the PLI are not subdivided, but are indicated as single discrete units. In reality, the mineralized sequences contain several distinctive and unusual sulphide-bearing rock types, and have complex internal stratigraphic patterns, which cannot be illustrated at the scale of the sections.

SOUTH INTRUSION

As currently understood, the South intrusion consists of two halves (Figures 10 and 11). The better-known of these is the north half, and is here termed the Sarah Hill lobe, because it underlies the prominent hill southwest of Sarah Lake. Only the central part of this lobe, to the south of the Pants River valley, was explored through drilling prior to 2002; however, Falconbridge completed a series of drillholes located north of the Pants River. The southern half of the South intrusion is here termed the Adlatok lobe, because it extends as far as the Adlatok River, but has not been traced beyond it. Fitzpatrick *et al.* (1999) use the term 'Tongue gabbro', for this region. The most recent mapping (Fitzpatrick *et al.*, 1999) indicates a thin tongue of gabbroic rocks linking the two lobes of the intrusion, based on limited surface data. The narrowest portion of the South intrusion corresponds with an east–west-trending unit of HLIS anorthosite, which lies between metasedimentary gneisses to the north and the Arc Lake granite (HLIS) to the south (Figure 9). The presence of anorthositic rocks in the deeper sections of hole SVB-97-91 suggests that the anorthosite–paragneiss contact dips northward. The Sarah Hill lobe is intruded into mostly metasedimentary gneisses, and the Adlatok lobe is intruded mostly into rapakivi granite of the Arc Lake granite. This pattern implies that the pre-existing geology has influenced the shape of the intrusion.

The Sarah Hill lobe (Figure 11) is dominated by fine- to medium-grained, variably layered olivine gabbro. Holes SVB-97-79 and 97-86 provide the 'type sections', as they penetrate the thickest part of the body (Figure 12). The coarse-grained massive leucogabbro unit occurs only as narrow intervals (with sharp contacts in drillcore), close to the surface. These intervals have the general appearance of intrusive veins or sheets. Coarse-grained, plagioclase-rich rocks, intersected to at least 1200 m below surface in holes SVB-97-89 and 97-91 (Figure 12), were at first considered to be related to the massive leucogabbro, but are now viewed as anorthosites of the HLIS.

Five drillholes (SVB-97-79, 86, 89, 94 and 98-100) were completed in the Sarah Hill lobe and the distribution of mineralized melagabbro and peridotite provides a geometric key. In holes SVB-97-79 and 97-86, these rocks are interlayered with fine-grained olivine gabbro, and define a basal mafic cumulate sequence, partly sulphide-bearing, located 500 to 600 m below the surface (Figure 12). Identical cumulate rocks (also sulphide-bearing) occur close to surface in hole SVB-98-100, where they are also defined by a shallow EM anomaly due to the sulphides (Fitzpatrick *et al.*, 1998). A thin intersection of sulphide-bearing gabbro at the very top of hole SVB-97-89 may also represent this horizon, as it resembles a more leucocratic mineralized rock located immediately above the basal contact in other holes noted above. The basal contact region in hole SVB-97-79 (beneath the sulphide-rich rocks) also contains a fine- to medium-grained, barren gabbro that grades downward into a chilled zone. This chilled rock provides a possible sample of the initial magma that entered the chamber, which must have solidified prior to the formation of the overlying mafic cumulates.

The basal contacts of the intrusion in these four holes define a plane striking at about 10°, and dipping west at about 15° (Figures 11 and 12). The gabbro has a continuous true thickness of about 600 m in the area of hole SVB-97-79, but the nearby hole SVB-97-94 (abandoned at 501 m) contains a central intersection of gneisses, separating two gabbroic units, of which the upper hosts basal sulphide mineralization. At the equivalent stratigraphic level in hole SVB-97-79, minor sulphide mineralization is associated with thin screens of older foliated plutonic material, of uncertain identity. The upper gabbroic section in nearby hole SVB-97-86 contains a higher density of diabase dykes and sheets compared to the lower section, and the lower (largely diabase-free) section appears to be finer grained close to its upper boundary. Such features indicate that the South intrusion may be composite, and record two or more magmatic influxes. Farther to the northeast, in hole SVB-98-110 (Figure 12), the upper section appears to represent a discrete sill, underlain by at least 250 m of gneisses. The gabbro has basal mineralization and a thin upper section of massive leucogabbro. Although the evidence is by no means conclusive, the observed features imply that the upper section is an earlier magmatic pulse that was subsequently intruded by the main (deeper) portion of the South intrusion. The suggested limits of these two subtly different bodies are indicated in Figure 12. MacDonald (1999) examined olivine compositional variations and found that the sec-

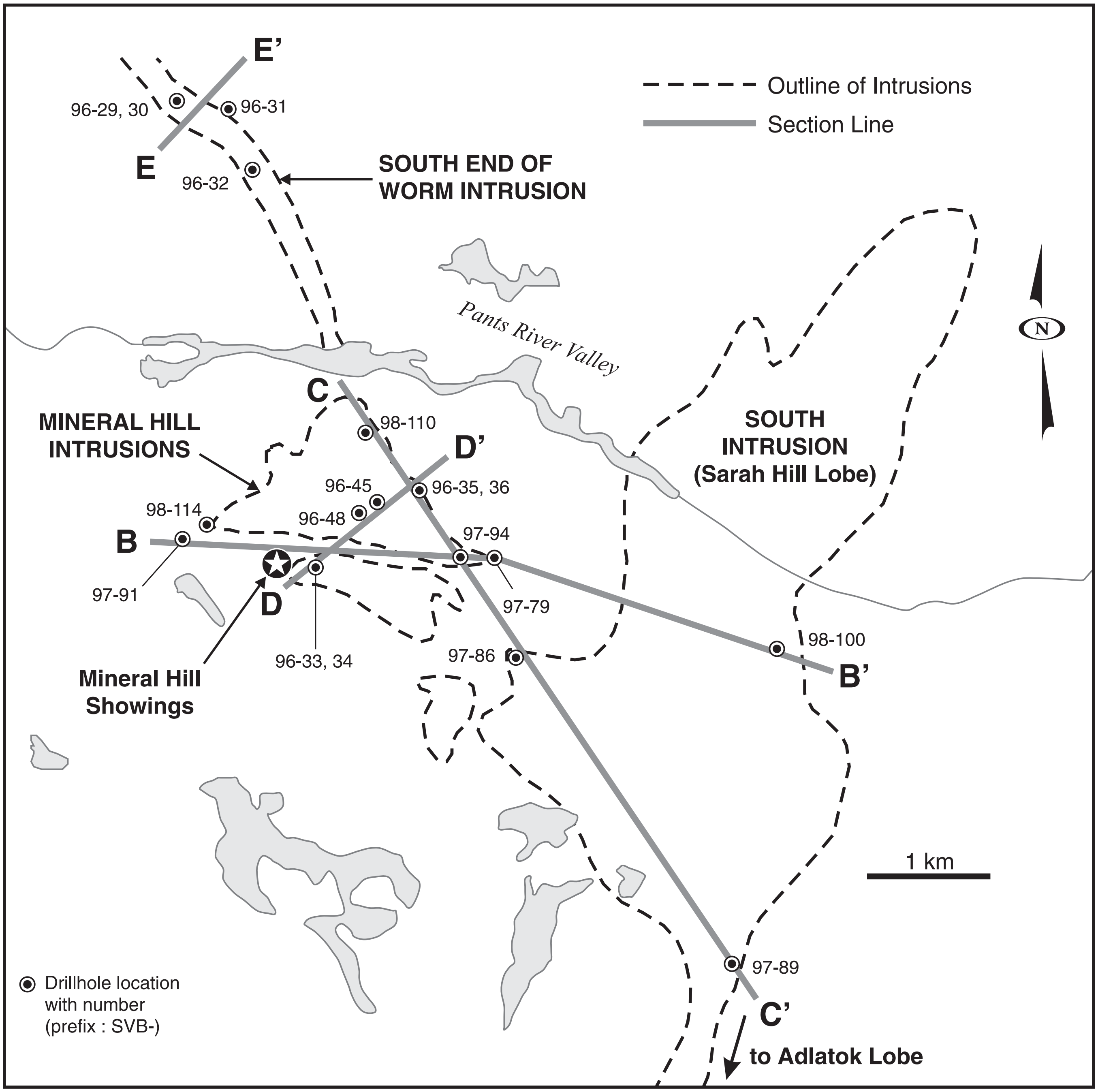


Figure 11. *Outline map of the Sarah Hill lobe of the Pants Lake South intrusion and adjacent areas, showing the locations of drillholes discussed in the text, and locations of cross-sections given in Figures 12, 13 and 14.*

tion of hole SVB-97-79 above about 250 m shows a distinctly different compositional trend from the section below 250 m, and that the mineralized rocks have a distinctly different (magnesian) olivine composition compared to overlying gabbros. She also noted some differences in the trace-element geochemistry above and below this level, but these are less evident in this study. All of these lines of evidence point to a significant discontinuity in this part of the body. The sample that yielded the age of 1338 ± 2 Ma (Smith *et al.*, 2001) is reported to have come from the lower part of hole SVB-97-79, although the exact depth was not specified (Smith, 2006; *see* Appendix).

The western limit of the South intrusion in the subsurface is not well-defined. Simple extrapolation suggests that it should be present in the lower part of the deep hole SVB-97-

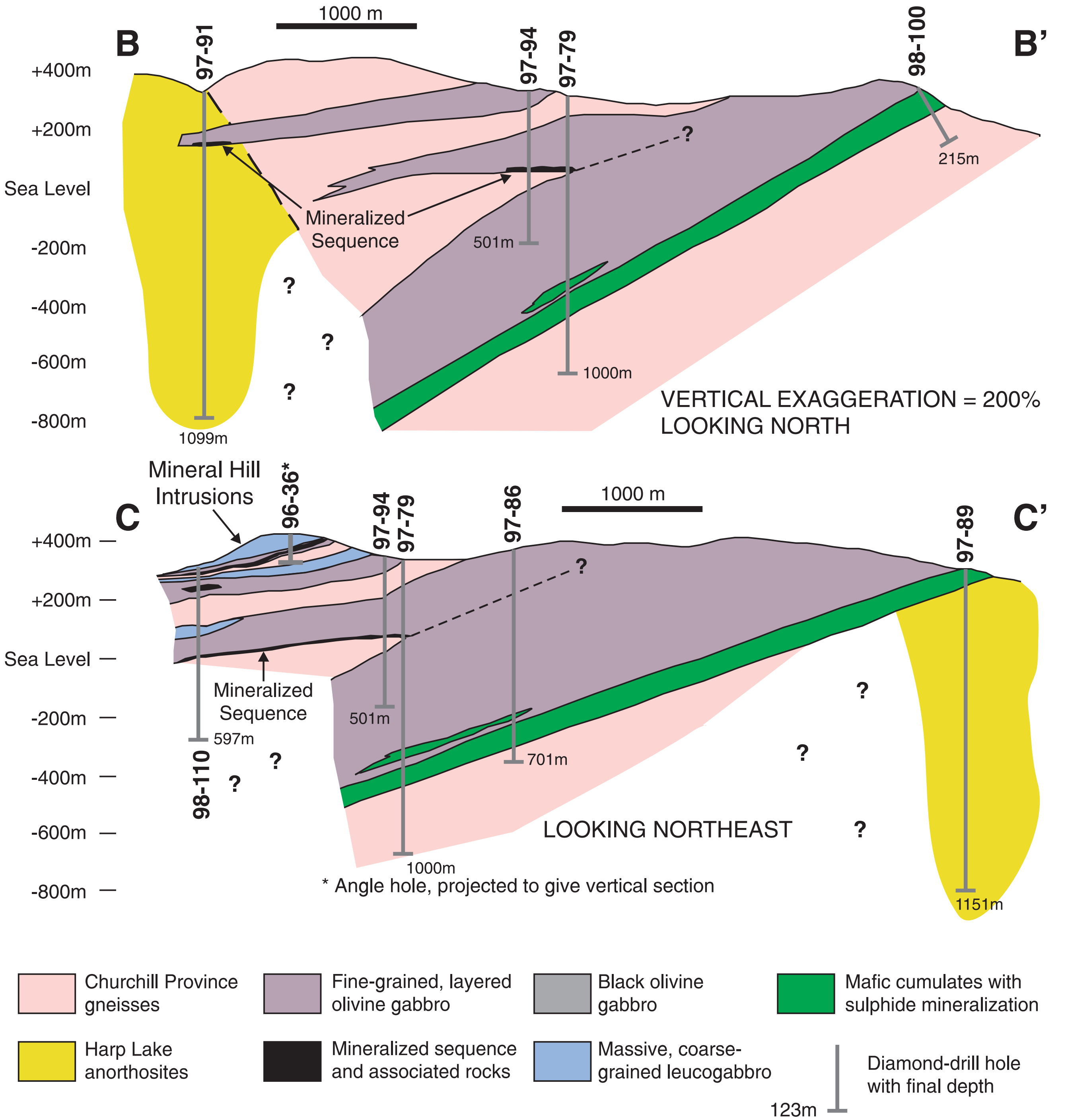


Figure 12. *Cross-sections of the South intrusion; locations of section lines are indicated in Figure 11. All cross-sections have 200% vertical exaggeration for clarity.*

91 and also in hole SVB-98-110 (Figure 12), but the rocks seen at appropriate levels are either metasedimentary gneisses or older HLIS anorthosites, cut by ferrodiorites, diabase and granite. However, if the South intrusion thins slightly downdip, or its dip increases by as little as 5 to 10°, its top would actually lie below the base of hole SVB-97-91 (note that vertical exaggeration (Figure 12) overstates the extent of this problem). The interpretation shown in Figure 12 differs from that proposed by Fitzpatrick *et al.* (1999), who suggest that the intrusion is instead funnel-shaped. They correlated the basal contact of the sill in hole SVB-98-110 with the deeper basal contacts of holes SVB-97-79 and SVB-97-86.

Whilst this configuration is certainly permitted by the drillhole data, the thin mineralized sequence in hole SVB-98-110 is entirely different from the sulphide-bearing ultramafic cumulates seen elsewhere.

Until 2002, there was no drilling north of the Pants River valley (Figure 11), but the general outcrop pattern is compatible with the deduced geometry of Figure 12, although the gabbro does not extend all the way to Sarah Lake. Holes completed by Falconbridge in 2002 (summarized by Kerr, 2002b) contained a sulphide-bearing melagabbro and peridotite sequence at the base of the intrusion. This indicates that the stratigraphy indicated in Figure 12 is continuous. Drilling in the Pants River valley (targeted on an EM anomaly) intersected only paragneisses containing graphitic horizons. This implies that the lower contact of the intrusion is indented westward as a result of the topographic variations, as would be expected if it dips in this direction at 15° or so. The geometry of the Adlatok lobe in the third dimension is currently unconstrained, due to a lack of drilling. However, the eastern contact of this lobe is subparallel to its equivalent in the Sarah Hill lobe (*i.e.*, roughly at right angles to the dip inferred from the drillhole data), and similarly corresponds to a topographic escarpment. On this basis, it may represent a direct continuation of the Sarah Hill lobe, but partly separated from it by a 'wall' of massive anorthosite, which protrudes downward from the roof. If this is the case, the basal peridotite and melagabbro sequence should be present along the eastern contact and at depth in both bodies. An alternative interpretation by Fitzpatrick *et al.* (1999), is that the Adlatok lobe is a separate, originally deeper, body that is connected to the Sarah Hill lobe by a feeder conduit. However, there is no indication of such a lower body in hole SVB-97-89, which remained in coarse-grained anorthosite until it bottomed at 1151 m (Figure 12).

MINERAL HILL INTRUSIONS

A sill-like mafic body was initially recognized in the Mineral Hill area (*see* Map 2012-18, Figures 9 and 10), and basal sulphide mineralization also was noted (Thomas and Morrison, 1991). The Mineral Hill showing was evaluated further in 1995, and several short drillholes were completed in 1996 (Wares, 1997). Although mineralization proved to be widespread, the Ni and Cu grades were poor relative to the amount of sulphide, and only limited drilling was conducted in subsequent years, mostly to check for the presence of hidden gabbro bodies.

Figure 12 illustrates the interpreted geometric relationships between the South intrusion and thinner intrusions that host the sulphide mineralization, including the Mineral Hill showing. Hole SVB-98-110 intersected three discrete mafic intrusions. The two lower units correspond to the upper mafic intersections in hole SVB-97-94, and the uppermost unit correspond to mineralized gabbro in holes SVB-96-35 and -36 near Mineral Hill (*see* also Figure 13). Each of the three mafic intervals in hole SVB-98-110 contains an upper section of coarse-grained massive leucogabbro, and contains a mineralized sequence toward the base of the fine-grained gabbro unit. The upper part of hole SVB-97-91 also contains a thick mafic unit with an upper massive leucogabbro, underlain by fine-grained olivine gabbro and basal sulphide mineralization, but there is no sign here of the middle mafic unit projected from hole SVB-97-94 (Figure 12).

A more detailed view of the Mineral Hill showing and surrounding area is provided by several shallow drillholes illustrated in Figure 13. Holes SVB-96-33 and -34, located at the showing, indicate an upper massive leucogabbro, underlain by a thin mineralized fine-grained gabbro. The other holes, located farther to the northeast, define a similar pattern, but the lower mineralized unit is thicker. This pattern can be interpreted as a single sheet-like body, which has been gently folded or displaced by a fault (or which has a primary undulation dating from the time of intrusion). An alternative interpretation is that it represents two separate sheet-like intrusions. Given the evidence for 'stacked' sill-like bodies in hole SVB-98-110, the latter interpretation is preferred here. This interpretation implies that a second mafic unit, potentially mineralized, may sit below the base of holes SVB-96-33 and -34, which penetrate to a depth of only about 50 m (Figure 13).

In summary, the Mineral Hill intrusions consist of at least three, and perhaps four, discrete sheet-like bodies. Notwithstanding uncertainties in correlation, the Mineral Hill intrusions clearly represent stacked subhorizontal to gently west-dipping sheets sitting structurally above the South intrusion. The upper sheet(s) have a closely similar stratigraphy, in which mineralized sequence and fine-grained gabbro are overlain by massive leucogabbro. The lower sheets also contain the massive leucogabbro unit, but its distribution is more sporadic. The lowermost body may correlate with the upper section within the South intrusion, where the fine-grained unit apparently thickens to 250 m or more. In general, the anatomy of the Mineral Hill intrusions most closely resembles that of the North intrusion, but there are differences in their mineralized sequences. However, the geochemical data (*see* later discussion) suggest a genetic link to the North intrusion, rather than to the nearby South intrusion.

The relationship between the coarse-grained massive leucogabbro and the fine-grained gabbro at Mineral Hill is unclear. At the Mineral Hill showing, the contact is very sharp, but uninformative. In drillcore, the contact ranges from apparently gradational (hole SVB-96-36) to a complex, heterogeneous zone in which fine- and coarse-grained domains

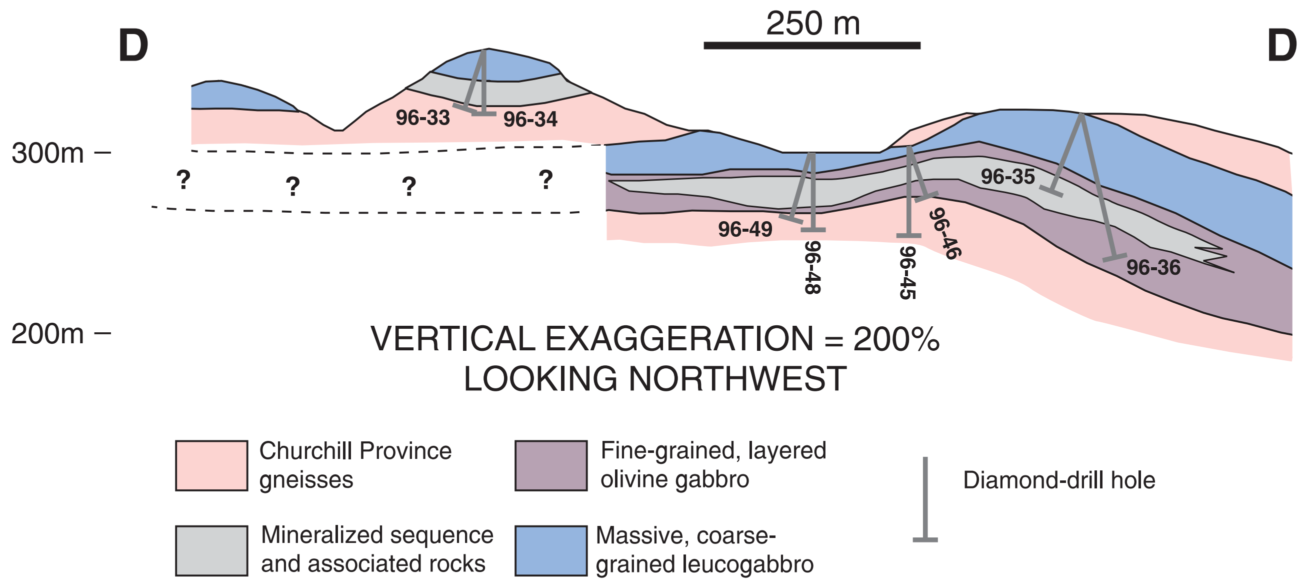


Figure 13. *Cross-section of the Mineral Hill intrusions; location of section line is indicated in Figure 11. Cross-section has 200% vertical exaggeration for clarity.*

are intimately associated. These unusual rocks, termed 'composite gabbro', are a well-known component of the North intrusion mineralized sequence and are discussed separately below. Hole SVB-96-36 is also notable for a well-developed (chilled) diabase zone at the basal contact, which is cut by sulphide veins. This indicates that it formed and solidified before the arrival of sulphide-bearing magmas.

DOUGHNUT INTRUSION

The Doughnut intrusion was defined by regional mapping during mineral exploration, and lies 3 to 4 km southwest of Mineral Hill, entirely within the Arc Lake granite (HLIS). As originally mapped, the Doughnut intrusion had a ring-like shape, but subsequent mapping adjusted its defined outline slightly and it now has an arcuate outline. Fitzpatrick *et al.* (1999) changed its name to the Slingshot gabbro, but the earlier, older name is retained (Kerr, 1999). The Doughnut intrusion is located at approximately the same topographic elevation as the Mineral Hill intrusions, and is separated from them by a low-lying area. The intrusion has not been drilled, and there are few direct constraints on its anatomy, but the general outcrop pattern suggests that it is a flat-lying or gently inclined sheet. Surface outcrops are dominated by coarse-grained, massive leucogabbro, but some fine-grained gabbro, containing poikilitic clinopyroxene, is also present (K. Emon, personal communication, 1999). The Doughnut intrusion thus almost certainly represents an extension of the upper Mineral Hill intrusion(s), which perhaps coalesce toward the southwest. Scattered outcrops of coarse-grained leucogabbro in the intervening valley may represent the roof of one of the lower sills discussed above. If the Adlatok lobe of the South intrusion resembles the Sarah Hill lobe in its general geometry, the Adlatok lobe probably lies at some considerable depth (1 km or more) below the Doughnut intrusion, and there may be other stacked sills in between, as seen above the South intrusion.

CARTAWAY INTRUSION

The Cartaway intrusion is a small, east–west-trending gabbro body originally described by Emslie (1980) as a flat-lying Harp Dyke. However, it contains the characteristic rock types of the PLI. It has an upper massive leucogabbro and a lower, fine-grained gabbro, locally with poikilitic clinopyroxene. Trace amounts of sulphide were observed near its base in one area. The area around the intrusion was part of a separate claim block that was never included within the South Voisey's Bay joint venture project, as it was held by Cartaway Resources. Little drilling or exploration was conducted in this area. The thickness of the body is between 50 and 70 m, and it clearly forms a gently north-dipping sheet that has intruded the rapakivi-textured Arc Lake granite. The extent of the unit has not been mapped and extensions of this body may be present elsewhere south of Pants Lake. This intrusion may be related to the Mineral Hill intrusions, and possibly to the North intrusion, but there is little data.

THE WORM INTRUSION

The Worm intrusion is probably the least understood component of the PLI. It lies within claim blocks that were excluded from the South Voisey's Bay joint venture project until 1998. Some drilling was conducted in this area during

1996, but there was only limited work in 1998. The external contacts of the Worm intrusion are poorly exposed, but it forms a ridge trending at about 140°. This general outcrop pattern suggests that it cannot be a subhorizontal sheet like the Mineral Hill intrusions. The nature of the southern contact, where it approaches the Mineral Hill and South intrusions, is completely obscured in the Pants River valley. In the north, it appears to merge with the North intrusion, somewhere to the south of the Major General showing (Figure 9), but a direct connection cannot be demonstrated in the field. The dominant rock type in the Worm intrusion is coarse-grained, massive leucogabbro, which locally is pegmatitic. There are local exposures, particularly on the west side, of fine-grained olivine gabbro containing poikilitic clinopyroxene. Sulphides occur locally in a small showing at the north end of the body, where a crude layering (defined by disc-like mafic inclusions in composite gabbro, as discussed later) is apparently truncated along strike by the massive leucogabbro. This relationship suggests that the massive leucogabbro is younger than the fine-grained gabbro and the mineralized sequence, at least in this location.

About 1 km north of the Pants River, holes SVB-96-29, -30 and -31 demonstrate that the Worm intrusion consists of a sheet, some 150 m thick, striking at 135°, and dipping some 35° to the northeast (Figure 14). The sheet consists largely of coarse-grained leucogabbro, which overlies the mineralized sequence and associated fine-grained gabbro. Several other drillholes, farther to the north, provide only single intersections (or missed the gabbro entirely), and thus do not constrain the attitude of the intrusion. Locally, the Worm intrusion becomes extremely attenuated; for example, in hole SVB-96-15, the entire sequence from coarse leucogabbro to the footwall gneiss is condensed to about 50 m. The relationship between the Worm and North intrusions is anything but clear. It is possible that the Worm intrusion represents the feeder system to the latter, but its general igneous stratigraphy is similar to that seen in many places in the North intrusion (*see* below), and it may instead simply be a more steeply dipping extension of the generally flat North intrusion. The pattern in Figure 14 represents the near-surface configuration only, and the attitude of the Worm intrusion at depth remains unknown.

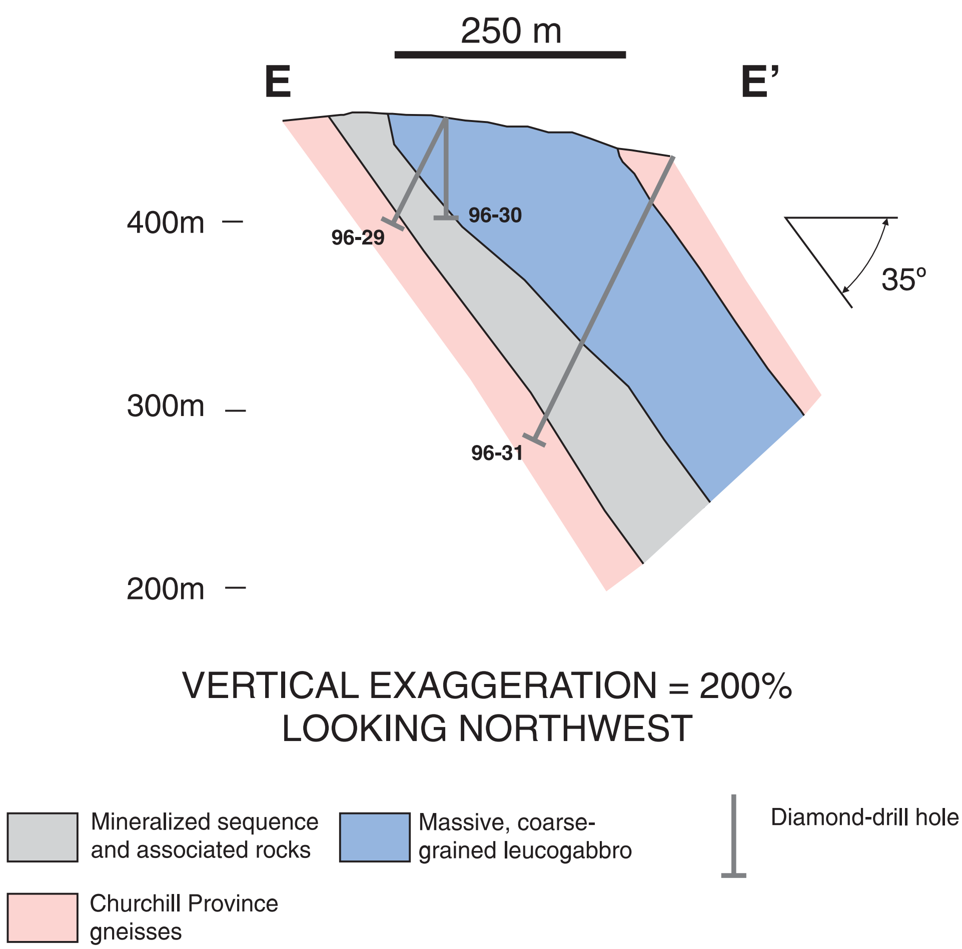


Figure 14. *Cross-section of the Worm intrusion; location of section line is indicated in Figure 11. Cross-section has 200% vertical exaggeration for clarity.*

NORTH INTRUSION

The North intrusion is the most complex component of the PLI, and has been the focus of most of the exploration effort. Its surface area is large, and it is also widely present in the subsurface beneath a cap of metasedimentary gneisses. Drilling is widely spaced in areas where the basal contact lies in the shallow subsurface. The only area of intense drilling is near the northern tip, in the Northern Abitibi drilling area (Figures 9 and 15), and in the adjacent claim block to the east, originally held by Major General Resources. Elsewhere, the North intrusion remains poorly understood at depth, and only a tiny fraction of its basal contact has been directly tested by drilling. The North intrusion is subdivided into three lobes; these are the NDT, Happy Face, and Taheke Lake lobes (Figures 9 and 15). Each of these shows a distinct stratigraphic and geometric pattern.

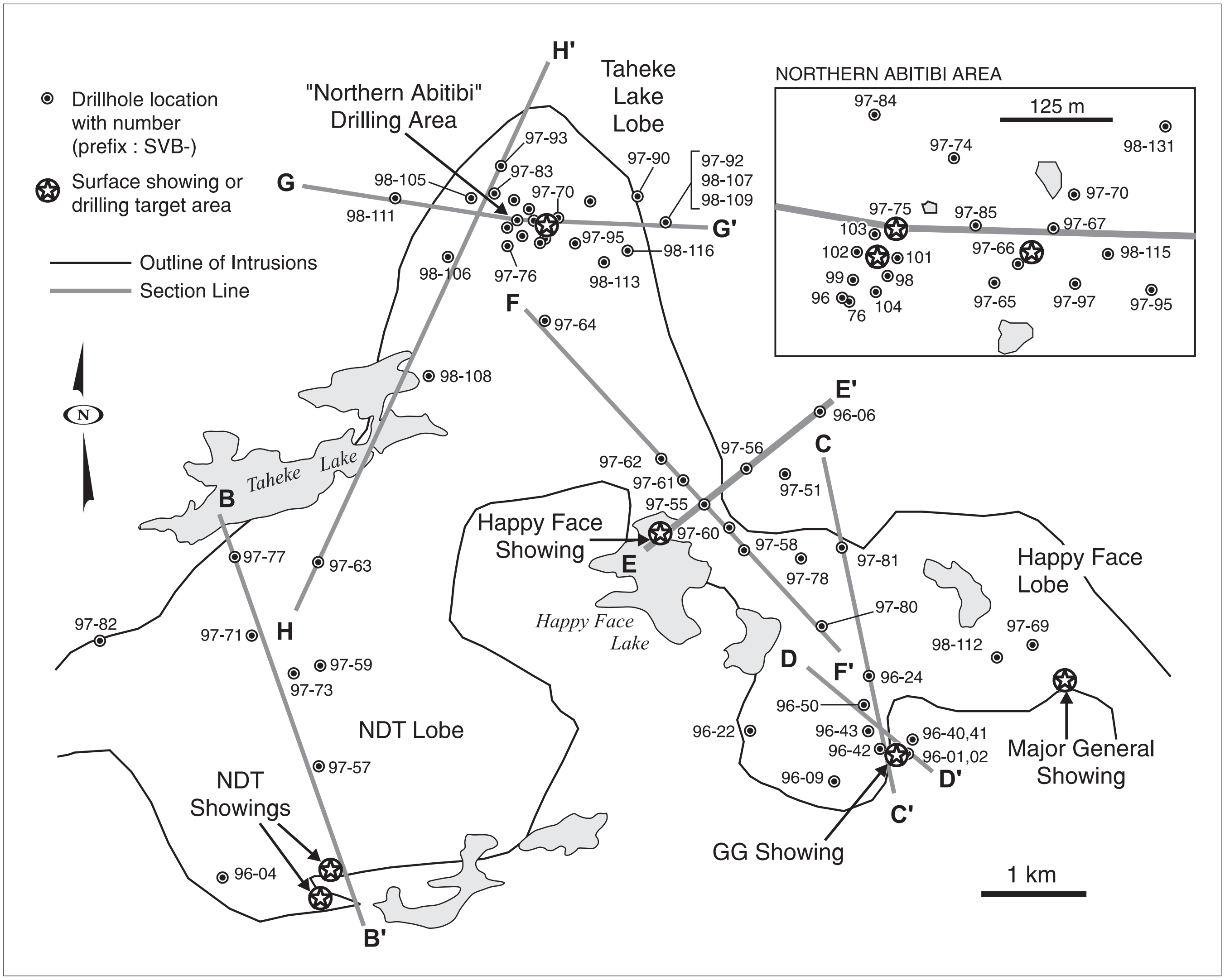


Figure 15. *Outline map of the Pants Lake North intrusion and adjacent areas, showing the locations of drillholes discussed in the text, and locations of cross-sections in Figures 16 to 19.*

NDT Lobe

The NDT lobe occupies the area between Pants and Taheke lakes (Figure 9; Map 2012-18), and includes the NDT surface mineral showings. It contains the most extensive exposures of the layered, fine-grained olivine–gabbro unit in the North intrusion. A north–south cross-section from the NDT surface showings to Taheke Lake (Figure 16) indicates a gently north-dipping intrusion at least 400 m thick, in which an upper massive leucogabbro is underlain by about 300 m of fine- to medium-grained olivine gabbro. A mineralized sequence, locally 30 to 40 m thick, sits just above the basal contact, and projects to the surface showings (Figure 16). The subsurface projection of the basal contact defines a plane, striking at 060°, and dipping at about 12° to the northwest. Highly altered gabbro at the top of hole SVB-97-82 (Figure 15) suggests proximity to the original roof, and may place a limit on the total thickness in this lobe. However, the roof and upper contact are not preserved in the drillcore. The geometry of the NDT lobe to the northwest of Taheke Lake is very uncertain, as there is little drilling in this area. However, there is no sign of a thick intrusion in hole SVB-98-111, located west of the Taheke Lake lobe, and this is a major unresolved problem (*see* later discussion). West of the NDT showing area, the intrusion narrows, and the basal contact must descend from about 500 m elevation north of Pants Lake, to only 31 m above sea level in hole SVB-97-82, within a distance of less than 1 km, implying a northward dip of 25 to 30°, significantly steeper then than indicated in Figure 16.

All of the drillholes in the NDT lobe intersect essentially the same rock types, which define similar relationships. Unfortunately, drillcore contacts between the massive leucogabbro and the layered olivine gabbro are ambiguous, but short

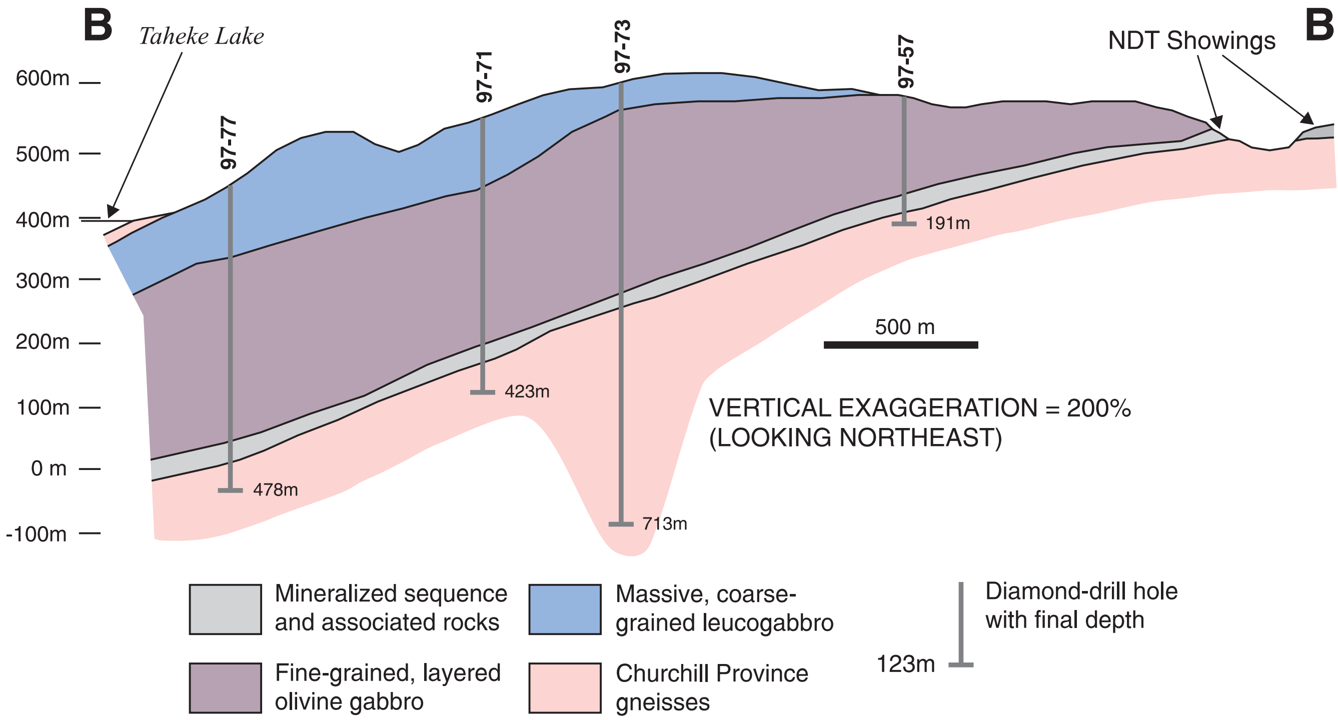


Figure 16. *Cross-section of the NDT lobe of the North intrusion; location of section line is indicated in Figure 15. Cross-section has 200% vertical exaggeration for clarity.*

intervals of coarse-grained gabbro within the latter may be intrusive veins or sheets. The fine-grained, layered olivine gabbro shows primary variations in grain size, colour and texture, and locally develops a speckled porphyritic appearance. Parts of the unit, notably toward the base, are almost as coarse grained as the leucogabbro unit, but retain the granular, cumulus olivine. Some of these coarse-grained rocks are troctolitic, and may represent zones of olivine accumulation. Similar rocks are present just above the mineralized sequence in hole SVB-96-04, west of the NDT showings. This implies that the troctolitic interval may be a persistent feature. Hole SVB-97-59 contains a narrow interval of melatroctolite and peridotite, interpreted as a local mafic cumulate horizon.

The characteristic rocks of the mineralized sequence are well developed in these holes (*see* later discussion) but the amount of sulphide in the NDT lobe is generally low (<10%). In the NDT lobe, the mineralized sequence is always separated from the massive leucogabbro by a thick sequence of layered olivine gabbro, in contrast to the Happy Face and Taheke Lake lobes. Poikilitic olivine diabase (probably a fine-grained variant of black olivine gabbro) was noted near the base of hole SVB-97-63, just above the mineralized sequence, and may correlate with the thicker sequence of black olivine gabbro seen in the Taheke Lake lobe. Similar rocks are also locally present within the mineralized sequence in other NDT lobe holes, but are exceedingly difficult to distinguish in drillcore from other fine-grained gabbroic rocks.

Happy Face Lobe

The Happy Face and the NDT lobes are separated by a region southwest of Happy Face Lake, which consists mostly of gneisses, overlain by scattered gabbro outliers (Figures 9 and 15). The Happy Face lobe includes the small Happy Face showing, and the larger Major General and GG showings. The base of the intrusion is commonly less than 300 m below surface in the Happy Face lobe, and is well-defined. Geometrically, the intrusion ranges from a thin subhorizontal sheet, to a northeast-dipping sheet between 100 and 200 m thick (Figures 17 and 18).

The GG showing was one of the first areas to be test drilled in 1996. Here, a west-northwest–east-southeast section (Figures 15 and 17; section D-D') reveals a typical sequence of massive, coarse-grained leucogabbro sitting above the mineralized sequence and/or fine-grained olivine gabbro as a subhorizontal sheet (Figure 17). Most of the fine-grained olivine gabbro sits within, or below, the sulphide-bearing rocks assigned to the mineralized sequence, and it cannot easily be represented in Figure 17. Hole SVB-96-02 indicates a second, and possibly a third gabbro unit at deeper levels (section D-D'); this is the only evidence in the North intrusion for stacked sheet-like intrusions akin to those documented at Mineral Hill. However, the lower units contain very little sulphide mineralization. A longer north-northwest–south-southeast section (Figure 17; section C-C') shows that the sheet dips

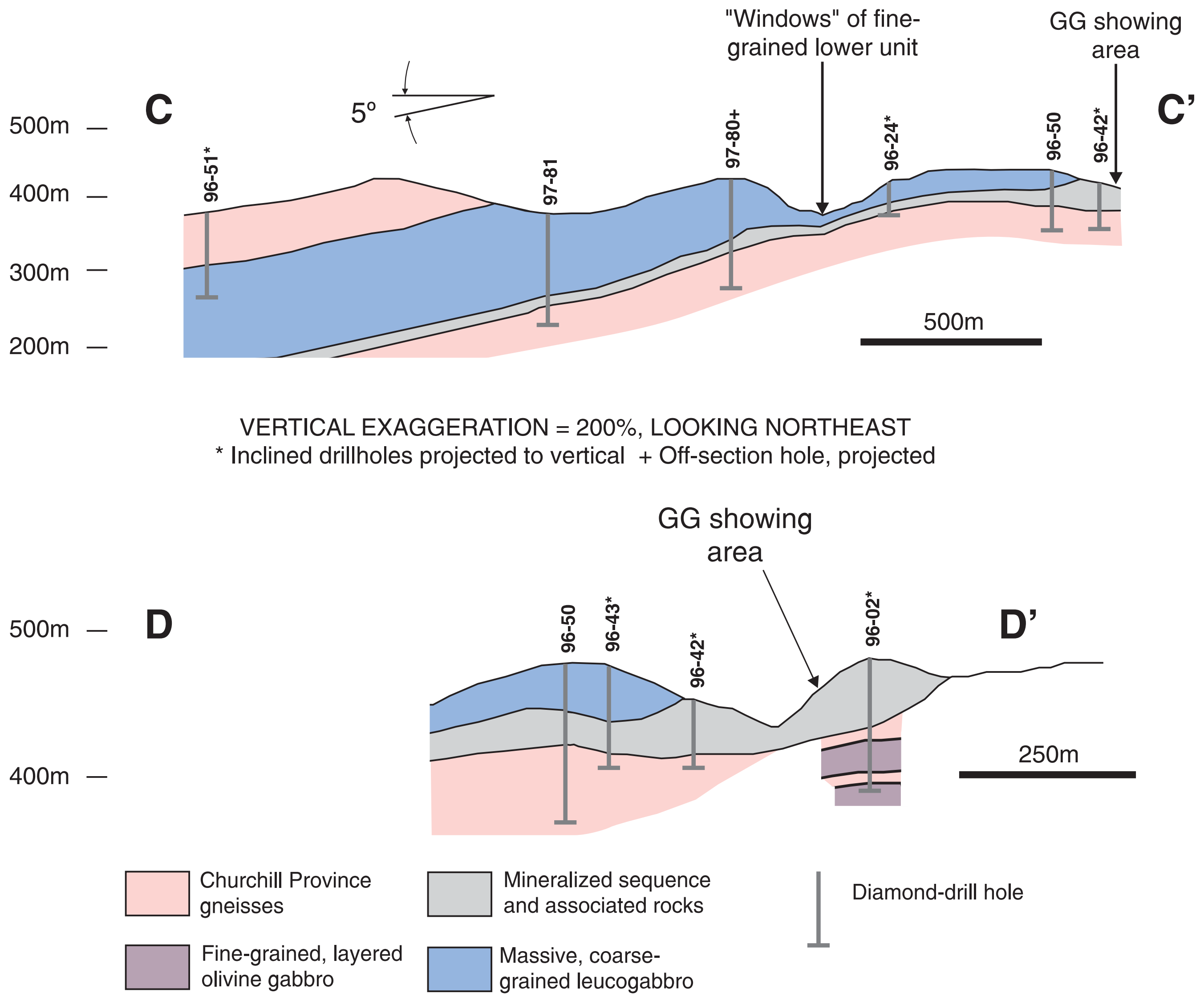


Figure 17. *Cross-sections of the Happy Face lobe of the North intrusion; locations of section lines are indicated in Figure 15. All cross-sections have 200% vertical exaggeration for clarity.*

very gently (*ca.* 5°) to the north, achieving a thickness of about 200 m, most of which is massive leucogabbro. The mineralized sequence and associated fine-grained layered gabbro sit persistently at the base of the sheet, below the massive leucogabbro unit. The gentle dip expressed on this section may be apparent, as a southwest–northeast cross-section from the Happy Face showing to hole SVB-96-06 indicates a northeast dip of about 12°, and changes in the dip of the upper and lower contacts (Figure 18; section E-E'). These variations could be interpreted either as a flexuring effect (as suggested by Fitzpatrick *et al.*, 1998) or as the effect of a normal fault. If it is a gentle flexure, it could be a function of either primary intrusive morphology, or mild deformation. A third explanation is that the variation simply indicates a thickening of the upper leucogabbro unit, as the base of the sheet is unconstrained beyond hole SVB-97-56. This is of particular interest because it preserves a chilled upper margin, grading downward into massive leucogabbro. There is also a well-developed zone of hydration and alteration at the top of the massive leucogabbro unit in hole SVB-97-56.

A final view of the Happy Face lobe, and its possible connection to the Taheke Lake lobe, is provided by a northwest–southeast cross-section from hole SVB-97-64 to hole SVB-97-80, which shows the presence of a trough-like structure near hole SVB-97-78, where the gabbro is 250 m thick (Figure 18; section F-F'). The depth of the axis of the trough is exaggerated slightly because hole SVB-97-78 lies slightly off-section, but the progressive deepening of the basal contact from <80 m (hole SVB-97-62) to 210 m (hole SVB-97-58) is very well defined. In this same area, thin sequences of poikilitic olivine diabase olivine are present in holes SVB-

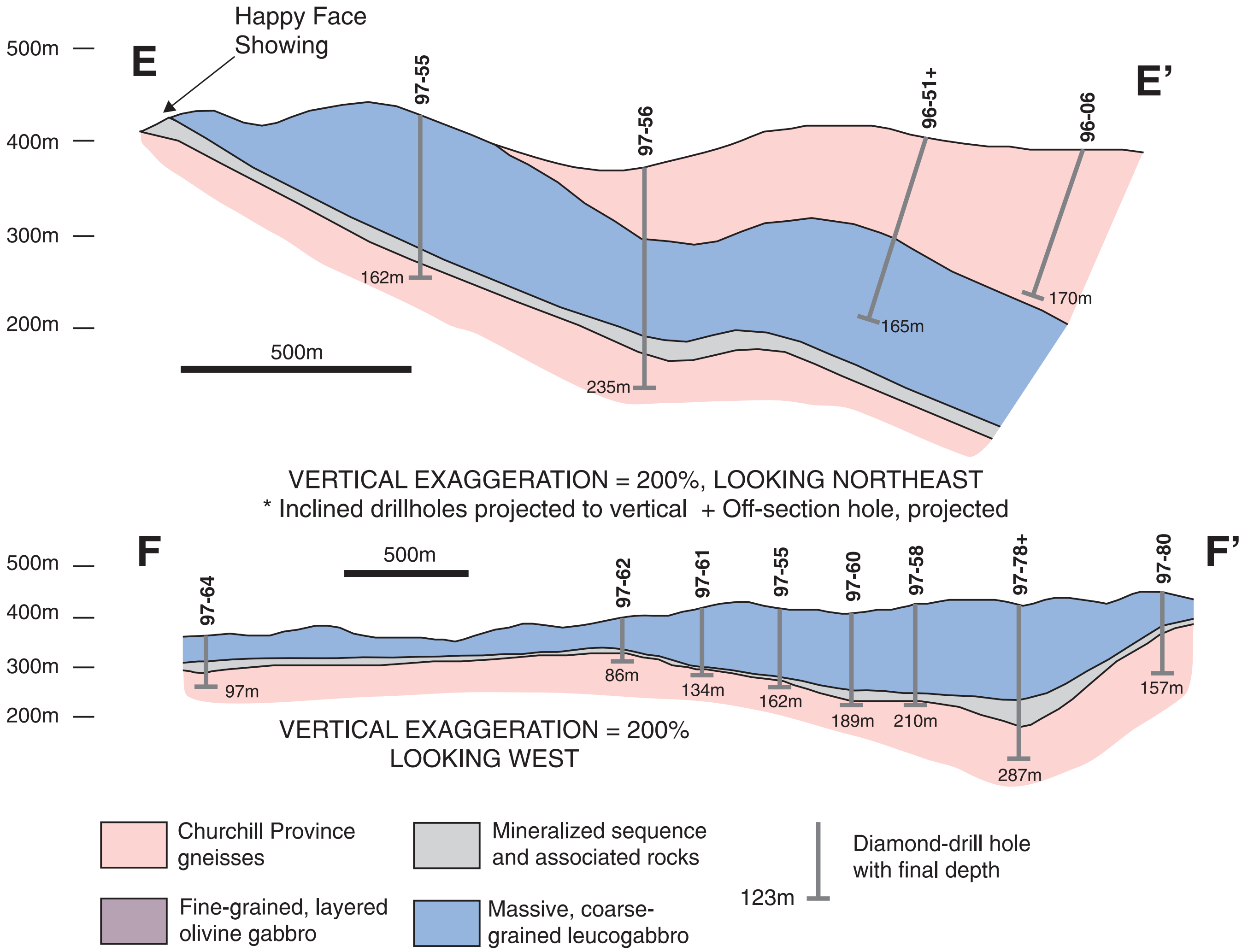


Figure 18. *Cross-sections of the Happy Face lobe of the North intrusion; locations of section lines are indicated in Figure 15. All cross-sections have 200% vertical exaggeration for clarity. Folding of basal contact in section E-E’ is schematic and not constrainted by any drillhole data.*

97-58 and 80 (and probably in SVB-97-78, which was not examined by the author), where they occur just above the mineralized sequence. The poikilitic olivine diabase is believed to correlate with the black olivine gabbro of the Taheke Lake lobe. In hole SVB-97-80, the black gabbro is overlain by fine-grained, granular-textured olivine gabbro, and the stratigraphic relationships appear to be identical to those of the Taheke Lake lobe. Possible black gabbro was also observed in the same stratigraphic context in hole SVB-98-112, northwest of the Major General showings (Figure 15). The elevation of the basal contact rises gently to the northwest, and the total thickness of gabbro is probably only 50 m or so south of hole SVB-97-64.

In the Happy Face lobe, the mineralized sequence is commonly developed a short distance below the base of the massive leucogabbro unit, and there is generally no thick-layered olivine gabbro sequence. The contact relationships are, as usual, enigmatic. The Happy Face lobe also contains rocks that probably equate to the black gabbro seen in the Taheke Lake lobe, although the identification of this rock type is always controversial. Hole SVB-98-112 is particularly instructive, as it contains the three main units of the PLI in only 120 m of core (Figure 19). The upper section is typical, coarse-grained, massive leucogabbro, which shows marked grain-size variations approaching its base. It is underlain by a fine- to medium-grained, speckled textured rock that is typical of the layered olivine gabbro unit. The upper part of this interval contains narrow zones of massive leucogabbro, which show fine-grained margins implying that the leucogabbro was chilled against the fine-grained, layered olivine gabbro. The fine-grained unit passes downward into a thick unit of the rock type termed composite gabbro, which contains fine- and coarse-grained domains; the latter contain minor sulphide.

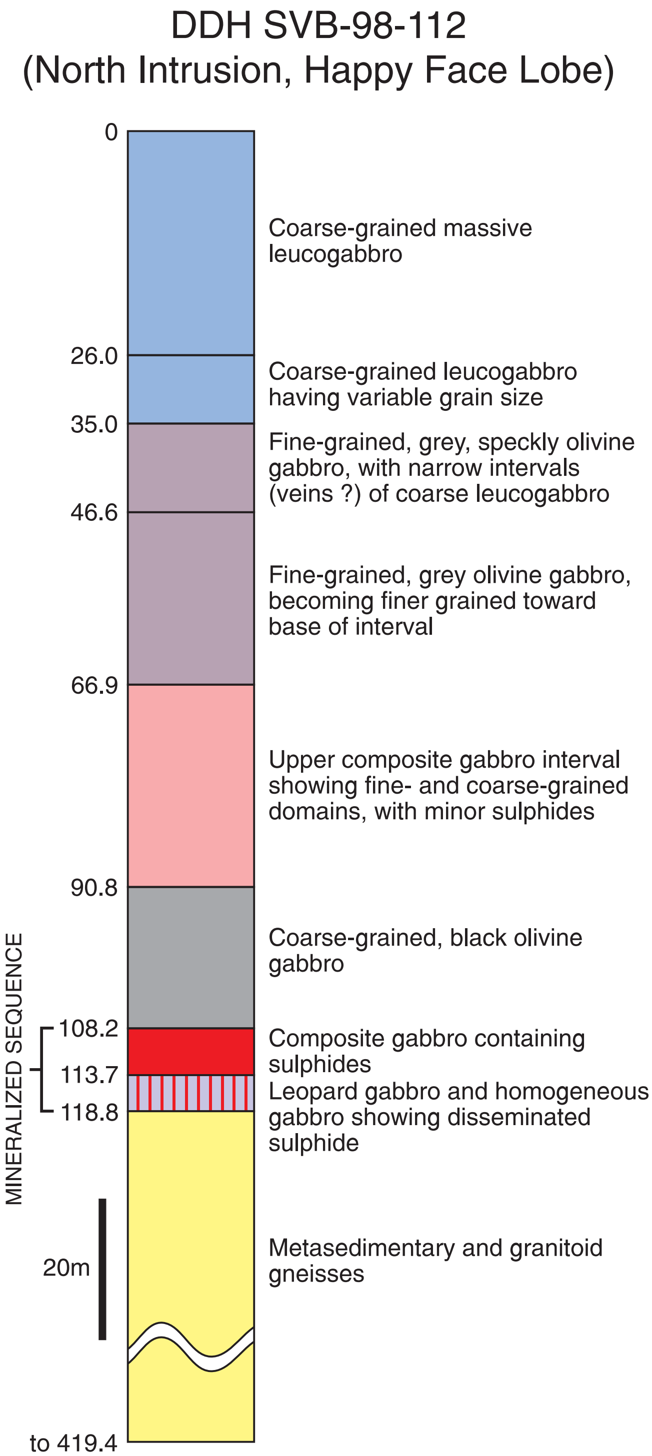


Figure 19. *Schematic summary of igneous stratigraphy in hole SVB-98-112, a key drillhole from the Happy Face lobe of the North intrusion.*

This unit passes abruptly into a medium-grained, homogeneous, dark-grey gabbro with poikilitic olivine that closely resembles the black gabbro seen in the Taheke Lake lobe. This unit is, in turn, underlain by the mineralized sequence. Hole SVB-98-112 suggests that the black gabbro and the massive leucogabbro have different relationships to the layered olivine gabbro. The massive leucogabbro appears to intrude the latter, but the relationship of layered olivine gabbro to black gabbro is ambiguous. Similar key sections that incorporate all three units are also present in the Taheke Lake lobe.

Taheke Lake Lobe

The Taheke Lake lobe forms the northern portion of the North intrusion, and contains more diamond-drill sites than the remainder of the PLI combined. There is no surface sulphide mineralization here, but several drillholes intersected zones of varying grades of semimassive and massive mineralization. However, outside this fairly small (<1 km^2) area, the 3-D geometry of the lobe is defined only by widely spaced drilling (Figure 15), and large areas of the basal contact remain untested.

An east–west cross-section through the northern part of the lobe indicates a sheet-like mafic intrusion having a thickness of around 200 m, which dips below the gneisses to the east (at about 15°) between holes SVB-97-85 and 98-109 (Figure 20; section G-G'). This eastern part consists mostly of medium- to coarse-grained black olivine gabbro that overlies a thin mineralized sequence. At the upper contact of the body in holes SVB-97-92, 98-107 and -109, black olivine gabbro sits directly below gneisses and older plutonic rocks. There are no thick sequences of fine-grained, layered olivine gabbro (although similar material exists within the mineralized sequence), and no sign of the coarse-grained massive leucogabbro unit seen in the Happy Face and NDT lobes. In the Northern Abitibi area, the basal contact is flat-lying to gently west-dipping. However, farther west, in hole SVB-98-105, the black olivine gabbro unit is significantly thinner, and underlies fine-grained, layered olivine gabbro. The western end of this cross-section presents some significant unresolved problems in interpretation (Figure 20). Hole SVB-98-111, which was drilled to seek the downdip extension of the mafic intrusion, failed to intersect any significant thicknesses of gabbro. Most of this hole consists of complex paragneiss and orthogneiss, but there is a 30 m intersection of mafic rocks, containing some minor sulphides. As discussed by Kerr (1999), there are several possibilities here. An increase in the westward dip to 40 to 45° is required for the upper surface of a sheet-like intrusion to descend below the base (Figure 20 overstates the dip required due to the 2:1 vertical exaggeration). Alternative explanations include structural disruptions, or a switch in dip direction that could bring the base of the intrusion to surface; however, the latter hypothesis is difficult to reconcile with the attitude of the NDT lobe. Fitzpatrick *et al.* (1999) suggest that the thin intersection encountered in this hole may actually represent a feeder conduit for the intrusion, rather than a subsidiary sill or dyke propagating from

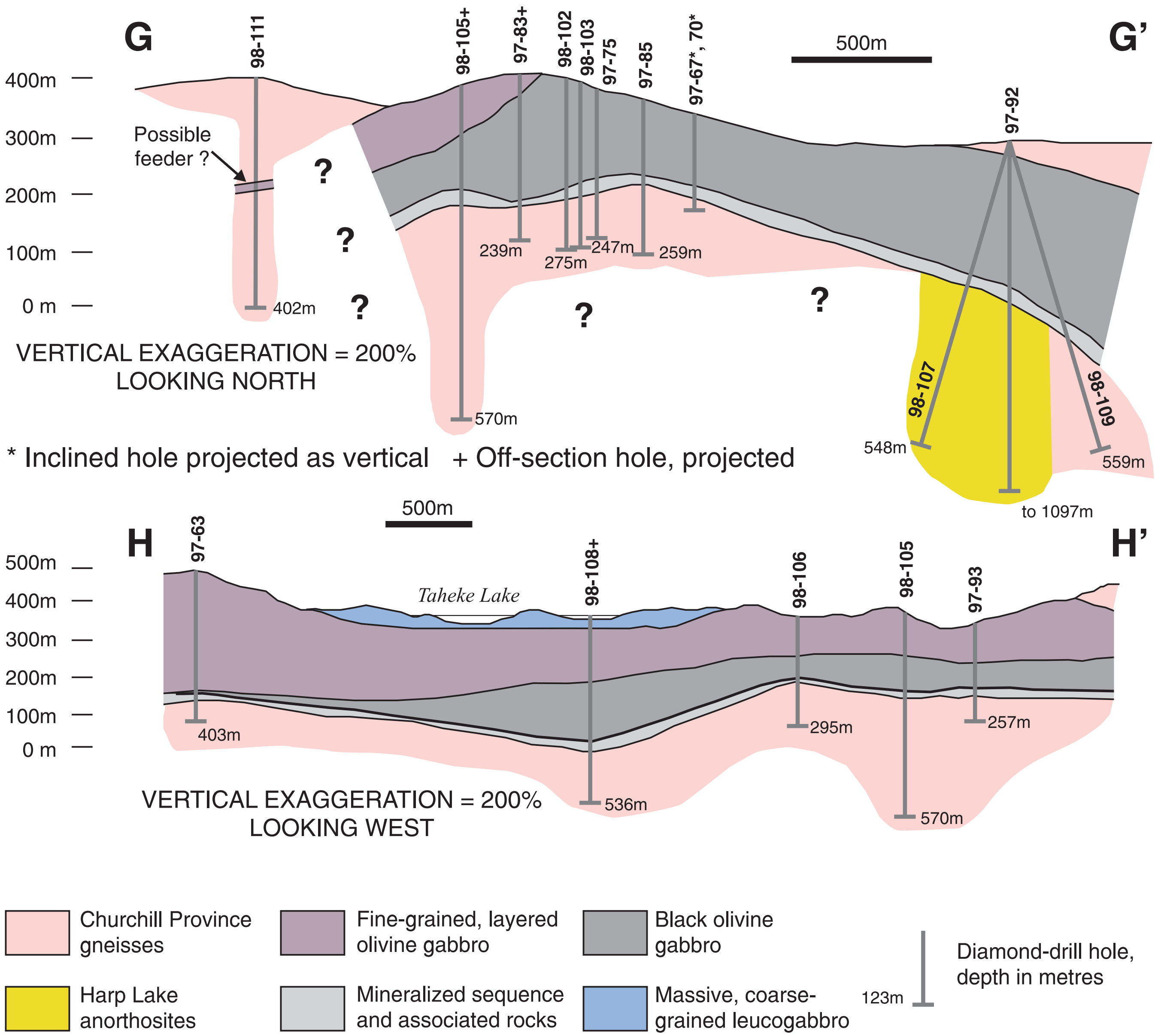


Figure 20. *Cross-sections of the Taheke Lake lobe of the North intrusion; locations of section line are indicated in Figure 15. All cross-sections have 200% vertical exaggeration for clarity.*

the main body. Subsequent examination of this intersection during the 2000 field season suggested that the mafic rocks do not belong to the PLI, but are instead biotite-rich ferrodiorite, likely an older component of the NPS. Thus, the North intrusion remains missing in this hole without any obvious explanation.

The mineralized sequence (including the usual assortment of complex rock types) is persistently present at the basal contact, and is locally very thick (*e.g.*, 50 to 60 m true thickness in hole SVB-97-70). Some fairly deep holes such as SVB-97-92, 98-105, 98-107 and 98-109 indicate that here, the North intrusion does not include stacked, sheet-like bodies within the depths explored to date. The long intersection of coarse-grained, plagioclase-rich rocks in hole SVB-97-92 was originally considered as a possible feeder system (to the massive leucogabbro?) but it is intruded by ferrodioritic rocks. This suggests that it is actually an older anorthosite. The plagioclase-rich rocks are also geochemically distinct from typical PLI mafic rocks, and are now interpreted as belonging to an older member of the NPS, or possibly to the HLIS.

A different perspective, including some critical stratigraphic relationships, is revealed by a southwest–northeast section along the northwest edge of the lobe, along the axis of Taheke Lake (Figure 20; section H-H'). The section reveals slightly undulatory geometry of the base of the intrusion, the presence of a deeper root zone beneath Taheke Lake itself, and locally, a thin cap of massive leucogabbro. The intrusion probably dips gently northeast (beyond hole SVB-97-93), beneath some high hills composed of gneisses and NPS rocks. It is not clear what happens to the northwest, beyond Taheke Lake, as the intrusion is entirely missing in hole SVB-98-111. This region preserves the most complete stratigraphy anywhere in the North intrusion. The black olivine gabbro forms a discrete lower unit in this region, which is 200 m thick in hole SVB-98-108, but thins northward and southward. This unit may actually extend southward all the way to hole SVB-97-63, where thin intervals of medium-grained gabbro with poikilitic olivine sit just above and within the mineralized sequence. The fine- to medium-grained, layered olivine gabbro forms the central part of the intrusion, and its contact with the underlying black olivine gabbro likely dips to the northwest. The fine-grained, layered olivine gabbro, however, has not yet been recognized widely in surface mapping of the Taheke Lake lobe. The massive leucogabbro unit, seen only in the upper part of hole SVB-98-108, sits above the fine-grained olivine gabbro unit, as it does throughout the NDT lobe.

Three drillholes in this area (SVB-97-93, 98-106 and -108) provide critical geological information, and hole SVB-98-108 is particularly important (Figure 21). In holes SVB-97-93 and 98-106, an upper sequence of fine-grained, layered olivine gabbro is underlain by black olivine gabbro with interstitial to poikilitic mafic minerals. This unit becomes finer grained toward the base, and varies to poikilitic olivine diabase. In thin section, the upper parts of the unit contain olivine of variable habit, and the lower part shows poikilitic olivine. Contacts are fairly abrupt in hole SVB-97-93, where they imply that the black gabbro is the younger unit (Fitzpatrick *et al.*, 1998), but the boundary is defined by a thick and heterogeneous composite unit in hole SVB-98-106. The composite unit consists of rounded and irregular patches of fine-grained olivine gabbro contained within a matrix of black olivine gabbro. In both drillholes, minor sulphides are present adjacent to the contact within the lower black gabbro unit. The textures of this transition zone are generally similar to those observed in the rock type termed composite gabbro, within the mineralized sequence. Hole SVB-98-108 displays a similar sequence, but also contains an upper massive coarse-grained leucogabbro section sitting above the fine-grained, layered olivine gabbro unit; the latter is cut by pale-grey leucogabbro veins with (relatively) chilled margins, which imply that the veins are younger. The relationships in these holes closely resemble those noted in hole SVB-98-112 in the Happy Face lobe (Figure 19), and indicate that the black olivine gabbro is indeed a discrete unit, with a very close temporal relationship to the layered olivine gabbro. The contact zones are rather diffuse, implying that the two units were partly consolidated or liquid when they interacted. The black

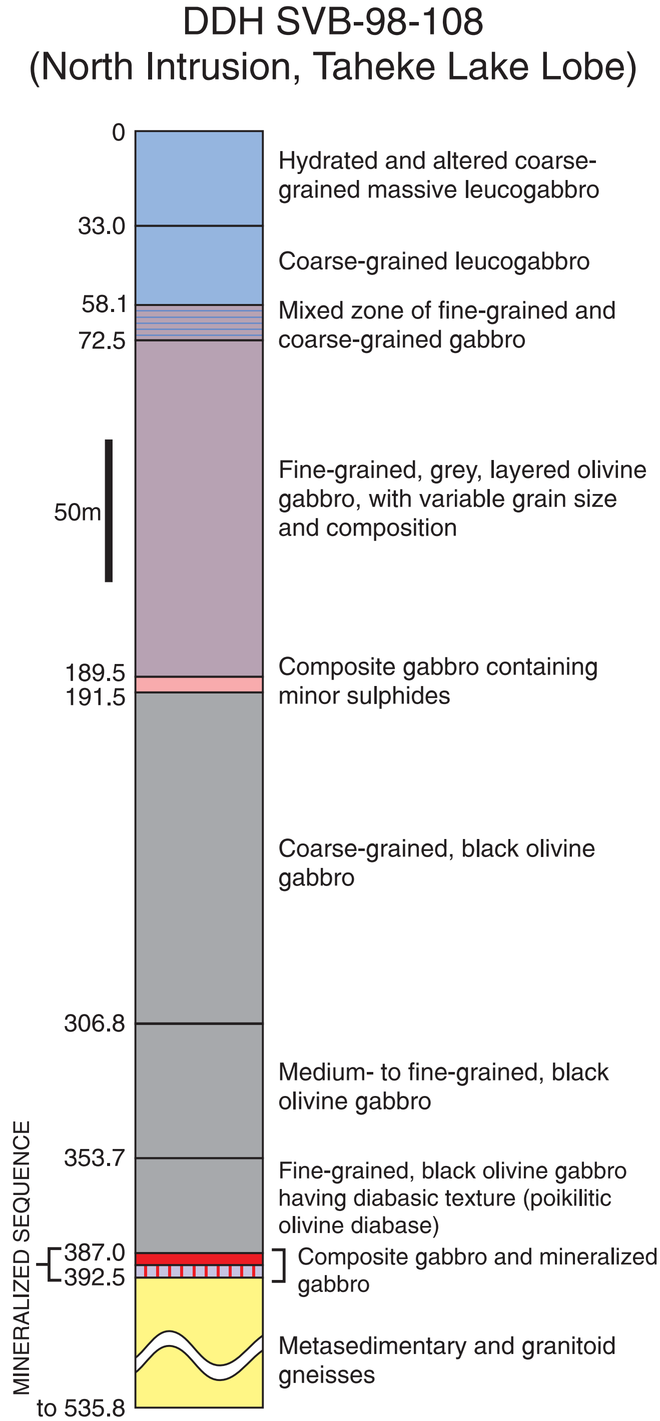


Figure 21. *Schematic summary of igneous stratigraphy in hole SVB-98-108, a key hole from the Taheke Lake lobe of the North intrusion.*

olivine gabbro sits beneath or within the fine-grained unit, whereas the massive leucogabbro sits above it, and apparently intruded it as veins and sheets. These relationships indicate that the massive leucogabbro unit postdates solidification of the fine-grained unit. To date, black olivine gabbro and coarse-grained leucogabbro have never been observed in contact in the field or in drillcore.

Correlation between the Lobes of the North Intrusion

Each lobe of the North intrusion has a distinctly different stratigraphic pattern (Figure 22), and the relationships between them are difficult to visualize. In the NDT lobe, the fine-grained, layered olivine gabbro dominates the intrusion, and is overlain by a thinner unit of massive coarse-grained leucogabbro. In the Happy Face lobe, most of the intrusion consists of coarse-grained leucogabbro and little fine-grained gabbro sitting beneath it. In the Taheke Lake lobe, the black olivine gabbro unit is a major component, and appears to sit at the base of the intrusion, below the fine-grained unit. The Taheke Lake lobe has a complete three-unit stratigraphy in the west, but the fine-grained gabbro and massive leucogabbro appear to be entirely absent in the east (Figure 20; section G-G'). However, there is one common thread amongst all these areas – a sequence of mineralized rocks invariably sits at, or just above, the basal contact. Not only is this unit omnipresent, but it also shows a remarkably consistent stratigraphic pattern (*see* section on *Magmatic Sulphide Mineralization*).

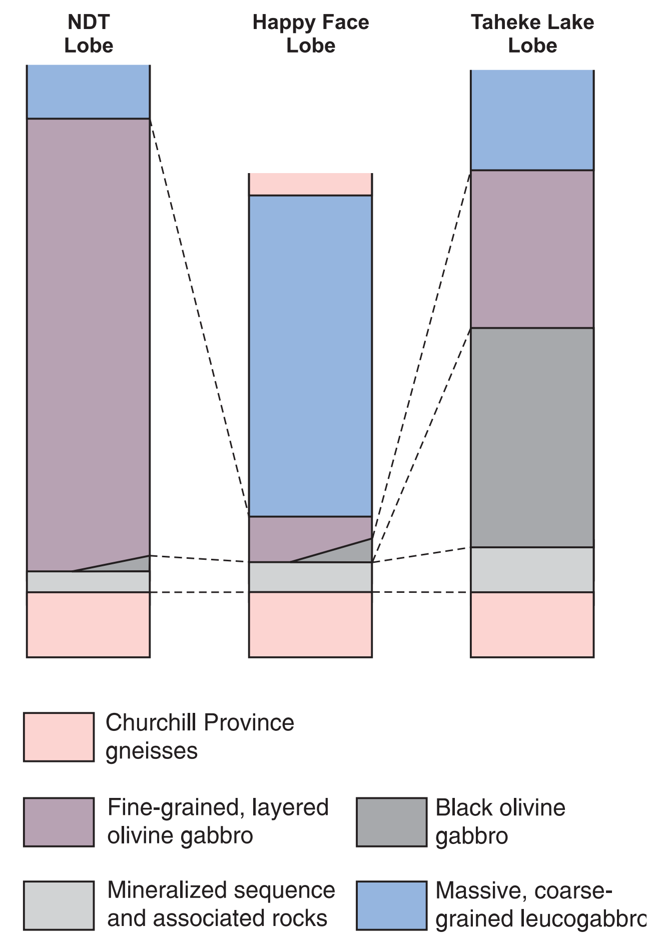


Figure 22. *Schematic summary of stratigraphic similarities and differences among the NDT, Happy Face, and Taheke Lake lobes of the North intrusion.*

If the black olivine gabbro is a distinct unit, sitting at the bottom of the intrusion, then the fine-grained olivine gabbro must come to surface somewhere between holes SVB-97-64 and SVB-98-106, and must thicken appreciably between them (Figure 15). The fine-grained olivine gabbro and the massive leucogabbro must either lie above the erosion surface in the intensely drilled Northern Abitibi area, or were never present. The occurrence of black olivine gabbro right at the roof of the body to the east (Figure 20; section G-G') implies that they were never present in this area. The longitudinal section through Taheke Lake (Figure 20; section H-H') implies that the black olivine gabbro pinches out to the south, to provide for the simpler two-unit stratigraphy of the NDT lobe, although it may form a thin zone in hole SVB-97-63. There is also some evidence for thin sequences of black olivine gabbro in the Happy Face lobe, notably in hole SVB-98-112, where its stratigraphic position is the same as in the Taheke Lake lobe. The correlation of the Happy Face and eastern Taheke Lake lobes is fraught with particular uncertainty, because it appears that both the fine-grained gabbro and the massive leucogabbro must pinch out northward.

Some of these correlation problems can be resolved if one assumes that the mineralized sequence is intimately connected with the black olivine gabbro unit. If this is so, then the mineralized sequence at the base of the intrusion in the NDT and Happy Face lobes may be the lateral equivalent of the combined black olivine gabbro and mineralized sequence in the Taheke Lake lobe. In the light of this assumption, all parts of the North intrusion exhibit the same stratigraphy, but with differing unit thicknesses. There is some petrographic evidence to support this line of thought, notably the presence of poikilitic olivine diabase (a fine-grained version of the black olivine gabbro) above and within the mineralized sequence (*see* later discussion), and the textural similarities between the matrix of coarse-grained sulphide-bearing 'composite' gabbro in the mineralized sequence and typical black olivine gabbro.

The 3-D Geometry of the North Intrusion

If only one thing is clear from the above discussion, it is that the North intrusion has a complex 3-D geometry. A useful synthesis of the patterns and problems is revealed by contour maps of the depth to the basal surface of the intrusion and the topography of this basal surface (Figure 23B). Although considerable interpolation is required to produce the contour maps, they illustrate some important features.

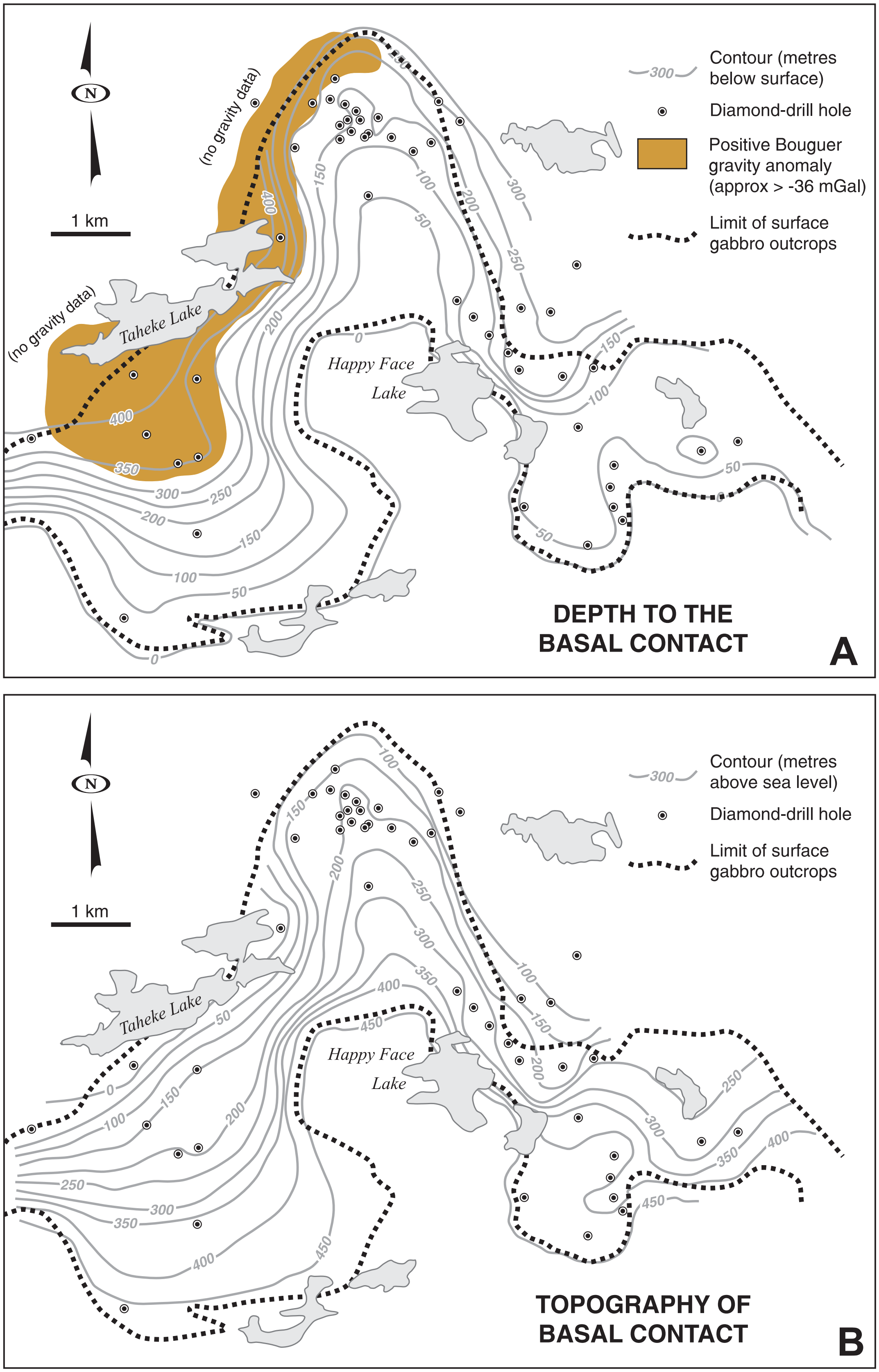


Figure 23. *Geometric reconstructions of the thickness and basal contact surface of the Pants Lake North intrusion. A. Depth to the basal contact in metres. B. Topography of the basal contact of the intrusion, expressed as metres above sea level.*

Thickness contours (isopachs) provide an ease of exploration map, which shows that the base of the intrusion is relatively close to surface throughout the Happy Face lobe and in the southeastern sections of the NDT and Taheke Lake lobes (Figure 23A). The results correlate well with the results of regional gravity surveys, which show an elongate high along the southeast side of Taheke Lake, and extending into the centre of the NDT lobe. Contours on the basal contact provide a more rigorous geometric view, as they are independent of surface topography, but they define a pattern that is generally similar to the isopach map (Figure 23B). The topography of the basal contact is complex, but the basal contact essentially resembles an eroded hillside, with a central ridge running from the Happy Face area through the centre of the Taheke Lake lobe. Interestingly, the intensely explored Northern Abitibi drilling area sits right on the top of this ridge, which apparently plunges northward. The topographic pattern exhibited in this area resembles the crest of a north-plunging anticlinal fold. Another part of this topographic high protrudes northwest toward Taheke Lake, and apparently separates the NDT lobe from the remainder of the intrusion. Near the east end of Taheke Lake, the dip of the basal surface must steepen to above 25°, and it must similarly steepen at the west end of the NDT lobe. As discussed above, a significant steepening may be required north of Taheke Lake, to account for the absence of gabbro in hole SVB-98-111. It is not yet clear if this escarpment projects north of Taheke Lake.

This topographic pattern resembles a north-plunging fold, with gently dipping limbs, and a fold axis trending at about 150°, which is roughly parallel to the regional structural grain in the Churchill Province. This raises the possibility that the geometry is entirely secondary, *i.e.*, the North intrusion was an originally flat-lying body that has been gently warped. However, given the variations in stratigraphy and thickness (Figure 22), the pattern may, in part, reflect the original geometry of the intrusion, modified by regional tilting and/or folding during uplift. For example, the valley that defines the NDT lobe could be an originally deeper section of an originally flat-lying intrusion, now tilted to the northwest, and the central ridge could be a primary topographic high in the basal contact. The present evidence is insufficient to choose between these alternatives.

The inference of possible folding in this area is interesting, because the NPS is supposedly undeformed and posttectonic. However, it should be noted that this folding or warping (if it is present) is very gentle (it is overstated by vertical exaggeration in the cross-sections), and would not be expected to result in penetrative deformation of the PLI. Also, such gentle folding of this magnitude would likely never be detected in the largely steeply dipping to subvertical basement units of the Churchill Province gneisses, or in the massive plutonic rocks of the NPS and HLIS – the only way to perceive such folding is through geometric analysis of originally subhorizontal or gently dipping surfaces, such as those provided by the PLI. Markers of this type are rare within the NPS, and the PLI provide the only one in which the third dimension is directly constrained by drilling. In fact, other patterns (*e.g.*, the complex basal contact geometry of the sheet-like Cabot Lake intrusion south of Nain; Ryan, 1990) could have similar causes. If there is a tectonic component to the geometry of the PLI, there are no constraints on its timing, aside from the fact that it postdates crystallization at 1322 Ma. Possible explanations include very mild distal compression related to the *ca.* 1000 Ma Grenvillian Orogeny, or even gentle extensional effects associated with the opening of the Labrador Sea during the Mesozoic. Alternatively, it could have developed as part of an extensional event connected with the overall emplacement of the NPS.

SUMMARY

Correlation between the different bodies within the PLI remains provisional, but some general inferences are possible.

The stratigraphic pattern of the South intrusion appears to be distinct from that of all the other bodies, even though the dominant rock type (fine-grained, layered olivine gabbro) is very similar. The most important differences are the presence, in the South intrusion, of a lower mafic cumulate zone, associated with magmatic sulphide mineralization. As discussed later, the basal mineralized sequence in the South intrusion lacks the distinctive stratigraphy seen in the North intrusion, and elsewhere. This provides good evidence that the gabbroic rocks intersected in the South intrusion belong to a discrete body. The South intrusion is itself composite, as indicated by the discontinuity at about 250 m below surface. These differences, coupled with subtle geochemical contrasts (*see* section on *Geochemistry*), are consistent with the age differences indicated by U–Pb geochronological data (Smith, 2006; *see* Appendix).

Results of the drilling in the South intrusion (Figures 12 and 13), show that the Mineral Hill intrusions are located, structurally, above the South intrusion. It was previously suggested that they might be fed from the South intrusion (Kerr, 1999), but geochemical data show that they have more affinity with the North intrusion, and their internal stratigraphy more closely resembles that of the North intrusion.

Correlation between the South intrusion–Mineral Hill area and the Worm intrusion is very uncertain, because the intervening Pants River valley is devoid of outcrops. The southern end of the Worm intrusion dips northeast at about 35°; its attitude farther north is unknown. The stratigraphy of the Worm intrusion is very similar to that of the Happy Face lobe in the North intrusion (Figure 22), and the Worm intrusion is likely continuous with it, and perhaps represents a more steeply inclined extension of it. As discussed, the three lobes of the North intrusion can be correlated, but there are significant primary variations in stratigraphy from place to place. There is evidence for some weak deformation of the 1322 Ma North intrusion, producing a gentle north-plunging fold structure, and this must also have affected the South intrusion and Mineral Hill intrusions. However, it is difficult to separate original variations in thickness and attitude from possible later effects.

MAGMATIC SULPHIDE MINERALIZATION

OVERVIEW

Magmatic sulphide mineralization was first noted by Thomas and Morrison (1991), who described the gossan zone at Mineral Hill, and also noted rusty zones to the west of Sarah Lake. In 1995, Landsat Thematic Mapper images led to the identification of nearly 1700 potential gossans (von Einsiedel and St. Hilaire, 1996), most of which were not related to sulphides. However, several of the strongest colour anomalies were related to disseminated sulphide mineralization hosted by mafic igneous rocks. The principal surface showings known as the NDT, Major General and GG zones were discovered and sampled at this time, and the Mineral Hill zone was also investigated and sampled. Numerous other (generally smaller) surface showings associated with mafic rocks were also located in the area north and east of Pants Lake. All of these areas were investigated in detail during 1996, and the surface showings were eventually tested by drilling.

Initial geological work in 1996 confirmed that all the main surface showings were associated with the basal contact(s) of sheet-like mafic units, and in particular were situated below fine-grained olivine gabbro. Drilling around the surface showings provided a better understanding of the location and continuity of mineralization. Drilling of EM anomalies within areas underlain by massive mafic rocks, including the massive leucogabbro unit, demonstrated the existence of similar, blind sulphide mineralization elsewhere in the North intrusion. In 1997, drilling in the northern part of the Taheke Lake lobe of the North intrusion encountered disseminated and massive sulphide mineralization beneath 100 to 200 m of barren gabbro; this area became known as the Northern Abitibi zone (in reference to the name of the joint venture partner) and was intensely explored during 1998. Mineralization was also discovered by deep drilling at the base of the South intrusion during 1997 and 1998. There are virtually no surface exposures of mineralization in either of these areas.

Although sulphide mineralization throughout the PLI is closely associated with basal contact regions, there are some important differences in the character of mineralization from place to place. For this reason, the various component bodies are treated separately in this section. The best-known mineralization is in the North intrusion, where a distinct 'package' of basal sulphide-bearing rocks (termed the mineralized sequence) displays remarkable stratigraphic consistency. However, there are some subtle variations in the character of the mineralized sequence among the various lobes of the North intrusion, and between the main part of the body and other areas such as Mineral Hill. Mineralization in the South intrusion is associated with mafic cumulate rocks, and its setting is therefore different, as are the associated silicate rocks. In this section of the report, the primary emphasis is on describing the setting, field relationships and textural characteristics of the sulphide mineralization, with some reference to concentrations of Ni, Cu and Co in mineralized rocks. The data for Ni and Cu are discussed both in raw format, and also as sulphide metal contents. The latter represent calculated estimates of the Ni and Cu contents of magmatic sulphide liquids, and are derived using an estimate of the mass-fraction of sulphides, provided by analysis of elemental sulphur. The data are corrected for metals present in non-sulphide minerals, *e.g.*, Ni contained in olivine. This is a widely used procedure in the study of magmatic sulphide deposits. For a discussion of the method, and some of the limitations upon it, readers are referred to Kerr (2003). A more detailed discussion of the major- and trace-element geochemistry of mineralized rocks is presented in the section entitled '*Geochemistry*'.

MINERALIZATION IN THE SOUTH INTRUSION

The South intrusion mineralized sequence is mostly known from drilling, although some weakly mineralized outcrops on the east side of the intrusion likely form part of its surface expression. Holes SVB-97-79 and 98-100 (Figure 24), encountered mineralization in mafic and ultramafic cumulate rocks near the base of the intrusion, as did hole 97-86. A fourth drillhole (SVB-97-89) recovered a short intersection of sulphide-bearing gabbroic rocks, before entering a very thick sequence of coarse-grained anorthosite and leuconorite, interpreted as part of the nearby HLIS. These four holes outline an area of approximately 5 km^2, the interior of which remains untested. Hole SVB-98-136, drilled in the Pants River valley (Figure 11), did not intersect any thick sequences of mafic rocks, and is believed to have been collared below the basal contact of the South intrusion, as outlined in the preceding chapter. It intersected 36 m of mafic rocks, containing minor sulphides toward the basal contact. The relationship of this thin zone to the remainder of the South intrusion is unknown. Falconbridge drilled several holes north of the Pants River in 2002, all of which intersected sulphide mineralization associated with identical mafic cumulates near the basal contact. Thus, mineralized rocks exist at the base of the South intrusion on a regional scale.

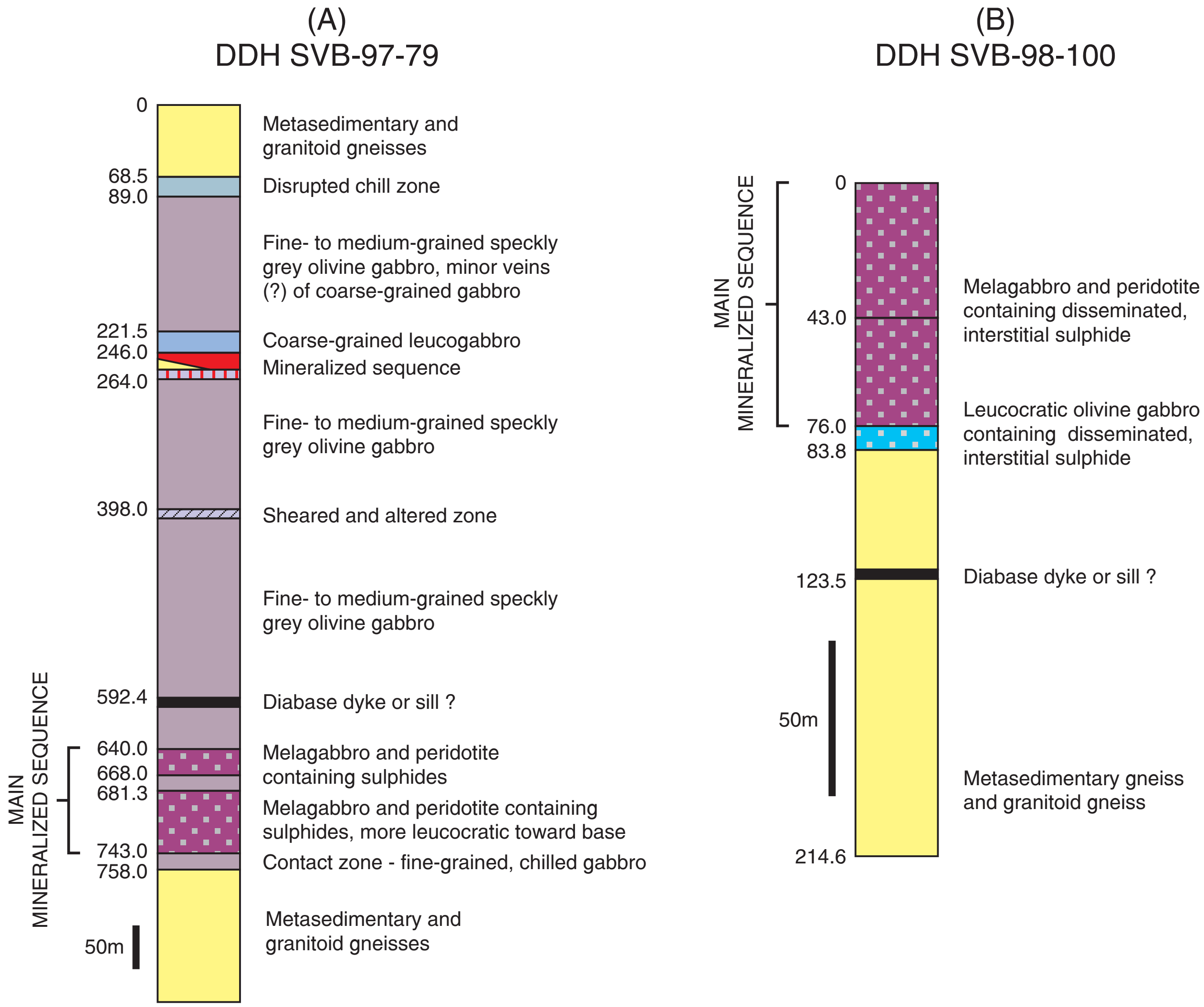


Figure 24. *A. Schematic illustration of the South intrusion mineralized sequence in the wider context of the deep hole SVB-97-79. B. More detailed view of the South intrusion mineralized sequence as seen in hole SVB-98-100.*

Mineralized Intersections

Hole SVB-97-79 intersected two discrete mafic–ultramafic intervals, consisting of mineralized melatroctolite and melagabbro, at the base of the South intrusion (Figure 24). The upper interval, which is about 28 m thick, is only weakly mineralized (mostly <3% sulphides). The sulphides are dominantly pyrrhotite and chalcopyrite, and no pentlandite is visible to the naked eye; the sulphide grains are clearly interstitial with respect to all silicate minerals (Plate 23A, B). The lower interval, which is over 50 m thick, contains a higher proportion (locally 30 to 50%, generally 5 to 15%) of sulphide, with a similar interstitial habit (Plate 23B). Interstitial sulphide patches are locally up to 4 cm across, and locally contain visible pentlandite. The host rocks are generally homogeneous, but contain numerous, partially digested, blue-grey to white gneissic fragments, some of which show light-coloured reaction rims (Plate 23A). These have not been examined in thin section, but by analogy with identical fragments observed in the North intrusion these likely contain corundum–spinel–plagioclase assemblages. The most sulphide-rich rocks, at the very base of the sequence, are gabbroic rather than melagabbroic. These rocks eventually fade into a medium-grained, barren gabbro, which is chilled against footwall gneisses. The nearby hole SVB-97-86 intersected a very similar sequence, including almost 90 m of variably mineralized rocks, again distributed in two distinct zones. In each of these zones, there appears to be a distinct downhole increase in the amounts of sulphides and gneissic fragments. Hole SVB-98-100 provided only a short (84 m) intersection, consisting of mafic and ultramafic cumulates containing interstitial sulphides, and a basal zone of more leucocratic composition. Hole SVB-97-89 recovered about 15 m of medium- to coarse-grained gabbro containing interstitial sulphides, but did not contain mafic and ultramafic cumulate rocks. The mineralized gabbro generally resembles the rock type encountered at the bases of holes SVB-97-79, -89 and -100.

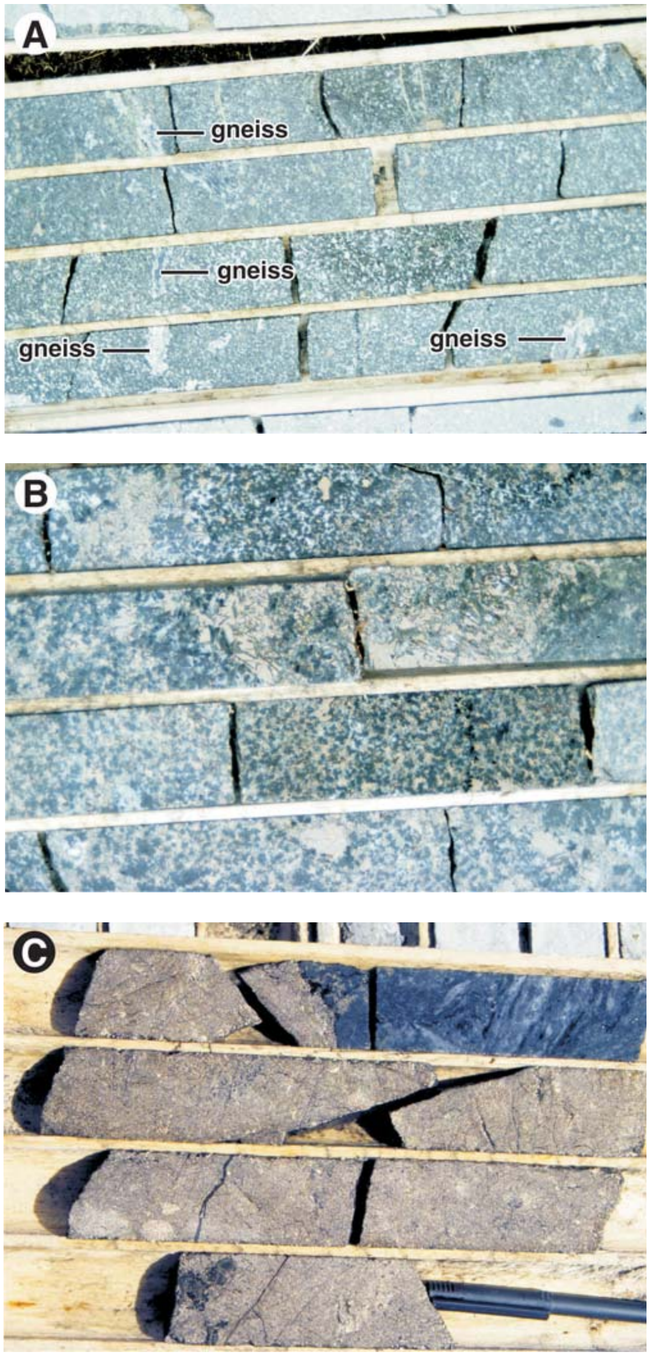


Plate 23. *A. Melagabbro containing interstitial sulphides (bronze colour) and abundant digested gneissic fragments, hole SVB-97-79. B. Gabbro containing more abundant interstitial sulphides, from the base of hole SVB-97-79. Drillcores are approximately 4 cm in diameter. C. Massive sulphides from a thin intersection in gneisses below the base of the South intrusion, hole SVB-02-138.*

Assay Results and Metal Contents

The disseminated sulphide mineralization in the South intrusion has unremarkable absolute grades of 0.1 to 0.55% Ni, and 0.1 to 0.32% Cu (Fitzpatrick *et al.*, 1998; Geological Survey data), and these values correspond to low amounts of sulphide. Rocks in the uppermost part of the sequence, where the proportions of sulphide are very small, were not always assayed during exploration. The most complete dataset comes from hole SVB-97-79, where recalculated metal contents at 100% sulphide (sulphide metal contents; *see* Appendix for explanation of calculation procedures) range from 0.7% to 4.0 % Ni, and 0.4% to 1.5% Cu (Table 1; Figure 25). In the upper section of hole SVB-97-79, where sulphides are less abundant, the sulphide metal contents are highest, typically 2.0 to 4.0% Ni and 0.7 to 1.4% Cu. This part of the sequence also shows higher Ni/Cu ratios (>2) than most PLI mineralization. There is a steady decrease in sulphide nickel contents toward the base of the drillhole, and no obvious correlation between sulphide metal contents and the amount of sulphide (Figure 25). However, the basal units are relatively metal-poor, with sulphide metal contents of only 0.7% Cu and 0.4% Ni. The values here resemble those from the thin zone of mineralization in the uppermost part of the hole (above 260 m), where sulphides contain only about 0.5% Ni (Table 1). Hole SVB-97-86 shows a trend similar to SVB-97-79 in the lower part of the mineralized sequence. The upper part of the sequence in this hole was not assayed, and there are no data available from hole SVB-98-100, which was not assayed (Fitzpatrick *et al.*, 1998). Assay data from holes drilled by Falconbridge north of the Pants River resemble the profiles illustrated in Figure 25. Falconbridge did, however, intersect some thin zones of massive sulphides at the base of the gabbro, and in the underlying gneisses (Plate 23C).

Mineralization in hole SVB-97-89 has sulphide Ni contents in the upper range, and shows some signs of copper enrichment, particularly at the base (Table 1). Nickel/copper ratios are typically slightly over 1.0 in most parts of the sequence, except for the Ni-enriched section in hole SVB-97-79 (Figure 25). The correlation between Ni and Cu is illustrated in Figure 26.

MINERALIZATION IN THE NORTH INTRUSION

Introduction

Mineralization in the North intrusion is vastly more complex than in the South intrusion, and a different approach to its description and interpretation is required. Surface mineralization is exposed mostly along the southern boundary of the North intrusion, and includes the NDT, Happy Face, GG Zone and Major General surface showings, as well as several smaller zones. Significant sulphide mineralization also forms

Table 1. Summary of assay results from South intrusion mineralization

Sample ID	From (m)	To (m)	Length (m)	Co (ppm)	Ni (ppm)	Cu (ppm)	S (%)
Drillhole SVB-97-79							
75252	257.00	257.30	0.30	1400	3480	2480	32.30
75253	257.30	259.00	1.70	283	847	1610	4.95
Avg. (2 m)	257.00	259.00	2.00	450	1242	1740	9.05
13701	649.00	650.50	1.50	177	1140	357	1.36
13702	650.50	652.00	1.50	173	1200	325	0.97
13703	652.00	653.50	1.50	176	1260	371	1.11
13704	653.50	655.00	1.50	185	1150	419	1.32
13705	655.00	656.30	1.30	195	1350	449	1.32
13706	692.00	693.50	1.50	154	868	287	0.94
13707	693.50	695.00	1.50	155	1070	343	1.07
13708	695.00	696.50	1.50	158	1080	398	1.17
13709	696.50	698.00	1.50	157	1070	472	1.42
13710	698.00	699.40	1.40	167	1250	547	1.41
13711	699.40	701.00	1.60	195	1310	802	2.32
11001	723.00	724.50	1.50	232	1650	1250	3.95
11002	724.50	726.00	1.50	301	2110	1440	5.14
11003	726.00	727.50	1.50	369	2560	1910	6.58
11004	727.50	729.00	1.50	287	2080	1610	5.03
11005	729.00	730.50	1.50	410	3180	2240	8.52
11006	730.50	732.00	1.50	405	3150	2210	8.60
11007	732.00	733.50	1.50	540	4150	2680	11.80
11008	733.50	735.00	1.50	551	3810	3600	11.70
11009	735.00	736.50	1.50	612	4240	3200	13.60
11010	736.50	738.00	1.50	611	4480	2640	13.20
11011	738.00	739.50	1.50	505	3610	3140	12.10
11012	739.50	740.50	1.00	438	3210	2750	11.00
11013	740.50	742.50	2.00	226	1090	994	4.11
Avg. (16 m)	724.50	740.50	16.00	457	3325	2493	9.75
Drillhole SVB-97-86							
13712	625.90	627.40	1.50	194	1660	795	1.71
13713	627.40	628.80	1.40	199	1590	851	2.07
13714	628.80	630.30	1.50	194	1460	734	2.09
13715	630.30	631.80	1.50	208	1630	807	2.01
13716	631.80	632.80	1.00	212	1650	1090	2.44
13717	632.80	633.90	1.10	216	1870	1040	2.37
13718	633.90	635.40	1.50	195	1800	1070	2.43
13719	635.40	636.90	1.50	153	1040	806	1.97
13720	636.90	638.40	1.50	165	1010	831	2.30
13721	638.40	639.90	1.50	164	1030	874	2.54
13722	639.90	641.40	1.50	190	1230	660	2.89
13723	641.40	642.90	1.50	263	1920	1050	2.66
13724	642.90	644.40	1.50	186	1080	884	2.48
13725	644.40	645.05	0.65	256	1390	887	3.86
16851	645.05	645.65	0.60	1010	4530	2460	21.30
16852	645.65	646.70	1.05	183	1320	1250	3.20
16853	646.70	646.90	0.20	1100	5480	3140	27.10
Avg. (21 m)	625.90	646.90	21.00	228	1563	961	3.17
Drillhole SVB-97-89							
16679	10.10	11.60	1.50	156	1280	938	1.61
16680	11.60	13.10	1.50	439	4000	1890	6.21
16681	13.10	14.60	1.50	312	3220	2030	4.65
16682	14.60	16.10	1.50	254	3060	2160	4.15
16683	16.10	17.60	1.50	244	3060	2360	3.97
16684	17.60	19.10	1.50	191	2890	2720	3.74
16685	19.10	20.60	1.50	104	1500	1690	1.64
16686	20.60	22.10	1.50	51	402	447	0.37
16687	22.10	23.60	1.50	91	2650	2350	2.15
16688	23.60	24.30	0.70	75	3470	6130	1.88
Avg. (14.2 m)	10.10	24.30	14.20	198	2502	2054	3.10
Drillhole SVB-02-137							
n/a	397.47	399.00	1.53	200	2700	2300	3.81
n/a	399.00	399.86	0.86	300	2400	1900	3.87
n/a	399.86	400.71	0.85	700	4200	2700	11.37
n/a	400.71	401.53	0.82	1000	6200	3700	23.72
n/a	401.53	402.29	0.76	300	1700	3900	6.32
n/a	402.29	402.75	0.46	1300	8500	4600	29.30
n/a	402.75	403.62	0.87	300	3500	2400	13.35
n/a	403.62	404.50	0.88	800	4200	3400	16.98
n/a	404.50	405.34	0.84	1300	8400	5100	27.73
Avg. (7.87 m)	397.47	405.34	7.87	618	4301	3167	13.52
Drillhole SVB-02-138							
n/a	264.52	264.80	0.28	1300	9800	1700	27.01
n/a	264.80	266.00	1.20	300	2100	1300	4.51
n/a	270.37	270.87	0.50	600	4900	3200	8.86
n/a	271.62	272.55	0.93	300	2000	2400	7.01
n/a	272.55	273.10	0.55	900	6000	5300	20.55
n/a	273.10	274.00	0.90	300	2400	1600	6.43
n/a	274.00	275.00	1.00	300	2400	2300	4.83
n/a	275.00	276.00	1.00	300	2600	6500	5.78
n/a	276.00	277.00	1.00	400	4000	2400	7.59
n/a	277.00	278.00	1.00	200	2300	1900	3.53
Avg. (8.36)	264.52	278.00	13.48	391	3150	2790	7.50
n/a	281.38	281.83	0.45	400	7000	3400	7.53
n/a	282.39	282.79	0.40	800	13100	5800	9.75
n/a	297.74	298.51	0.77	1600	13700	6400	34.79

NOTES

Data from Fitzpatrick *et al.* (1998, 1999) assessment reports; sample numbers (where reported) are those listed in assessment reports

Data for holes SVB-02-137 and SVB-02-138 are from a press release issued by Donner Minerals and Falconbridge Canada (October 30, 2002); data for Co, Ni and Cu were reported in % and have been reconverted to ppm (± 50 ppm)

the blind target known as the Northern Abitibi area (Figure 9). However, mineralization is not restricted to these localities, as almost every drillhole that penetrates the basal contact encountered at least some sulphides.

Mineralization in the North intrusion is, in all cases, associated with a distinctive package of variably sulphide-bearing mafic rocks at the base of the intrusion. This mineralized sequence displays a remarkably consistent stratigraphic pattern, and a detailed account of its features is required before individual zones of sulphide mineralization can be documented. The first part of this section thus outlines the general anatomy of the mineralized sequence, and describes the distinctive rock types that occur within it. This is followed by an account of mineralization in the three lobes of the North intrusion as revealed both by surface exposures and drillhole information. The mineralized sequence of the North intrusion was also the principal topic of the thesis study by Smith (2006), who proposed a fourfold division of its rock types. Although these, in part, correspond to subdivisions outlined

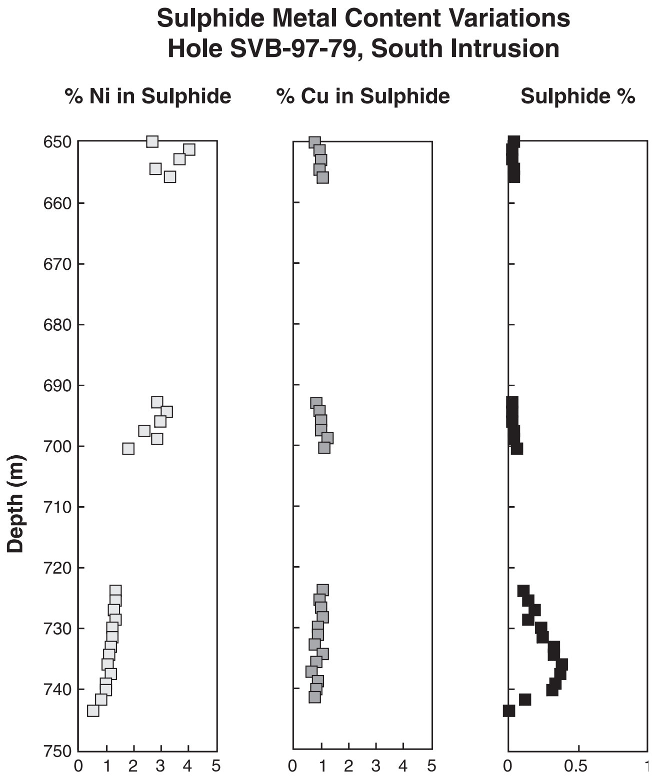


Figure 25. *Variation of Ni in sulphides, Cu in sulphides and total sulphide content against depth in hole SVB-97-79.*

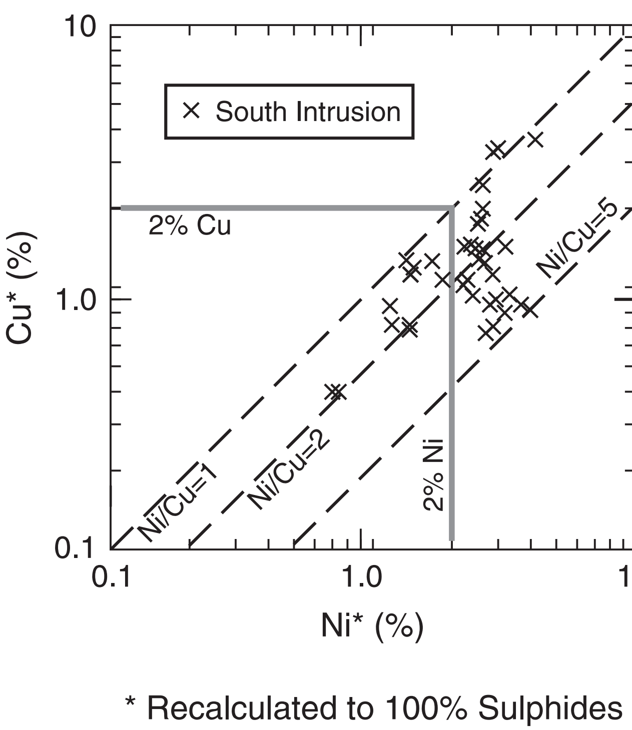


Figure 26. *Variation of Ni and Cu in the sulphides of the South intrusion mineralized sequence. Recalculation of sulphide metal contents after Kerr (2001, 2003b).*

below, Smith (2006) described and interpreted them in more general terms. The conclusion of Smith (2006), *i.e.*, that the mineralized sequence recorded the effects of country-rock contamination and sulphide liquid segregation, are the same as those outlined in this report and in earlier publications (Kerr, 1999, 2003a).

General Characteristics of the Mineralized Sequence

Surface exposures of the mineralized sequence are present at all of the main surface showings along the southern boundary of the North intrusion (Figure 9). It is difficult to document geological relationships or obtain fresh samples in these areas, as the extensive gossan development obscures most details. However, all these surface showings share some common features. All are very close to the basal contact of the intrusion, which generally sits on a mixture of metasedimentary gneiss and garnetiferous orthogneiss. The underlying gneisses locally contain small veins and pockets of sulphides, but are otherwise unmineralized. The mineralized sequence ranges from 3 to about 20 m in thickness. The lowermost mafic rocks, just above the contact, are barren, or contain only very minor amounts of sulphide. The sulphide-rich sections of the showings commonly contain an upper unit that weathers to egg-like or disc-like masses of unweathered rock, surrounded by a friable, recessive matrix. This is commonly underlain by rocks of more homogeneous appearance that commonly contain disseminated sulphide, where fresh material can locally be found. It is very difficult to estimate the amounts of sulphide. Locally, this lower unit develops a 'knobbly' weathering texture where unweathered (sulphide-free) nodules about 1 cm in diameter are set in a recessive, sulphide-bearing matrix. Where fresh, this rock is recognizable as 'leopard gabbro', consisting of clinopyroxene crystals in mineralized matrix; this rock type is discussed in more detail below. The sulphide-bearing rocks generally lie a short distance below unmineralized, massive, coarse-grained leucogabbro at surface localities, but there is commonly a thin zone of unmineralized or weakly mineralized fine-grained gabbro separating the mineralized rocks from the coarse-grained leucogabbro. At the NDT showing, the mineralized sequence is overlain by a much thicker sequence of fine-grained olivine gabbro.

Most of the information about the mineralized sequence comes from diamond-drill core, which provides fresh material and preserves original textures and geological relationships. Much of the following discussion is based on field and petrographic studies of core samples, in part, reported previously by Kerr (1998a, b, 1999). As discussed below, the mineralized sequence of the North intrusion is logically subdivided along the same lines as the intrusion itself because it shows subtle stratigraphic and compositional variation from lobe to lobe. However, all three lobes of the North intrusion contain essentially the same collection of rock types within the mineralized sequence that are present in a consistent stratigraphic arrangement. The upper part of the mineralized sequence, termed the heterogeneous subsequence, is dominated by heterogeneous, breccia-like rocks collectively termed composite gabbro. The distinctive egg-like weathering pattern developed in surface exposures reflects the concentration of easily weathered sulphides in the matrix of composite gabbro. This is underlain by the homogeneous subsequence, which contains gabbro and disseminated sulphides, 'leopard-textured' gabbro, barren gabbro and (locally) semimassive to massive sulphides. Idealized 'stratigraphic sections' through the mineralized sequence in various parts of the North intrusion are illustrated in Figure 27. Individual sequences may not contain all of the components indicated. The distinctive rock types are described and discussed below.

Composite Gabbro

The simple non-genetic term 'composite gabbro', is used in this report for an entire spectrum of distinctive rock types that generally form the upper part of the mineralized sequence, termed the heterogeneous subsequence. These rock types correspond to 'gabbroic pseudobreccia', 'inclusion gabbro' and, in part, the 'transition gabbro' as labelled by Smith and Wilton (1998) and Smith (2006), and which are simply gradational textural variants. Examples of typical composite gabbros (Plate 24A, B) amply illustrate their diversity and complexity, but all are clearly composed of discrete inclusion and matrix components. The inclusions consist of a dark-grey to green, fine-grained to aphanitic mafic rock that forms aligned 'bands' and lenses, commonly oriented subparallel to the basal contact of the intrusion (*i.e.*, perpendicular to the core axis in vertical drillholes). These bands and lenses represent ellipsoidal inclusions within a 'flattened' shape, a strong preferred alignment and variable amounts of imbrication; these features are suggestive of lateral flow. Although difficult to recognize where inclusions are large, flattening and imbrication are clearly visible in areas where the inclusions are smaller than the width of the drillcore (Plate 25A, B). The inclusions are surrounded by coarser grained matrix

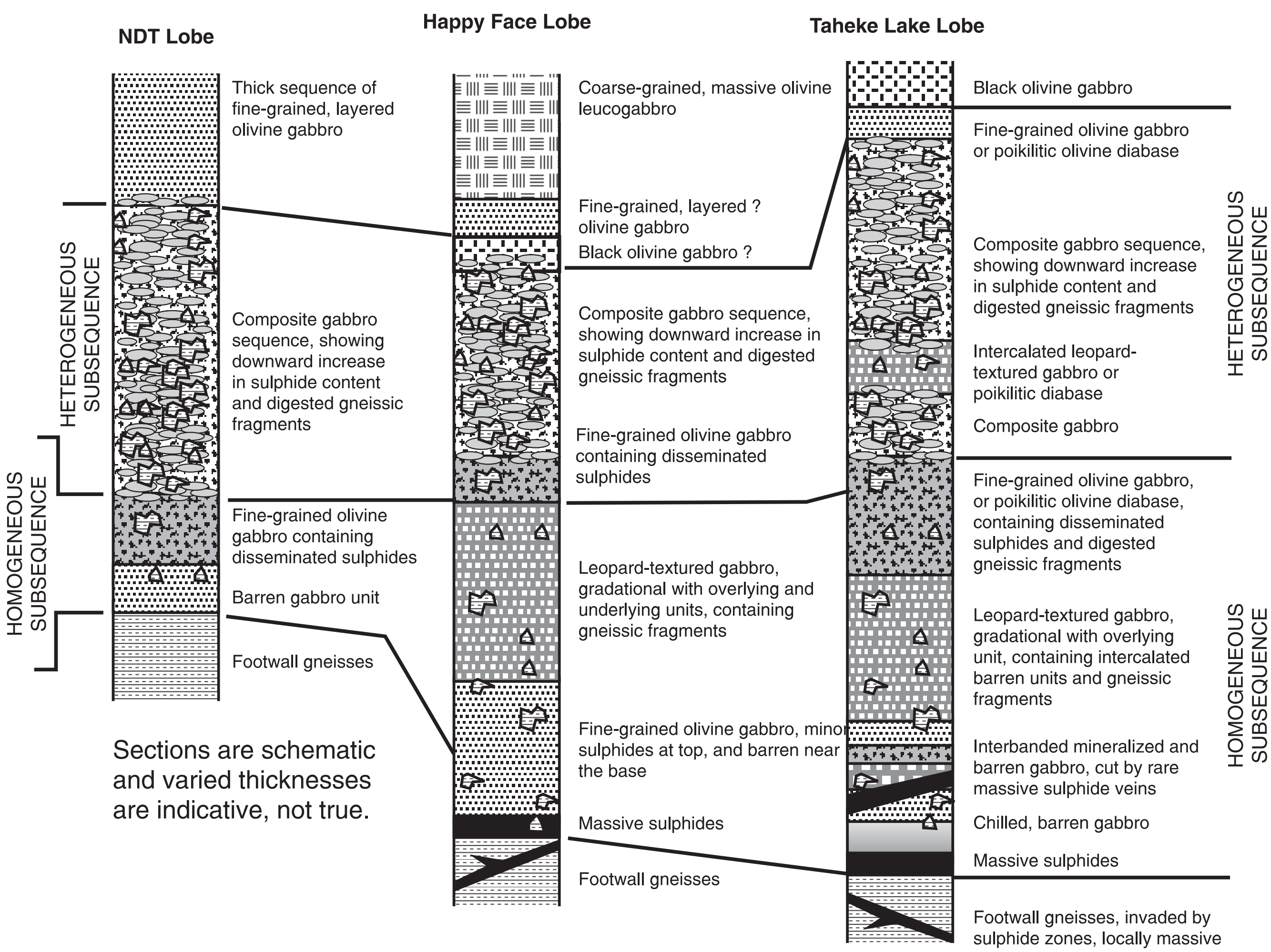


Figure 27. Schematic illustration of the stratigraphy of the North intrusion mineralized sequence, indicating variations among the three main lobes of the North intrusion.

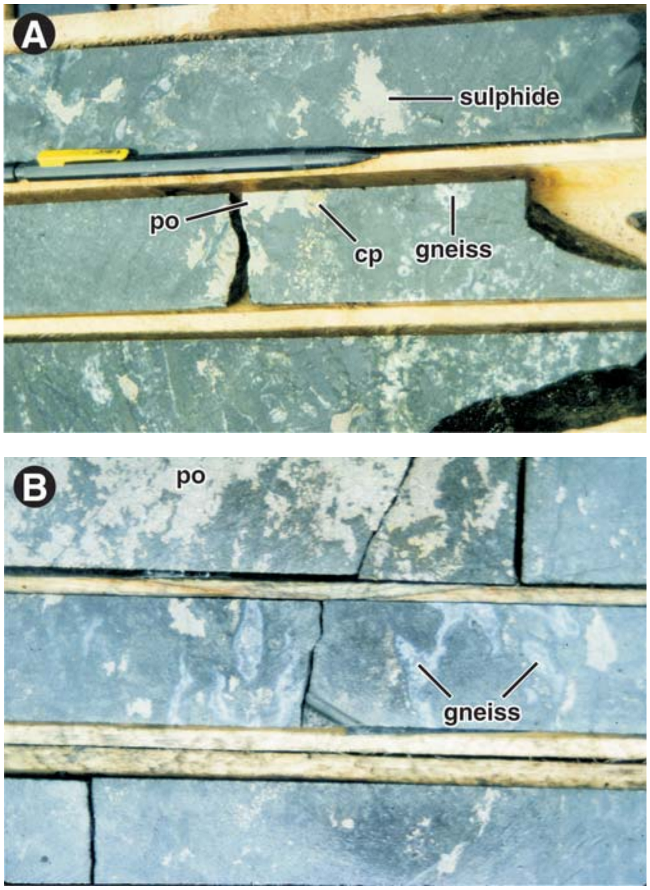


Plate 24. A. *Sulphide-bearing 'composite gabbro', containing coarse interstitial sulphide patches, hole SVB-96-04. B. Similar composite gabbro containing abundant bluish-white digested gneiss fragments, hole SVB-98-98 (po–pyrrhotite, cp–chalcopyrite). Drillcores approximately 4 cm in diameter.*

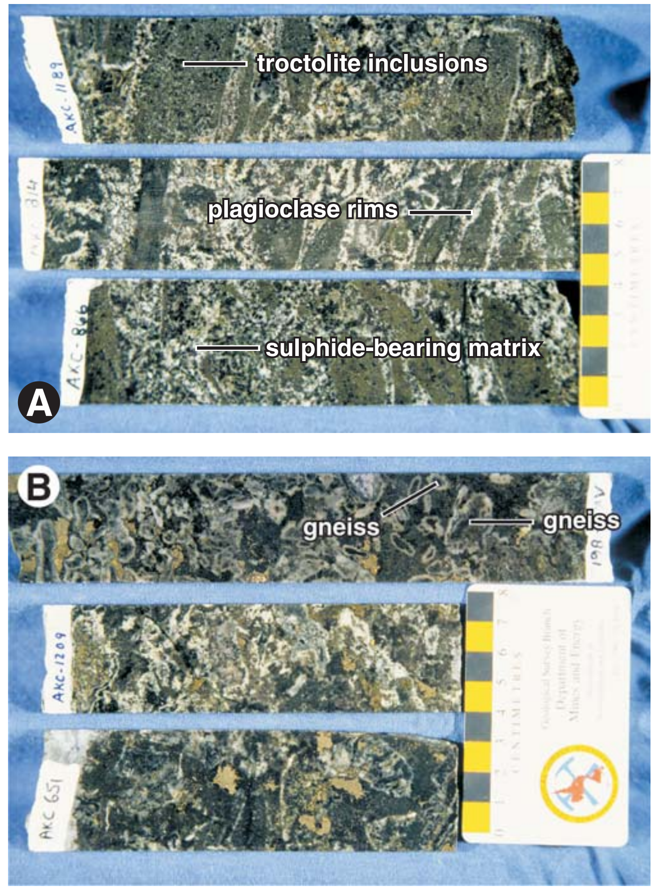


Plate 25. *A. Examples of sulphide-poor composite gabbros dominated by troctolitic inclusions in a gabbroic matrix. B. Examples of sulphide-rich composite gabbros also containing abundant digested gneissic fragments.*

material, which consists of a 2 to 10 mm intergrowth of white to dark-grey plagioclase, clinopyroxene and olivine, associated with large clots of sulphide (up to 5 cm across) that are complexly intergrown with the coarse matrix silicates (Plates 24 and 25). Fine-grained sulphide is locally present within the mafic inclusions, but all significant mineralization is associated with the coarser matrix. This accounts for the recessive weathering of the matrix in surface exposures. The inclusions in some composite gabbros are outlined by white, fine-grained, plagioclase rims. Although inclusions most commonly have an ellipsoidal, rounded form, there are local examples that contain angular fine-grained inclusions that have sharp external contacts, in a similar sulphide-bearing matrix; these examples have textures that are reminiscent of true intrusive breccias. There is also a spectrum, from rocks in which inclusion-matrix contacts are clear and sharp, to diffuse, blotchy rocks, in which the fine- and coarse-grained domains appear almost gradational and intermixed; this texture is referred to as 'curdled' (Plate 25A). The proportions of inclusions and matrix vary widely and, to use the analogous sedimentary terminology, composite gabbros can be viewed as either clast-supported or matrix-supported; relationships are usually clearer in the latter.

In addition to mafic inclusions, most composite gabbros contain round to flat or amoeboid gneissic inclusions that range from recognizable country-rock-types (*e.g.*, granitoid gneiss) to diffuse, fine-grained, grey-blue or white patches with dark reaction rims, or dark centres with pale-grey rims (Plates 24 and 25). These inclusions are mostly contained within the coarser matrix, but also locally appear to be within the fine-grained domains, thus representing inclusions within inclusions. The amount of such debris varies widely, and in gneiss-rich examples, it becomes very difficult to discern fragment–matrix relationships (Plate 25B), or even to separate such rocks from true gneisses cut by mafic veins. In most cases, the amount of gneissic debris appears to be greater in the lower part of the heterogeneous subsequence, and this is accompanied by a general increase in the proportion of sulphides. Conversely, composite gabbro toward the top of the sequence is commonly sulphide-poor or entirely barren. However, strong local variations in fragment and sulphide abundance are superimposed on this general trend (Figure 27). The larger gneissic fragments locally contain discordant vein-style sulphide mineralization, which is distinct from the interstitial style of the matrix sulphides, and is locally chalcopyrite-rich. In addition to fragments of mineralized silicate rocks, composite gabbros may also contain exotic sulphide inclusions. These are difficult to verify because solid sulphide immersed in a mafic magma cannot retain an angular form for long. A subangular to rounded patch of high-grade, copper-rich sulphide observed in composite gabbro with pyrrhotite-rich mineralization (Plate 26) is difficult to explain by any other process. This particular example is interpreted as a transported fragment of high-grade footwall mineralization akin to that encountered in hole SVB-97-75; Cu-rich veins in gneissic fragments likely represent the same type of source. An alternative explanation (T. Clarke, personal communication, 2003) is that such Cu-rich zones are of later, hydrothermal origin, but such features are rarely observed in rock types other than composite gabbro.

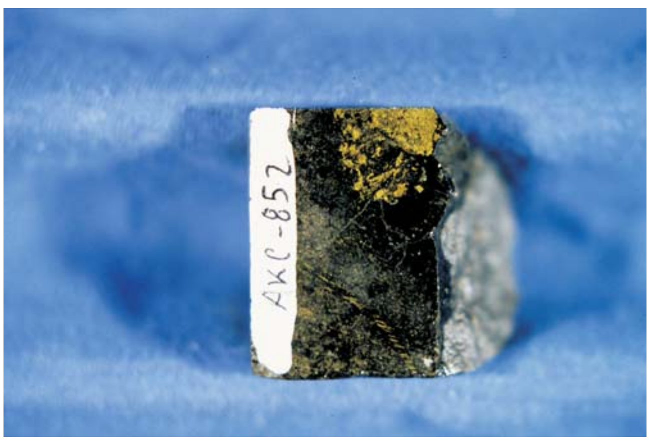


Plate 26. *Copper-rich sulphide inclusion within composite gabbro, hole SVB-97-70. This is interpreted to have been derived from fractionated sulphide veins in the footwall of the North intrusion. Drillcore is approximately 4 cm wide.*

Despite their complexity, most composite gabbros have common petrographic characteristics, illustrated in Plate 27. The fine-grained mafic inclusions normally consist of a granular olivine-rich gabbro or troctolite, dominated by tiny rounded olivines and later lath-like plagioclase, and lesser late subophitic clinopyroxene. The inclusions are texturally and mineralogically identical to the layered olivine gabbro (*see* section on *Geology and Petrology*), but generally finer grained. Their green colour in core samples reflects their high olivine content, and variable serpentinization. In addition to 'granular troctolite', some composite gabbros also contain inclusions of a fine-grained diabase-like rock containing poikilitic clinopyroxene and olivine, which closely resembles 'poikilitic olivine diabase' (*see* earlier sections for details; this rock type is considered to be the fine-grained equivalent of black olivine gabbro). More rarely, this is the dominant or only inclusion component. One example from the NDT lobe contains inclusions of fine-grained hypersthene-rich norite, which is completely unknown elsewhere in the PLI. The coarser grained gabbroic matrix typically consists of plagioclase, purplish clinopyroxene and grey-green olivine, with variable amounts of biotite, magnetite and sulphides; olivine forms late subophitic to poikilitic crystals. The matrix texture is very similar to that of the massive leucogabbro and black olivine gabbro. The similarity of this matrix to black olivine gabbro is locally very striking. Sulphides, where present, are interstitial to all silicates, and commonly occur in the coarsest parts of the matrix, where they are locally associated with biotite. Pyrrhotite and chalcopyrite are the most common sulphide minerals, although visible coarse pentlandite is present in some larger clots. The textures of fine-grained 'inclusions' and coarser grained 'matrix' are entirely distinct, their mutual boundaries range from sharp (often marked by a thin rind of fine-grained plagioclase around the inclusion) to fuzzy and gradational. Locally, the coarse olivine in the matrix is optically continuous with the olivine in inclusions that have poikilitic textures, but it is never continuous with the olivine in the inclusions that have granular textures.

Larger gneissic fragments are dominated by fine-grained, strained, granular plagioclase, associated with variable amounts of quartz, cordierite corundum and spinel (Plate 28). The plagioclase and cordierite are difficult to separate optically, and proportions are hard to estimate. The fragments are locally surrounded by rims of dark-green, granular, hercynitic spinel. Locally, acicular corundum is present within plagioclase (and/or cordierite?) and is visibly replaced by the dark-green spinel (Plate 28A). There is also abundant 'cryptic' gneissic material, which appears as clumps and clots of strained, metamorphic plagioclase, commonly dusted with fine-grained, granular spinel. Digested gneissic material is present even within samples that lack visible fragments, where scattered individual crystals of strained plagioclase become incorporated as an integral part of the matrix igneous texture, *i.e.*, they are completely enclosed by oikocrystic olivine and pyroxene of magmatic origin (Plate 28B). Diffuse ring-like zones of dark-green spinel may represent the outlines of former gneissic fragments that have been almost entirely consumed. In other examples, all three dominant igneous phases (plagioclase, olivine and clinopyroxene) are riddled with anhedral spinel inclusions (Plate 28B). These textures are regarded as the final stage in the assimilation process, in which the spinel restite remains suspended in the magma.

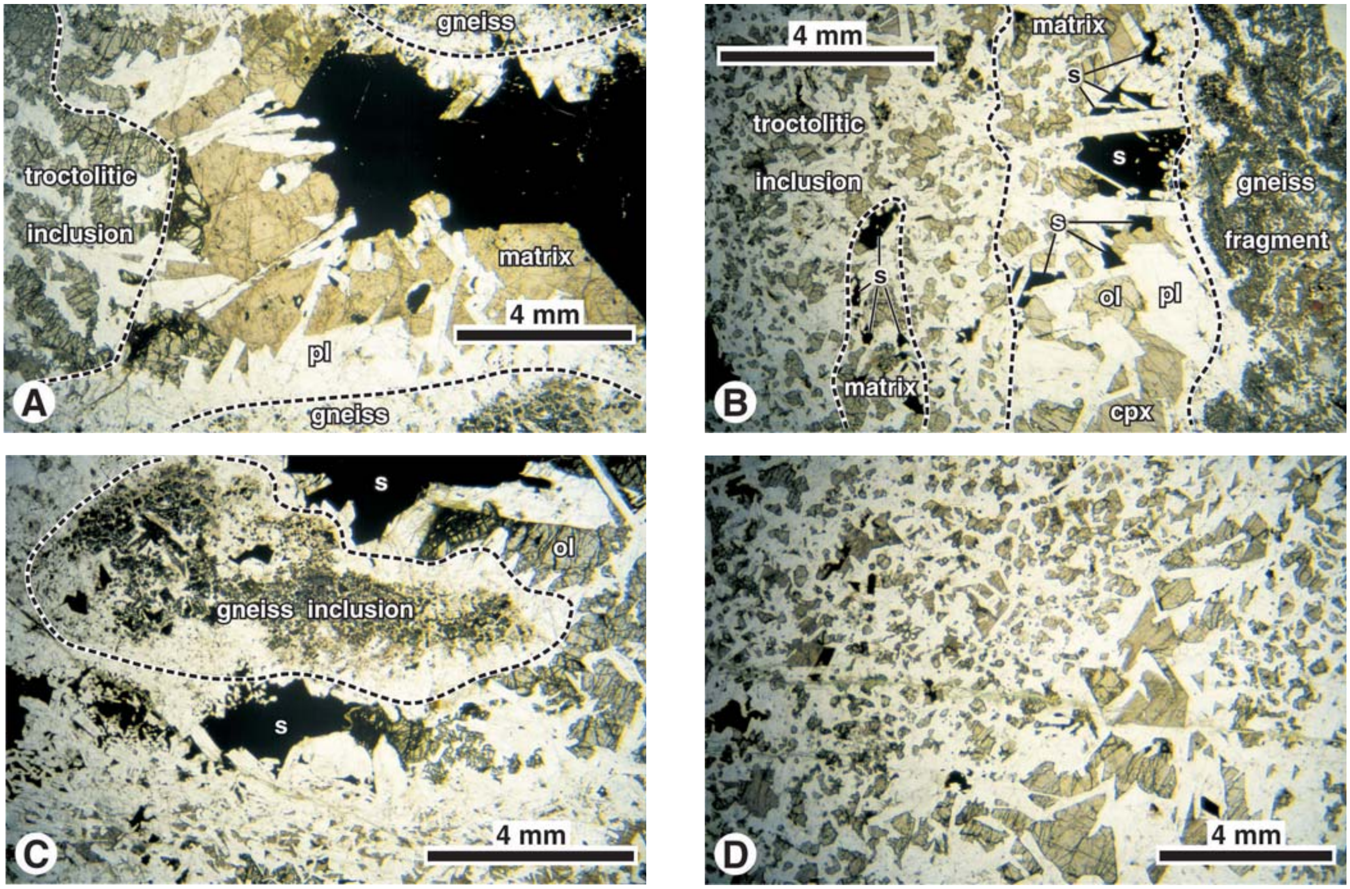


Plate 27. *Features of composite gabbros seen under the microscope. A. Coarse-grained sulphide-bearing matrix (most of picture) containing interstitial olivine. Gneissic fragments visible at top and bottom; granular olivine in a mafic inclusion visible at left. B. Textural contrasts of the three main components, visible from left to right. (1) fine-grained, granular troctolite, (2) coarse-grained, sulphide bearing gabbroic matrix and (3) gneissic inclusion consisting largely of spinel and plagioclase. C. Reacted gneiss inclusion, consisting of plagioclase, corundum and spinel, in sulphide-bearing matrix. D. Small-scale textural variation in sulphide-free composite gabbro that probably reflects more extensive mixing; note the granular and interstitial olivine habits typical of fine-grained and coarse-grained domains, respectively. All photos taken in PPL (PPL–plane polarized light, pl–plagioclase, s–sulphide, ol–olivine, cpz–clinopyroxene.*

Leopard Gabbro and Related Rock Types

The heterogeneous subsequence is in almost all cases underlain by more homogeneous, fine- to medium-grained gabbroic rocks, which contain disseminated sulphide mineralization that exhibits varied textures. The 'leopard gabbro' is the most distinctive example and has a textural (but not necessarily a direct genetic) equivalent in the 'leopard troctolite' at Voisey's Bay (Naldrett *et al.*, 1996). The leopard gabbro was recognized at an early stage in the exploration program (Wares, 1997), and was regarded as a positive indication of similarities to the Voisey's Bay area. In reality, the leopard gabbro is just one variant of a range of gabbroic rocks containing disseminated, interstitial mineralization, and it is entirely gradational with these closely related rock types. These rocks collectively define the homogeneous subsequence (Figure 27).

Examples of leopard gabbro from hole SVB-96-02 at the GG showing were described and illustrated by Kerr (1998a) as a mixture of oikocrystic clinopyroxene and sulphide-bearing (5 to 20% sulphide) troctolitic groundmass (Plate 29). Examples from other areas all fit this basic description, with some variations. Texturally, the leopard gabbro is very similar to the unmineralized, fine-grained, layered olivine gabbro that forms the lower part of much of the North intrusion (*see Geology and Petrology*). Olivine is largely of granular, cumulus habit, suggesting early crystallization, and the larger clinopyroxene oikocrysts are simply larger versions of late subophitic clinopyroxene crystals seen in all other fine-grained gabbro samples (Plates 14B and 29A). The equivalent texture (minus the sulphide, and therefore less striking) is also locally developed outside the mineralized sequence. The larger clinopyroxene crystals rarely (if ever) contain sulphide, but commonly include plagioclase laths and olivine grains. Sul-

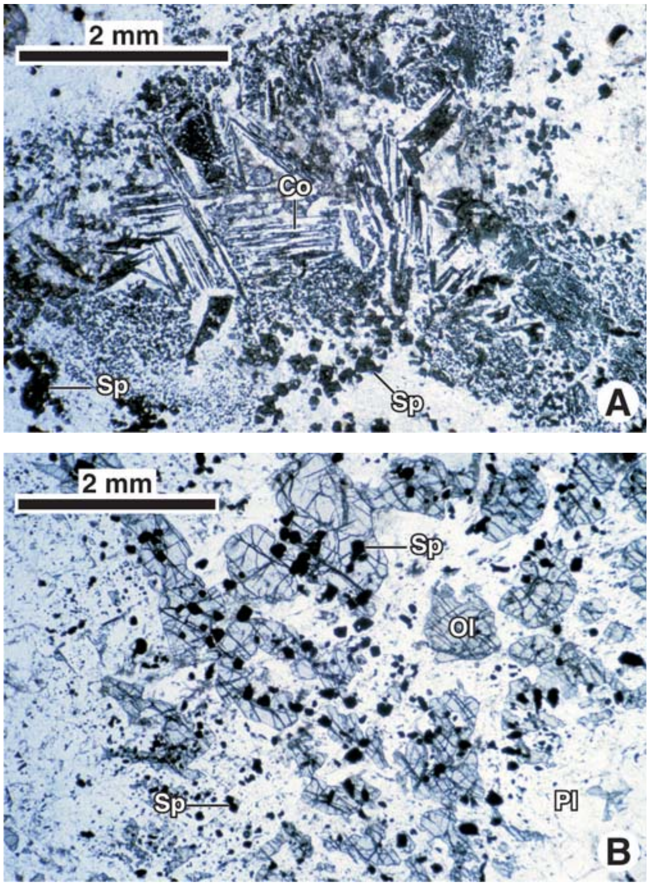


Plate 28. *Features of gneissic inclusions seen under the microscope, all photos in PPL. A. Inclusion consisting of plagioclase, corundum and spinel, in which acicular corundum appears to pseudomorph original cordierite sector twinning. B. Granular spinel (dark spots) dispersed through igneous minerals (mostly plagioclase and olivine) in the matrix of composite gabbro; the spinel is interpreted as "restite" from disaggregated and digested gneissic fragments (PPL–plane polarized light, sp–spinel, co–corundum, ol–olivine, pl–plagioclase).*

phides are mostly confined to the groundmass as a late-crystallizing interstitial phase (Plate 30A), but larger patches also occur, and these patches contrast texturally with the groundmass (Plate 30B, C). Some were originally suggested to be resorbed exotic sulphide fragments (Kerr, 1998a), but this is hard to prove, as they could equally represent coalesced sulphide droplets. Indeed, many leopard gabbros have a strikingly bimodal size distribution for sulphides, in which the fine-grained interstitial sulphides contrasts markedly with larger patches up to 1 cm in diameter. A few larger sulphide clots are associated with coarse mafic silicates, including clinopyroxenes with orthopyroxene cores, which are unknown elsewhere in the PLI, and these might be of exotic origin. However, many other rounded sulphide masses in these

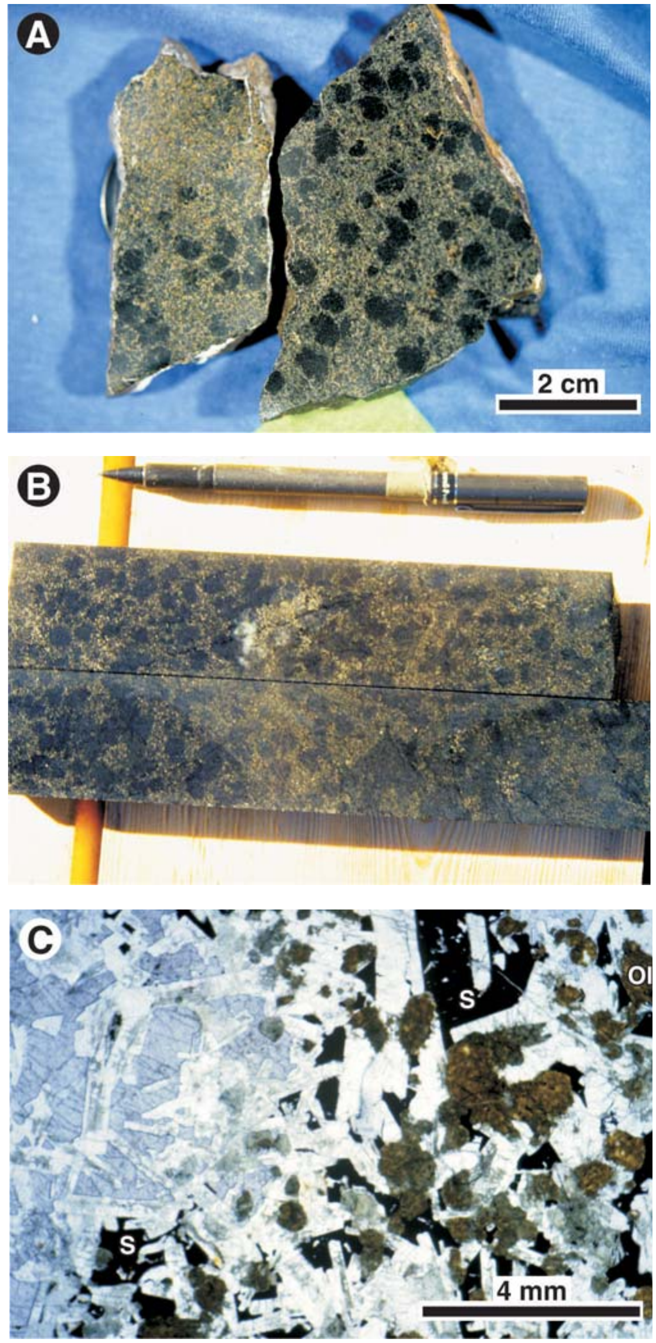


Plate 29. *A. Leopard-textured gabbro from the area of the NDT showings; dark spots are clinopyroxene oikocrysts. Matrix is olivine, plagioclase and sulphide. Spots are up to 1 cm diameter. B. Leopard-textured gabbro in drillcore from the GG showing, hole SVB-96-02. C. Leopard-textured gabbro in thin section (PPL); photo shows part of clinopyroxene oikocryst at left, olivine-bearing matrix at lower right, and interstitial sulphides at upper right (PPL–plane polarized light, s–sulphide, ol–olivine).*

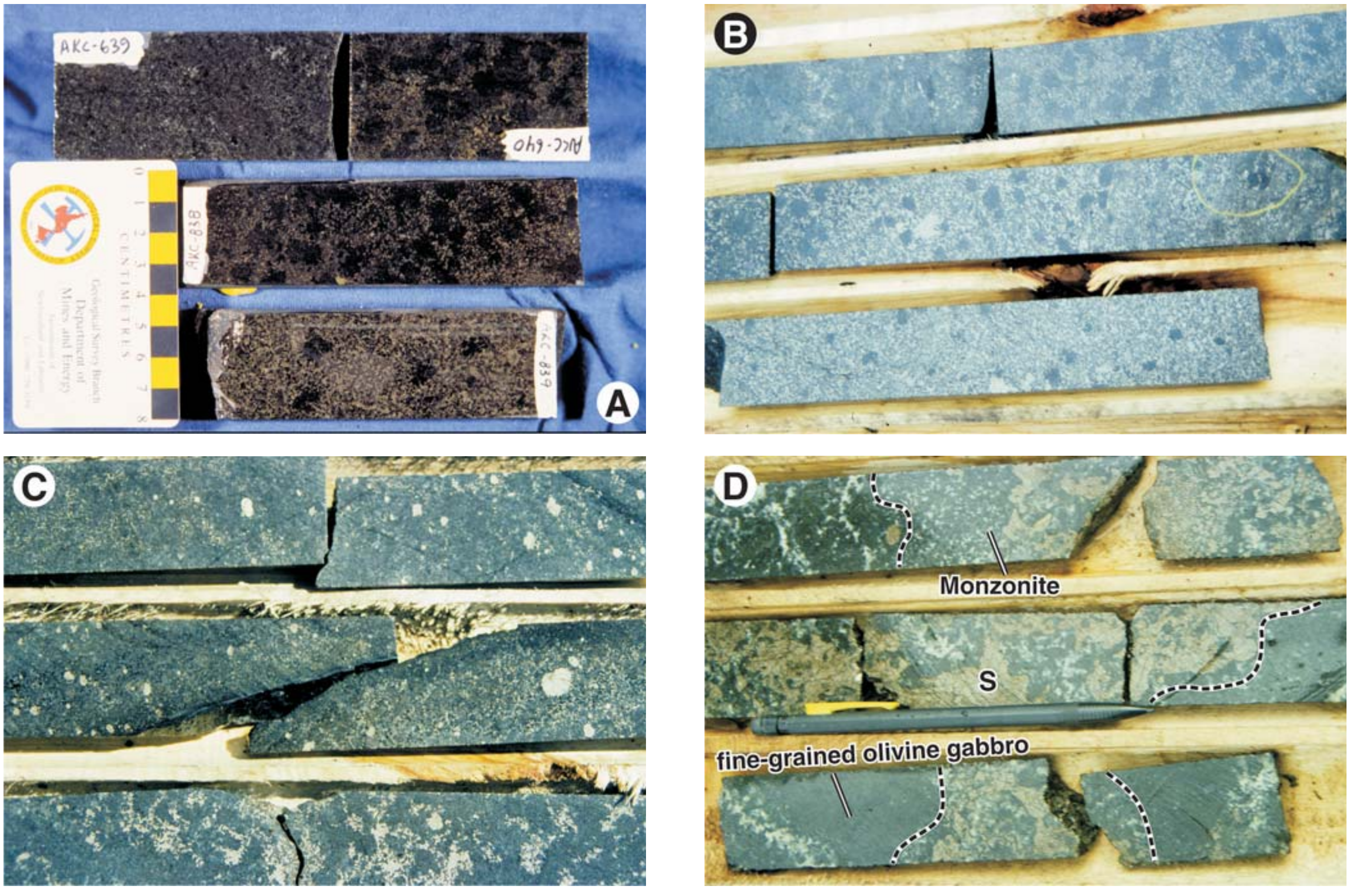


Plate 30. *A. Progressive development of leopard texture in samples containing variable amounts of sulphide from various drillholes in the North intrusion; all samples contain clinopyroxene oikocrysts, but they are simply more visible where sulphides are more abundant. B. Downhole gravitational accumulation of sulphides in leopard-textured gabbro from top left to bottom right, hole SVB-98-103B. Drillcore approximately 4 cm wide. C. Contrasting sulphide habits in fine-grained, homogeneous gabbros from the mineralized sequence; sulphide occurs both as fine interstitial material and larger rounded patches. D. Inclusions of a coarse-grained igneous rock containing vein-style sulphide mineralization, contained within essentially barren gabbro near the base of the mineralized sequence at the GG showing, hole SVB-96-43. These are interpreted as samples of footwall rocks invaded by sulphides (s–sulphide).*

rocks more likely represent coalesced or larger droplets of sulphide liquids.

Most leopard gabbro samples contain variably digested gneiss fragments, which resemble those in the overlying composite gabbro, and have similar reaction rims of granular hercynitic spinel. Clots of metamorphic plagioclase, integrated into the igneous texture, and anhedral spinel inclusions in primary igneous minerals, also provide local evidence for near-total digestion of gneissic inclusions. However, the proportion of xenolithic and digested material is much less than in the overlying heterogeneous subsequence, except close to their mutual boundary, where it may be high. The 'transition gabbro' of Smith and Wilton (1998) and Smith (2006) is simply a leopard gabbro with abundant gneissic fragments, sitting directly below fragment-rich composite gabbro.

The leopard gabbro is invariably gradational with fine-grained, sulphide-bearing gabbros containing dispersed magmatic sulphide (Plate 30A to C). Some of these gabbros also contain clinopyroxene oikocrysts, but simply lack sufficient sulphide to delineate them, whereas others contain only interstitial clinopyroxene, and are thus essentially identical to typical fine-grained olivine gabbro, with the addition of sulphides. All contain scattered digested fragments and/or sulphide patches larger than the dominant interstitial mineralization. In several drillholes (the best example is hole SVB-98-103 from the Northern Abitibi area), these rocks are interlayered with leopard gabbro, and it appears that the leopard gabbro formed by downward accumulation of sulphides through gravitational settling (Plate 30B). Hole SVB-98-103 contains at least two 'cyclic' units, in which virtually barren, fine-grained gabbro passes downward into disseminated sulphide, incipient leopard gabbro and eventually well-developed leopard gabbro; one of these units grades down into semi-massive sulphides that include clinopyroxene oikocrysts (Plate 30B). The evidence for gravitational sulphide accumulation suggests that the lower homogeneous subsequence represents a relatively tranquil magmatic environment compared to the upper heterogeneous subsequence.

Like the composite gabbro, the homogeneous mineralized rocks locally include recognizable fragments of other rock types that were previously mineralized. Hole SVB-96-43 at the GG zone contains xenoliths of coarse-grained clinopyroxene monzonite with interstitial granophyre, which contains magmatic sulphide veins, truncated by surrounding fine-grained gabbro (Plate 30). The xenoliths do not correspond to any known rock from the PLI, and are interpreted as older Mesoproterozoic igneous rocks containing footwall-style mineralization developed at some other (presumably deeper) location.

Mineralized Poikilitic Olivine Diabase

In most areas, the homogeneous subsequence is dominated by rocks such as the leopard gabbro, which are texturally akin to the fine-grained, layered olivine gabbro with cumulus olivine, as described above. However, mineralized poikilitic olivine diabase is also present locally, and may form cryptic units more widely within this part of the sequence. These fine-grained dark rocks are very hard to discriminate without thin-section data. Mineralized poikilitic olivine diabase is also an olivine gabbro, but it has a very different texture. Plagioclase laths are typically enclosed by a network of larger, poikilitic, olivine and clinopyroxene crystals (Plate 31A, B). Where recognizable in drillcore with the naked eye, this rock type is generally characterized by a blotchy, dark-grey and green appearance, as opposed to the even colouration of other fine-grained gabbros. The plagioclase is typically dark in drillcore and oxide-dusted in thin section, like that seen in the black olivine gabbro. Sulphide mineralization is interstitial and late, and also forms poikilitic crystals that include plagioclase. This rock type has a textural equivalent in fine-grained, diabase-like inclusions seen in some composite gabbros and it is also texturally akin to the composite gabbro matrix, albeit much finer grained. Unmineralized varieties are associated with the black olivine gabbro unit in the Taheke Lake lobe of the North intrusion. As with virtually all rocks in the mineralized sequence, it contains scattered, partly digested gneissic inclusions with the usual corundum-spinel reaction products.

Mineralized poikilitic olivine diabase was initially recognized in drillholes in the Northern Abitibi area, and has subsequently been recognized elsewhere. Its stratigraphic 'position' with respect to other components of the mineralized

Plate 31. *A. Mineralized poikilitic olivine diabase, considered to be the fine-grained equivalent of the black olivine gabbro. Bronze areas are sulphides. B. Thin section of poikilitic olivine diabase, showing distinctive interstitial habits of olivine, clinopyroxene and sulphide. The olivine and clinopyroxene crystals are actually large, optically continuous single crystals; hence the term 'poikilitic' (pl*–plagioclase, s–sulphide).

sequence is varied; in some cases it sits above the heterogeneous subsequence, but it is also commonly interlayered with leopard gabbro and related rocks in the lower, homogeneous subsequence. Whatever the exact relationship, it appears to have a close connection to the mineralized sequence.

Barren Fine-grained Olivine Gabbro

In most areas, the lowermost part of the mineralized sequence is a fine-grained, sulphide-free gabbro that appears to be gradational with the overlying mineralized rocks. Petrographically, the barren gabbro is identical to the fine-grained, layered olivine gabbro, and commonly contains granular, cumulus olivine. Chilled versions immediately adjacent to the footwall contact show diabase-like textures and ophitic clinopyroxene, which probably reflect rapid cooling.

Massive Sulphides

Massive sulphide (*i.e.*, >80% sulphide minerals) horizons, where present, are located very close to the footwall gneiss contact, and at least some are probably located below its original position, as they include gneissic inclusions, xenocrystic quartz, and graphite. The relationships between the massive sulphides and spatially associated mineralized gabbros are generally ambiguous. Thin massive sulphide veins are seen to cut overlying leopard gabbro and associated rock types (Plate 32D), and massive sulphides at the footwall contact are locally isolated from the remainder of the mineralized sequence by the chilled, barren gabbro described above. Veins of massive sulphides also commonly cut the gneisses below the footwall contact. These relationships collectively imply that sulphide liquids remained mobile after solidification of overlying rocks, and migrated along the footwall contact region. Although the absolute time difference is unconstrained, the massive sulphide zones are almost certainly genetically linked to other members of the mineralized sequence. Hole SVB-97-67 contains a massive sulphide zone with an unusual upper contact against gabbro that may actually be a chilled two-liquid boundary, as round blobs of sulphide are present in the overlying gabbro and vice-versa (Plate 32A). Very high-grade sulphide zones, such as the material with 11.7% Ni and 9.7% Cu from hole SVB-97-75 (Plate 32B) are presently known only from the footwall region; small zones of this type are particularly common in the Northern Abitibi drilling area. The highest grades reported from massive sulphides clearly associated with the gabbroic rocks above the contact region itself are 4.8% Ni and 2.6% Cu from a 20 cm zone in hole SVB-98-131.

Massive sulphides display considerable textural variation (Plate 32A to C). Some examples are coarse-grained, ‘clean’ sulphides consisting of pyrrhotite, chalcopyrite, and pentlandite (Plate 32A), which locally show ‘loop textures’ akin to those described from the Eastern Deeps deposit at Voisey’s

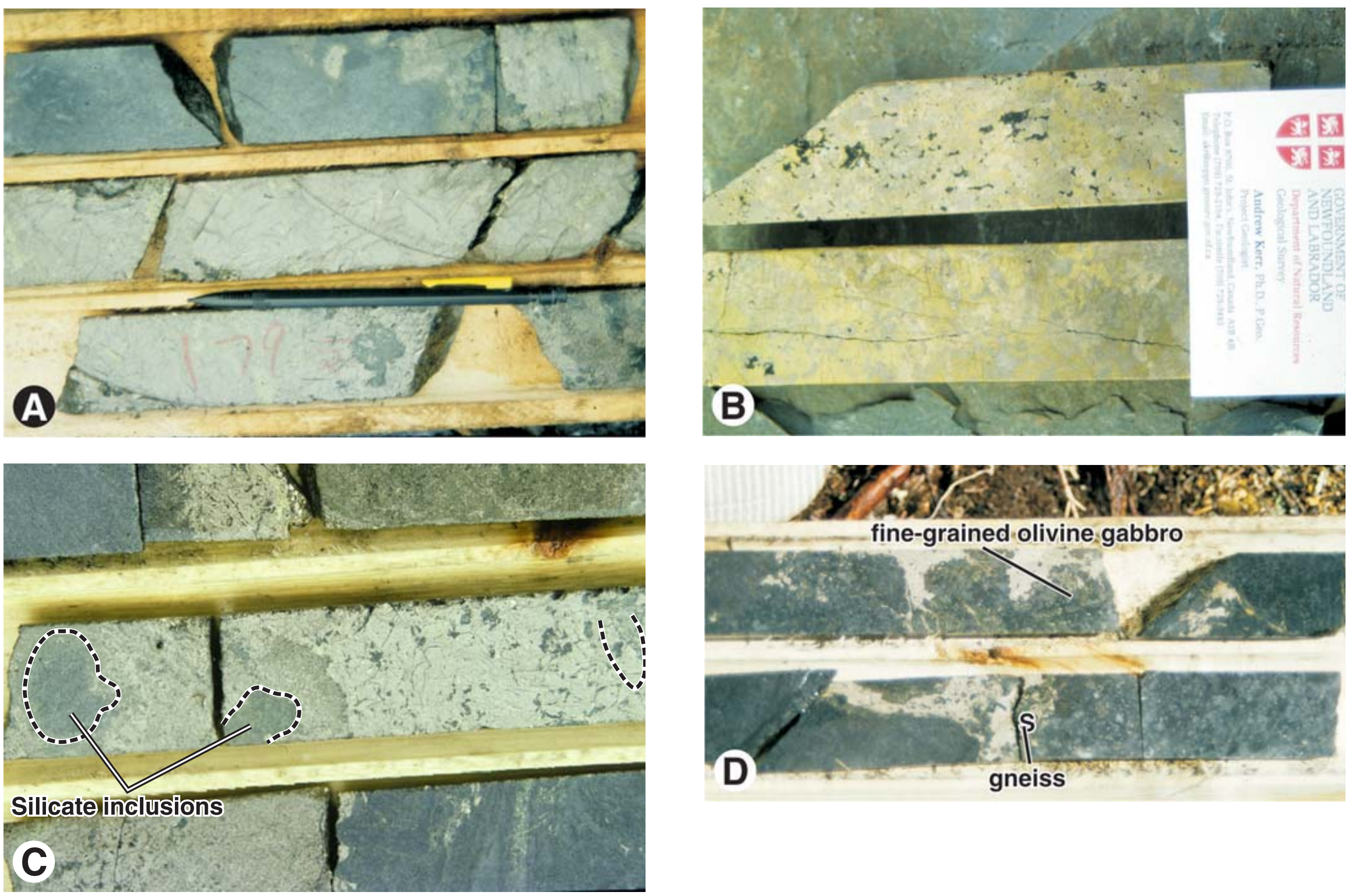


Plate 32. *A. Massive sulphide intersection from hole SVB-97-67, North intrusion. Note intricate contact relationships. B. High-grade sulphides from a footwall vein in hole SVB-97-75, containing over 11% Ni and 10% Cu. Sample is dominated by pentlandite and cubanite. C. “Dirty”, inclusion-rich massive sulphides, dominated by pyrrhotite, from the basal contact of the North intrusion in hole SVB-98-101. Inclusions indicated. D. Basal contact of the North intrusion in hole SVB-97-109, showing sulphide veins cutting the lowermost barren gabbro unit of the mineralized sequence. Drillcore approximately 4 cm wide (s–sulphide).*

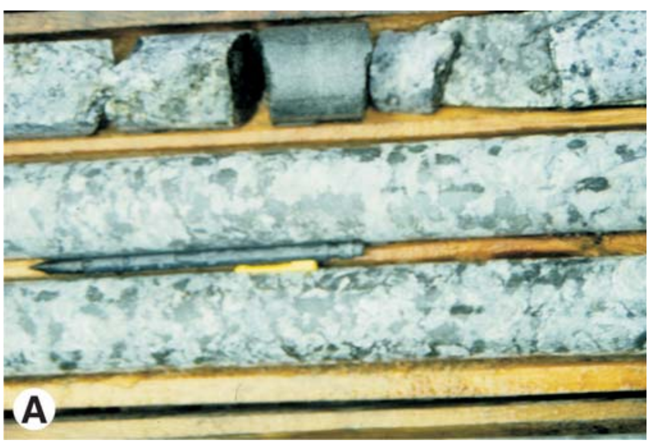
Bay (Naldrett *et al.*, 1996). High-grade footwall sulphide veins (Plate 32B) contain pentlandite, chalcopyrite, and possibly cubanite, niccolite and gersdorfite, and have a coarse crystalline texture (personal communication, A.J. Naldrett, cited by Fitzpatrick *et al.*, 1998). Other examples of massive sulphides, commonly dominated by pyrrhotite, and giving lower metal grades, are finer grained and 'dirty', with variable texture, abundant silicate inclusions, quartz grains, and graphitic patches (Plate 32C). These have either assimilated and entrained country rocks through thermal erosion, or are partially derived by melting and mobilization of primary sulphides from the metasedimentary gneisses, *i.e.*, they contain a higher proportion of locally derived material than the cleaner, inclusion-free massive sulphides.

Massive sulphides from the thickest intersection in the PLI (hole SVB-97-96) were examined in detail as part of a study by Naldrett *et al.* (2000). The results showed that samples contained higher proportions of troilite (pure FeS, without the metal deficiency that is characteristic of pyrrhotite) than typical Voisey's Bay material. Other minerals include chalcopyrite and pentlandite (the latter is notably Co-rich at Pants Lake), and also cubanite, which is the most abundant copper-bearing species. Magnetite is also present in variable amounts. Naldrett *et al.* (2000) concluded that both Pants Lake and Voisey's Bay sulphides have higher metal:sulphur ratios than most other magmatic sulphide deposits. Graphite was suggested to be involved as a reducing agent, promoting conditions that favoured the development of troilite. The influence of graphite was suggested to be more significant at Pants Lake than at Voisey's Bay. Such an interpretation is entirely consistent with the presence of graphitic country rocks and inclusions.

Footwall Gneisses

The gneisses below the basal contact of the North intrusion are not strictly part of the mineralized sequence, but it is commonly difficult to position the contact precisely, especially if massive sulphides are present. The 'footwall gneisses' are a research topic in their own right, and no attempt is made to describe them in detail here. The most common rock type is a coarse-grained garnetiferous granitoid orthogneiss, which shows contact metamorphism and reaction over a distance of 25 to 50 m below the basal contact (Plate 33A). The original rock type was probably a garnetiferous leucogranite, which is commonly mixed on an outcrop scale with biotite-rich paragneiss. Contact effects include transformation of original garnet to grey cordierite and/or orthopyroxene pseudomorphs, and a peculiar texture where grain boundaries are 'etched' by fine-grained biotite and/or amphibole aggregates. Invasive, vein-style sulphide mineralization is also common in the immediate footwall region. Kerr (1998a) also reported the presence of hercynitic spinel and corundum that are characteristic of the more digested inclusions seen in the mineralized sequence. The footwall gneisses may preserve the initial stages of reactions that eventually led to the digestion and assimilation of gneissic country rocks, and they are an important avenue for future research in the area. Plate 33B shows other examples of footwall gneisses including biotite-rich paragneiss and medium-grained granitoid gneiss. Note the chalcopyrite-rich sulphide vein in one of the drillcore samples.

As discussed earlier, Hearn (2001) examined contact metamorphic effects in these rocks, mostly in the area around the GG showing, where several early drillholes provide excellent examples. Thermal metamorphism generated new gar-



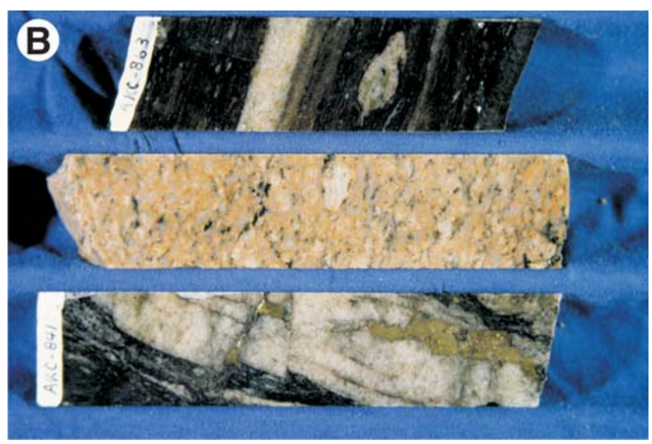


Plate 33. *A. Granitoid gneiss from just below the basal contact of the North intrusion; the grey patches were originally garnets, but have now been entirely retrogressed to cordierite due to contact metamorphism. B. Assorted footwall gneiss rock types, including banded pelite paragneisses at top, pink granitoid gneiss in the centre, and migmatitic paragneiss at the bottom. Note the copper-rich sulphide vein in the lower sample, which resembles the high-grade zone intersected in hole SVB-97-75. Drillcore approximately 4 cm wide.*

net and cordierite growth after biotite in metapelitic rocks, and garnet was retrogressed to cordierite and orthopyroxene in orthogneisses (Plate 33A). Evidence of anatexis was also observed close to the basal contact of the North intrusion in this area (Hearn, 2001). If temperatures were high enough to melt granite in the immediate footwall, it must be assumed that country-rock inclusions transported from greater depths underwent more extensive partial melting, as suggested by the residual assemblages typical of inclusions in the mineralized sequence.

Mineralization in the NDT Lobe

The mineralized sequence in the NDT lobe differs from its equivalent in other parts of the North intrusion in that it is situated below a thick sequence of fine-grained, layered olivine gabbro, and is well-removed from the base of the massive coarse-grained leucogabbro unit (Figure 27). It is best exposed at the NDT surface showings and related gossans, where the basal 50 m of the intrusion forms a thin skin sitting on metasedimentary and granitoid gneisses (Figures 15 and 16). At this location, two parallel, linear gossans line the sides of a small erosional valley, and are clearly visible from a distance of several kilometres. However, very deep weathering makes it difficult to see any geological relationships or to sample fresh material. The main surface showing has not been drill-tested because virtually all the mineralization is exposed, and is clearly of limited extent. In the hillside exposures above the north side of the mineralized zone, the medium-grained olivine gabbro contains irregular, diffuse zones of coarser grained material that superficially resembles the coarse-grained massive leucogabbro unit; these appear to be veins.

Hole SVB-96-04, drilled about 750 m west of the showings, was collared in medium-grained olivine gabbro or troctolite with cumulus olivine. Locally, this unit is coarse grained, but it is texturally distinct from the coarse-grained leucogabbro unit. The mineralized sequence is dominated by about 30 m of spectacular composite gabbro, whose similarity to the Voisey's Bay basal breccia sequence was noted at an early stage in the exploration program (Wares *et al.*, 1997). Gneissic fragments and restite derived from resorbed gneissic material become more abundant toward the base, and fine-grained poikilitic olivine diabase inclusions accompany the dominant granular troctolitic inclusions in the composite gabbros. The composite gabbro is underlain by only a few metres of homogeneous, fine-grained gabbro with disseminated sulphide. There is no well-developed leopard gabbro in this particular intersection, although it does occur locally in the area of the surface showings. Other information on the mineralized sequence in the NDT lobe comes from several widely spaced drillholes (*see* Figure 15 for locations). In hole SVB-97-77, almost 300 m of fine-grained, variably layered olivine gabbro sits between the base of the massive leucogabbro and the top of the mineralized sequence. The lowermost 20 m of this upper-layered olivine gabbro sequence is a complex mixed zone, which includes fine- and coarse-grained material, and several heterogeneous, inclusion-rich sections that resemble composite gabbro, albeit with little or no sulphides. Locally, the coarse-grained material appears to be included in finer grained material, which is the reverse of the normal relationship. The mineralized sequence is dominated by composite gabbro, but the fine-grained mafic inclusions are angular, suggesting that inclusions were solid fragments. This is underlain by less than 2 m of fine-grained, homogeneous, sulphide-bearing gabbro. Most other holes in the NDT lobe display a similar pattern of a relatively thick heterogeneous subsequence, underlain by a thin, poorly developed zone of homogeneous fine-grained gabbro. In general, the amount of sulphide in the mineralized sequence is low (2 to 7%). Massive sulphides are absent, aside from a few centimetre-scale veinlets, most of which occur in footwall gneisses.

Two drillholes (SVB-97-59 and 97-63) are notable as they contain poikilitic olivine diabase, which locally occurs above the mineralized sequence, as well as within, and below it. In hole SVB-97-63, about 6 m of poikilitic olivine diabase are present above the heterogeneous subsequence, and closely resemble finer grained varieties of the black olivine gabbro known from the Taheke Lake lobe. Poikilitic olivine diabase is generally difficult to recognize in the field and therefore may be more common in other NDT lobe drillholes than is currently recognized.

Mineralization in the Happy Face Lobe

The Happy Face lobe includes a persistent basal mineralized sequence, which is well exposed (albeit deeply weathered) at the Happy Face, Major General and GG zone showings (Figure 9). In this region, the North intrusion is a thin sheet, and the basal region is well-defined by drilling. In all parts of the Happy Face lobe, the North intrusion is volumetrically dominated by the massive leucogabbro, and the mineralized sequence sits just below the base of this upper unit (Figure 27).

The GG showing is one of the more spectacular surface gossans. It is an erosional remnant of the mineralized sequence sitting above the gneisses, and forms a prominent rusty hill. Despite intense weathering, leopard-textured gabbro is locally preserved in talus material, and the barren gabbro that separates the mineralized zone from footwall gneisses is well-exposed. At the GG zone, the deepest hole (SVB-96-02) penetrated two, and possibly three, gabbroic sheets, but only the uppermost of these contains significant mineralization. Most other holes at the site passed through an upper zone of sulphide-bearing composite gabbro, before entering sulphide-bearing (locally leopard-textured) gabbro. Holes SVB-96-01 and 96-02 contain spectacular intersections of leopard-textured gabbro with striking textures. The mineralized sequence is thick here, with up to 30 m of composite gabbro sitting above 15 to 50 m of more homogeneous mineralized gabbro. Gneissic fragments are most abundant at the base of the composite sequence. Disseminated sulphides are most abundant in the upper 7 to 12 m of the homogeneous subsequence, and mineralized rocks are transitional downward into barren gabbro. The fine-grained gabbros of the homogeneous subsequence all contain granular, cumulus olivine, and resemble the layered olivine gabbro unit. Locally, this fine-grained gabbro also forms a thin zone above the heterogeneous subsequence, but elsewhere the composite gabbro appears to be directly overlain by massive leucogabbro. Other drillholes in the area around the GG zone encountered a similar sequence, overlain by variable thicknesses of coarse-grained massive leucogabbro. Hole SVB-96-43 is notable for the presence of mineralized monzonite inclusions in the lower part of the mineralized sequence. This indicates that footwall-style mineralization has been transported as inclusions from some other location. Hole SVB-97-50 intersected complex, hornblende-rich mafic and intermediate rocks within the footwall gneisses, but these rocks are probably unrelated to the PLI. This hole, and nearby drillholes, also provide some of the best evidence for contact metamorphic reactions in gneisses close to the basal contact of the intrusion (Hearn, 2001).

The Major General showing is geologically similar to that of the GG zone. However, it is a larger feature, and has a thicker cap of massive leucogabbro. It is a direct extension of the GG zone mineralization, but the intervening gabbro has been eroded. The surface exposures display spectacular egg-like, nodular, weathering indicating the presence of composite gabbro, with a sulphide-bearing matrix. Drillhole intersections are dominated by locally spectacular composite gabbro, underlain by a thin, but apparently discontinuous, zone of homogeneous olivine gabbro above the footwall contact. Composite gabbros in this area (notably in hole SVB-96-20) contain both granular troctolite and poikilitic olivine diabase inclusions. Generally, the lower homogeneous section of the mineralized sequence is less well-developed here than at the GG showing.

The Happy Face showing itself is a thin zone exposed on a small peninsula in Happy Face Lake, and the mineralized sequence displays essentially the same twofold stratigraphy, sitting beneath the coarse-grained massive leucogabbro. However, some of the drillholes completed to the east of the showing lack the lower homogeneous subsequence, and pass directly from composite gabbro into footwall gneiss. Two holes that contain the black olivine gabbro and poikilitic olivine diabase units are of particular interest. In hole SVB-98-112, the medium-grained black olivine gabbro sits beneath fine-grained granular olivine gabbro, and seems to pass downward directly into composite gabbro, underlain by 5 m of homogeneous gabbro containing disseminated sulphide. The homogeneous subsequence shows a striking bimodal size distribution of sulphides, which occur as tiny interstitial grains or rounded patches about 5 mm in diameter. A closely similar sequence is seen in nearby hole SVB-97-80, where the sulphides in the composite gabbro are unusually pentlandite-rich. A linear array of holes drilled to the southeast of the Happy Face showing demonstrates the continuity of the mineralized sequence very well in this area. Thin massive sulphide intersections were present in some of these holes, located at, or just beneath, the contact with underlying gneisses. However, the Ni and Cu grades from these intersections were in general rather low.

Mineralization in the Taheke Lake Lobe

In the Taheke Lake lobe, the mineralized sequence is not exposed at the surface. However, it is well-defined by closely spaced drilling in the Northern Abitibi area, and its presence is established elsewhere by more widely spaced holes (Figure 11). In all areas, the mineralized sequence occurs at, or just below, the base of the black olivine gabbro unit, which extends all the way to surface in the east. However, the black olivine gabbro sits beneath fine-grained, layered olivine gabbro in the west (Figures 20 and 27). There are marked variations in the thickness of the mineralized sequence throughout the Taheke Lake lobe, and it is particularly thick in parts of the Northern Abitibi area. The thickest section penetrated is in hole SVB-97-70, where it exceeds 60 m. In this area, an array of angled holes indicates a progressive thickening to the northeast.

In most parts of the Taheke Lake lobe, the mineralized sequence has the characteristic twofold stratigraphy known from other parts of the North intrusion, although there are local instances where the heterogeneous subsequence sits directly upon the gneisses. There is commonly an upper section dominated by composite gabbro, underlain by more homogeneous gabbros containing disseminated sulphide that are locally leopard-textured (Figure 27). Generally, the heterogeneous subsequence is thicker than the homogeneous subsequence, with almost 50 m of composite gabbro in hole SVB-97-70. In hole SVB-97-67, some fine-grained gabbro containing granular, cumulus olivine occurs between the base of the black olivine gabbro and the top of the composite gabbro. However, some of the more homogeneous mineralized rocks beneath the heterogeneous subsequence in this hole are composed of poikilitic olivine diabase, locally containing significant amounts (>25%) of sulphide. Other holes in the 'Northern Abitibi' area show a similar pattern, but in some cases the black olivine gabbro passes directly downward into composite gabbro, and in one example it passes directly down into mineralized poikilitic olivine diabase, suggesting that the two are closely linked. The heterogeneous subsequence commonly shows a striking downhole increase in gneissic debris, and probably also in sulphide content, although the latter is variable on a local scale. The homogeneous subsequence shows clear evidence for gravitational sulphide accumulation in the development of leopard gabbro (*e.g.*, hole SVB-98-103, *see* earlier discussion). The transition from heterogeneous to homogeneous subsequences locally shows intercalation of composite gabbro and homogeneous mineralized gabbro. This suggests that there are lateral as well as vertical facies changes. Barren gabbro, locally chilled, is sporadically present at the base of the sequence. Massive sulphides generally occur just above the footwall contact or within gneisses and, in some cases, clearly invade chilled basal gabbro and overlying leopard gabbro.

The most significant zone of mineralization was discovered by hole SVB-97-96; drilled toward the end of the 1997 exploration season, this hole intersected 15.7 m of massive sulphide, grading 1.13% Ni, 0.78% Cu and 0.2% Co. In this hole, the massive sulphides occur near the base of the homogeneous, sulphide-bearing gabbros in the lower part of the mineralized sequence, and appear to have thermally eroded into underlying paragneisses. The massive sulphides contain abundant gneissic debris, including quartz and graphite. No pentlandite is visible to the naked eye, but it is present as exsolved material in pyrrhotite and troilite (Naldrett *et al.*, 2000). A ring-like array of vertical holes was completed in 1998 to test the lateral continuity of this zone. All holes intersected massive sulphides of essentially the same location within the mineralized sequence. However, these were much thinner, generally less than 3 m, which suggests that the massive sulphides thin rapidly in all directions. Thus, the size of this massive sulphide accumulation is limited.

In the same general area, the best grades recorded from any Labrador exploration property (including Voisey's Bay) were encountered in hole SVB-97-75. In the upper part of this hole, black olivine gabbro is underlain by a typical mineralized sequence in which composite gabbro and underlying homogeneous gabbro are locally interbanded. There are no massive sulphides within the gabbro, but a 1.1-m-thick zone of massive sulphides was intersected 13 m beneath the basal contact of the PLI. This zone contained 11.75% Ni, 9.7% Cu and 0.43% Co, with 54 g/t Ag, 109 ppb Pt and 794 ppb Pd (Fitzpatrick *et al.*, 1998). Several other thin, vein-like zones of similar high-grade sulphide mineralization occur at other depths in the footwall gneisses from hole SVB-97-75, and also in other holes in this area, including hole SVB-97-96. Attempts were made to trace the high-grade zone from hole SVB-97-75 by later drilling, but these have, so far, proved unsuccessful.

Other massive sulphide intersections were recovered from hole SVB-98-131, which was drilled to test the apparent thickening of the mineralized sequence to the northeast of hole SVB-97-70. Two massive sulphide zones had previously been intersected in hole SVB-97-67, located in the same general area. The mineralized sequence proved to be much thinner in hole SVB-98-131 (about 14 m) but a zone of massive sulphides located at the basal contact contained 4.5% Ni, 2.6% Cu, and 0.28% Co over 0.2 m. A slightly thicker zone a short distance below the basal contact contained 3.4% Ni, 0.5% Cu, and 0.46% Co. This hole was drilled close to the end of the 1998 season, and this region remains inadequately tested. The grades are comparable to those known from Voisey's Bay.

Assay Results and Metal Contents

As almost every drillhole collared within the North intrusion encountered at least some sulphide mineralization near the basal contact, there are large amounts of data available through assay results. These are listed in detail in assessment reports for the area (Wares *et al.*, 1997; Fitzpatrick *et al.*, 1998, 1999). Table 2 summarizes data from selected drillholes in the North intrusion, drawn from these sources. These results represent split core samples, ranging from 0.5 to 1.5 m in length, which are substantially larger than the samples collected by the Geological Survey, and thus provide a more representative picture of the mineralization. For details of the analytical procedures, *see* Appendix. In addition to the unprocessed Co, Ni and Cu data, sulphide metal contents can be calculated with knowledge of elemental sulphur abundances. For details of calculation procedures, *see* Kerr (2003). Sulphide metal contents for Ni and Cu are illustrated graphically in Figure 28.

The mineralized sequence within the NDT has low absolute Ni and Cu contents (<0.30% combined), due to a generally low sulphide abundance (Table 2). Sulphide Ni contents are generally consistent at 1.5% to 2.0% Ni, and are commonly accompanied by equivalent or marginally lower Cu contents (Figure 28A). As discussed above, the mineralized sequence in the NDT lobe is dominated by the upper heterogeneous subsequence, and relatively few of the underlying homogeneous gabbros were assayed. Those that were assayed show significantly lower sulphide metal contents.

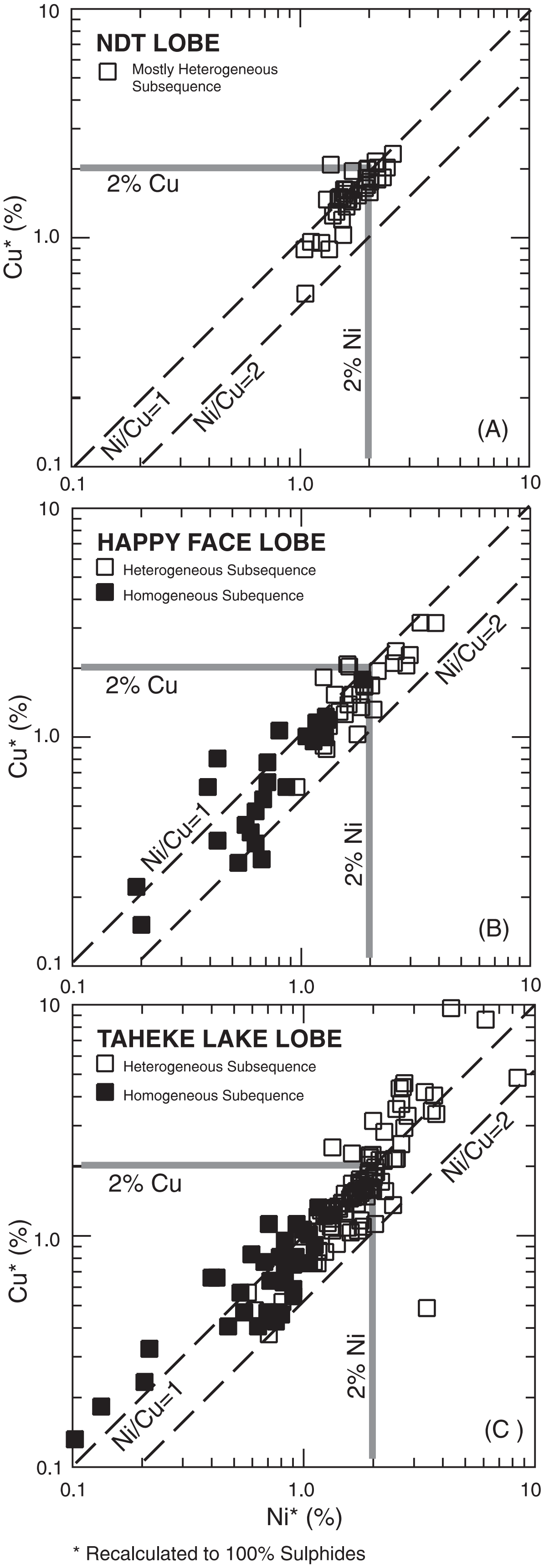
Grades from surface showings and drill intersections in the Happy Face lobe are variable, with the best results around 0.6% Ni, 0.45% Cu and 0.03 to 0.14% Co (Table 2). The higher Ni values, however, represent rocks with variable sulphide content, from less than 20% sulphides in the best examples of leopard gabbro and composite gabbro to more than 75% sulphides in thin massive zones at or below the basal contact. Converted to sulphide metal contents, these results

Table 2. Summary of assay results from North intrusion mineralization

Sample ID	From (m)	To (m)	Length (m)	Co (ppm)	Ni (ppm)	Cu (ppm)	S (%)
Drillhole SVB-97-57 (NDT Lobe)							
120957	163.50	165.00	1.50	232	1130	1050	2.58
120958	165.00	166.30	1.30	271	1450	1150	3.93
120959	166.30	166.50	0.20	1020	5920	5220	18.90
Avg. (3 m)	163.50	166.50	3.00	301	1588	1371.3	4.3
Drillhole SVB-97-58 (Happy Face Lobe)							
120940	204.20	204.90	0.70	1330	4660	2460	29.4
Drillhole SVB-97-61 (Happy Face Lobe)							
120621	64.90	65.60	0.70	1150	3810	2290	21.20
120623	66.40	67.50	1.10	1040	3220	2260	18.20
Drillhole SVB-97-67 (Taheke Lake Lobe)							
120661	162.40	163.90	1.50	303	2050	1960	3.84
120662	163.90	165.40	1.50	194	1150	1050	2.07
120663	165.40	166.90	1.50	201	1220	1090	2.23
120664	166.90	168.40	1.50	294	1950	1640	3.4
120665	168.40	169.90	1.50	562	4410	4000	7.68
120666	169.90	171.40	1.50	363	2590	3010	4.66
120667	171.40	172.90	1.50	769	5860	5450	10.1
120668	172.90	174.40	1.50	332	2330	2110	4.01
Avg. (12 m)	162.40	174.40	12.00	377	2695	2539	4.75
120670	176.20	176.50	0.30	2320	17340	16400	32.7
120671	176.50	178.85	2.35	281	1850	2880	3.43
120672	178.85	179.50	0.65	2610	19260	10740	33.8
Avg. (3.3 m)	176.20	179.50	3.30	925	6687	5657.3	12.07
120673	179.50	180.30	0.80	287	2240	3090	3.14
120674	180.30	180.40	0.10	1730	13480	8390	28.1
120675	180.40	181.90	1.50	228	2360	2970	2.76
Avg. (2.4 m)	179.50	181.90	2.40	310	2783	3235.8	3.94
Drillhole SVB-97-75 (Taheke Lake Lobe)							
75610	175.30	176.80	1.50	52	806	5650	0.63
75611	176.80	177.90	1.10	4300	119000	96000	26.7
75612	177.90	179.40	1.50	143	2300	20700	2.63
Avg. (4.1 m)	175.30	179.40	4.10	1225	33063	35396	8.36
Drillhole SVB-97-70 (Taheke Lake Lobe)							
75503	176.30	177.80	1.50	176	1340	1680	2
75504	177.80	179.30	1.50	183	1520	2120	2.03
75505	179.30	180.80	1.50	180	1580	2600	2.05
75506	180.80	182.90	2.10	212	1410	1420	2.21
75507	182.90	184.00	1.10	334	2340	2290	4.23
75508	184.00	185.00	1.00	219	1340	1270	2.53
75509	185.00	186.50	1.50	97	307	266	0.74
75510	186.50	188.00	1.50	80	187	149	0.31
75511	188.00	189.50	1.50	188	1850	1690	1.68
75512	189.50	190.90	1.40	137	1040	1440	1.28
75513	190.90	192.55	1.65	250	3530	4970	2.01
75514	192.55	194.20	1.65	200	1980	7280	2.13
75515	194.20	195.80	1.60	412	4720	5250	4.53
75516	195.80	197.40	1.60	319	3670	3600	3.58
75517	197.40	198.90	1.50	183	1470	1590	1.81
75518	198.90	200.40	1.50	220	2070	4530	1.63
75519	200.40	201.70	1.30	225	1950	2290	2.36
75520	201.70	203.20	1.50	93	249	252	0.49
75521	203.20	204.70	1.50	86	207	173	0.44
75522	204.70	206.70	2.00	76	218	206	0.32
75523	206.70	208.50	1.80	172	1130	1850	1.36
75524	208.50	210.20	1.70	186	1170	1120	1.46
75525	210.20	211.30	1.10	602	4650	4030	6.52
75526	211.30	212.30	1.00	269	1870	3030	2.37
75527	212.30	213.60	1.30	148	766	1160	1.2
Avg. (37.3)	176.30	213.60	37.30	203	1662	2234	1.95
Drillhole SVB-97-96 (Taheke Lake Lobe)							
16656	184.30	185.80	1.50	1800	10600	8200	31.70
16657	185.80	187.30	1.50	2100	11900	6500	34.50
16658	187.30	188.80	1.50	1800	10200	7800	28.40
16659	188.80	190.30	1.50	1700	9900	7400	30.40
16660	190.30	191.90	1.60	2000	10900	9600	32.50
16661	191.90	193.40	1.50	2000	11500	7800	33.60
16662	193.40	194.90	1.50	2000	11300	7000	33.20
16663	194.90	196.40	1.50	2000	11100	8000	33.4
16664	196.40	197.90	1.50	2200	12700	8400	33.7
16665	197.90	199.00	1.10	2300	13400	7500	35.5
16666	199.00	200.00	1.00	2200	12200	6600	31.9
Avg. (15.7 m)	184.30	200.00	15.70	1996	11349	7761.8	32.6
Drillhole SVB-97-97 (Taheke Lake Lobe)							
16806	158.90	160.20	1.30	1010	8680	7100	15.60
16807	160.20	161.10	0.90	533	4910	5580	8.73
Avg. (2.2 m)	158.90	161.10	2.20	815	7138	6478.2	12.79
Drillhole SVB-98-103B (Taheke Lake Lobe)							
10033	164.50	165.80	1.30	409	1960	1530	5.70
10034	165.80	167.00	1.20	510	2430	1850	7.46
10035	167.00	168.20	1.20	1260	6240	4180	19.3
10036	168.20	169.10	0.90	586	2760	2100	8.61
10037	169.10	170.30	1.20	507	2340	1820	7.25
Avg. (5.8 m)	164.50	170.30	5.80	654	3146	2292.9	9.65
Drillhole SVB-98-104 (Taheke Lake Lobe)							
10047	146.50	148.00	1.50	204	1200	1110	2.07
10048	148.00	149.50	1.50	317	2290	2120	3.81
10049	149.50	151.00	1.50	196	1280	1130	2.22
10050	151.00	152.30	1.30	291	1750	1590	3.80
10051	152.30	153.20	0.90	429	2400	2620	6.79
10052	153.20	154.00	0.80	371	2180	2030	4.91
10053	154.00	155.00	1.00	368	2540	2080	5.74
10054	155.00	156.50	1.50	130	410	274	1.48
Avg. (10 m)	146.50	156.50	10.00	270	1650	1508	3.51
10059	160.80	162.00	1.20	657	5300	7460	11.6
Drillhole SVB-98-113 (Taheke Lake Lobe)							
10530	95.30	96.70	1.40	293	1670	1560	4.38
10531	96.70	98.30	1.60	342	1800	1490	4.64
10532	98.30	99.80	1.50	302	1560	1410	3.67
10533	99.80	100.40	0.60	2200	10470	7350	34.1
Avg. (5.1 m)	95.30	100.40	5.10	535	2714	2175.1	7.7
Drillhole SVB-98-121 (Happy Face Lobe)							
10906	129.70	131.40	1.70	1360	4320	3260	24.8
Drillhole SVB-98-130 (Taheke Lake Lobe)							
10556	189.00	190.50	1.50	543	2600	2080	8.34
10557	190.50	192.00	1.50	723	3340	2940	11
10558	192.00	193.50	1.50	747	3730	2840	11.6
Avg. (4.5 m)	189.00	193.50	4.50	671	3223	2620	10.3
10565	208.80	209.90	1.10	1310	9920	6530	22.1
Drillhole SVB-98-131 (Taheke Lake Lobe)							
10570	197.20	197.40	0.20	2810	44900	26030	19.1
10575	207.70	208.00	0.30	4640	34430	5000	36.2

NOTES

Data from Fitzpatrick *et al.* (1998, 1999) assessment reports; sample numbers (where reported) are those listed in assessment reports



resolve into two groups, and the best values invariably come from composite gabbro samples in the upper heterogeneous subsequence, where sulphides locally contain up to 3.9% Ni and 3.1% Cu (Figure 28A). Leopard gabbro and related rocks from the lower part of the homogeneous subsequence show lower sulphide metal contents of 0.6% to 1.8% Ni and 0.5% to 1.4% Cu. The highest values from the homogeneous subsequence were obtained from the GG zone itself. The best values overall come from hole SVB-97-80, where sulphides in composite gabbros contain 3.3 to 3.9% Ni and 3.1% Cu, values that are consistent with the presence of easily visible pentlandite in drillcore.

The Taheke Lake lobe shows the greatest variation in absolute metal grades, and range up to 11.75% Ni, 9.7% Cu, and 0.43% Co in hole SVB-97-75 (Table 2). However, if the results from this and other anomalous high-grade sulphide intersections are excluded, the highest absolute grades are 1.93% Ni and 1.64% Cu from nearly massive sulphides in hole SVB-97-67. The disseminated mineralization agrees well with these observations, and mostly has sulphide metal contents of 1.5% to 2.0% Ni and 1.2 to 1.8% Cu (Figure 28C). Generally, the data from the Taheke Lake lobe resemble those discussed above from the Happy Face lobe, and there appear to be similar variations in metal contents within the mineralized sequence (Figure 28B, C). Samples from the homogeneous subsequence commonly show lower sulphide Ni and Cu contents at 100% sulphide, but this pattern is not ubiquitous; as there are holes where values remain in the upper range throughout. Anomalously high metal contents, from 2.7% to 6% Ni and 3.3% to 8.5% Cu at 100% sulphide, occur in the lower part of the thick mineralized sequence in hole SVB-97-70. Although high-grade sulphide fragments (?) were observed in one part of this interval, their frequency does not seem to be high enough to explain this result. Generally, the Taheke Lake lobe data provide more abundant (albeit scattered) evidence for high-grade (*i.e.*, >3% Ni and >3% Cu) sulphides than do the data from other parts of the North intrusion. However, it should be noted that the amount of data from the Taheke Lake lobe far outweighs that from all other parts of the PLI combined.

Geochemical Variations within the Mineralized Sequence

As noted above, there appear to be significant contrasts between the sulphide metal contents of the heterogeneous and homogeneous subsequences, as indicated in Figure 28. These variation patterns are further illustrated by profiles of some

Figure 28. (left) *Variation of Ni and Cu in the sulphides for the A. NDT, B. Happy Face, and C. Taheke Lake lobes of the North intrusion mineralized sequence. Recalculation of sulphide metal contents after Kerr (2001, 2003b).*

selected drillholes (Figure 29). In the NDT lobe, contrasts are not well-developed, as the lower sequence is commonly thin and sulphide-poor. The patterns are well-developed in the Happy Face lobe, but range from a smooth downhole decrease (*e.g.*, hole SVB-97-61) to a sharp transition (*e.g.*, hole SVB-97-60; Figure 29B), with other 'intermediate' cases (Figure 29). Intersections from the Taheke Lake lobe also show these patterns, and the most common appears to be one of a smooth decrease in sulphide metal contents (*e.g.*, hole SVB-98-102; Figure 29A). There are examples of sharp, step-like declines (*e.g.*, hole SVB-97-95) and also a few holes that show no noticeable variation (*e.g.*, hole SVB-98-101). Figure 29 does not attempt to show all possible variations, but it does show that there is a persistent pattern throughout the North intrusion.

Metal Ratios and Related Parameters

The general similarity in the styles of mineralization throughout the North intrusion is accompanied by strong geochemical affinities. This coherency is well illustrated by a Ni–Cu plot (Figure 30A), which shows the strong covariance of the two elements. Nickel/copper ratios are slightly greater than 1 in most parts of the PLI, although a few samples have Ni/Co <1. Some of the high-grade sulphide intersections (notably from hole SVB-97-75) lie on the same trend where Ni/Co = 1-2, but others are enriched in either Ni or Cu, suggesting the involvement of a fractionation process in their formation. Mineralization from the North intrusion is compared to the Voisey's Bay intrusion in Figure 30A, which also includes data from the South intrusion for comparison. The Voisey's Bay data largely come from press releases issued prior to INCO's acquisition of the deposit in 1996. It is now well known that the massive sulphides at the Voisey's Bay deposit commonly contain >4% Ni, significantly higher than most of the sulphide metal contents from the PLI (Figures 28A, B and 30A). The Voisey's Bay deposits also have significantly higher Ni/Cu ratios, which are about twice the typical PLI value. A Ni/Cu–Ni/Co variation diagram (Figure 30B) also illustrates differences between the two areas. Mineralization from the PLI shows low Ni/Co ratios (average <7). Thus, for a given Ni content, the PLI sulphides contain significantly more Co than at Voisey's Bay, where Ni/Co ratios commonly exceed 20, except in the Reid Brook zone. Comparisons of sulphide

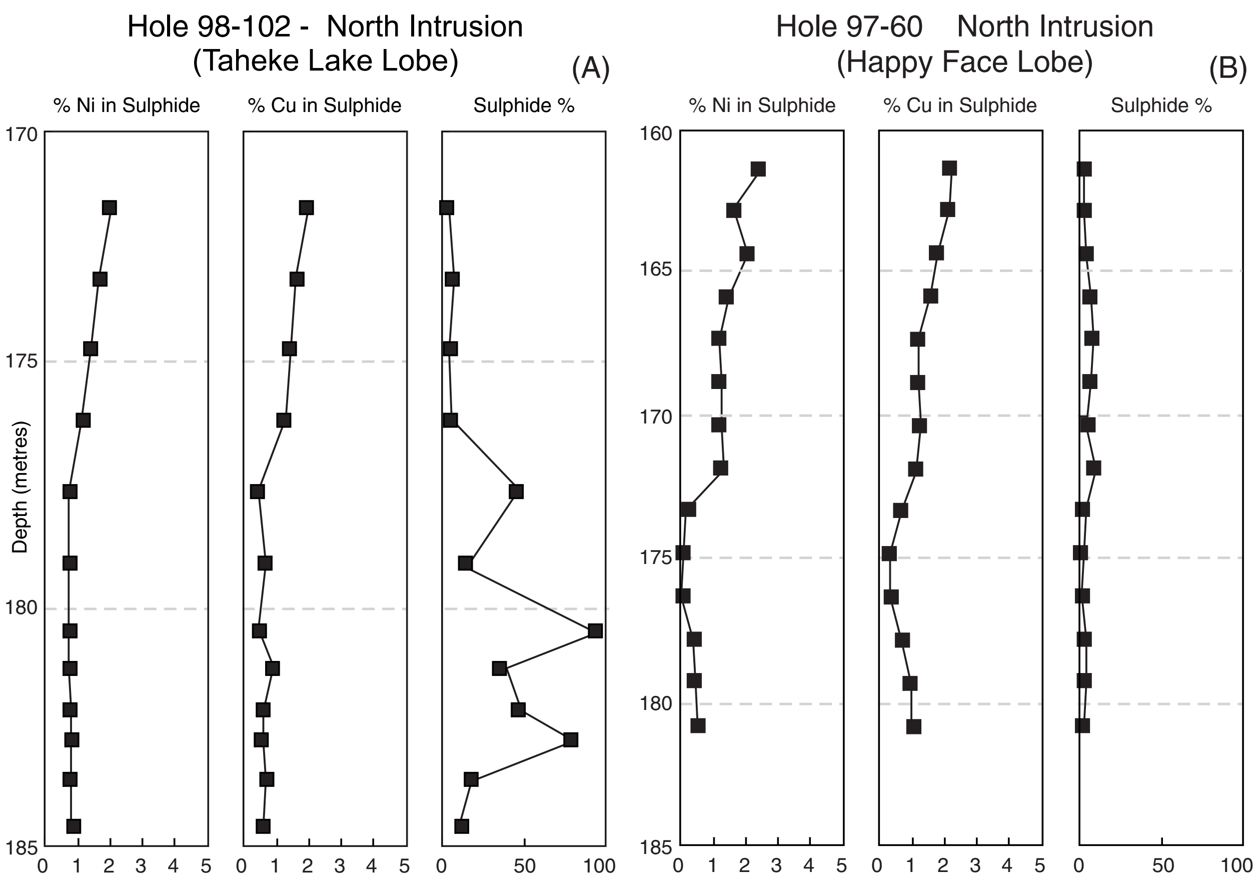


Figure 29. *Variations in sulphide metal contents within mineralized sequences of the North intrusion, as illustrated by two drillholes. A. Variation of Ni in sulphides, Cu in sulphides and total sulphide content against depth in hole SVB-98-102 (Taheke Lake lobe). B. Variation of Ni in sulphides, Cu in sulphides and total sulphide content against depth in hole SVB-97-60 (Happy Face lobe).*

Co contents have not been attempted, as they are very sensitive to assumptions about correction factors for silicate material (Kerr, 2003); however, the empirical data from massive sulphide zones in the PLI imply values in the 0.2 to 0.3% range, which is generally higher than at Voisey's Bay.

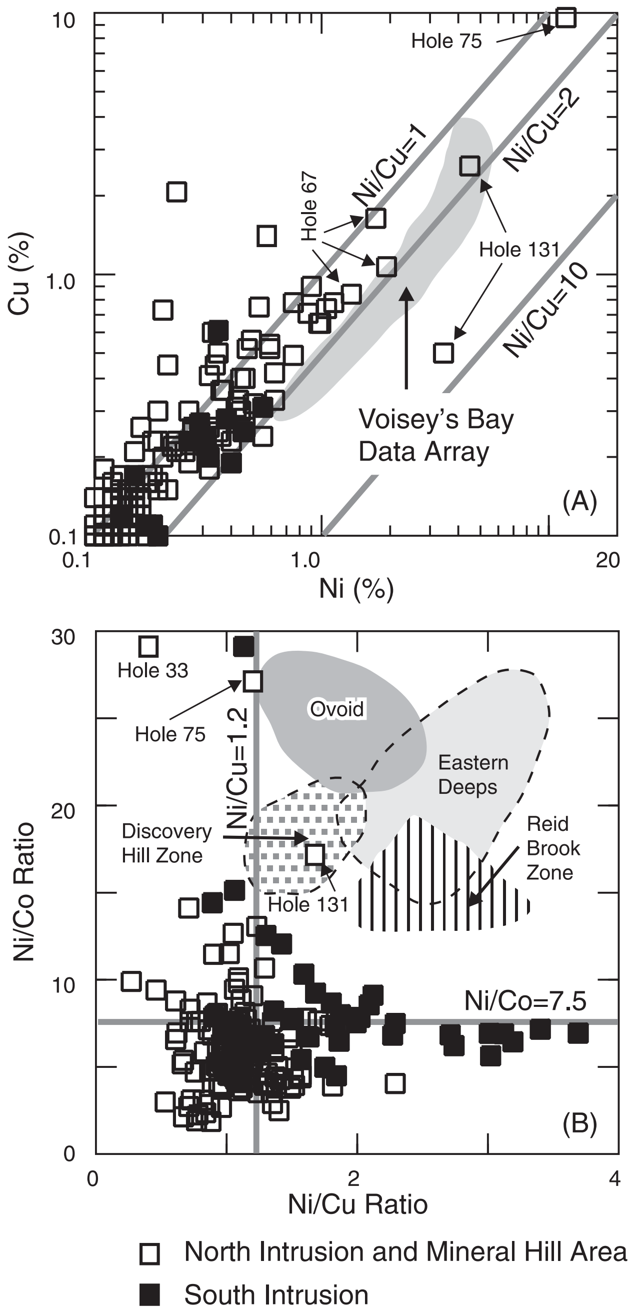


Figure 30. *Comparison of the Ni, Cu and Co contents of mineralization from the Pants Lake intrusions with Voisey's Bay mineralization. A. Cu* versus *Ni, using uncorrected whole-rock analytical data. B. Ni/Co* versus *Ni/Cu, using uncorrected whole-rock analytical data. Voisey's Bay data collated from various press releases reporting mineralized intersections in 1995 and 1996. These data are not corrected to 100% sulphides and the charts to not include all of the data in Table 2 (for the sake of clarity).*

Comparison of Table 2 and Figure 28 with equivalent information for the mineralized sequence in the South intrusion (Table 1; Figure 26) shows that parts of the latter have distinctly higher Ni/Cu, commonly >2.0. This is also evident in the comparison given by Figure 30. Despite its higher Ni/Cu ratios, the South intrusion mineralized sequence is characterized by a fairly low Ni/Co ratio, akin to values from the North intrusion, and below typical Voisey's Bay values (Figure 30B).

MINERALIZATION IN THE MINERAL HILL INTRUSIONS

Mineralization

The Mineral Hill showing is perhaps the most spectacular surface gossan in the area, but this area has undergone only limited exploration since 1996, and the mineralized sequence is not well documented. This inactivity reflects the generally low sulphide metal contents (<2% combined Ni and Cu; Figure 31). The main surface showing consists of a well-defined mineralized zone that has a layer-like geometry and subhorizontal attitude, sitting beneath unmineralized massive leucogabbro (Plate 34A). The continuity of the mineralized zone is clearly demonstrated by the presence of several adjacent showings at approximately the same topographic level. However, it is not clear whether the mineralized zone at the main showing is equivalent to the blind zone, defined by additional

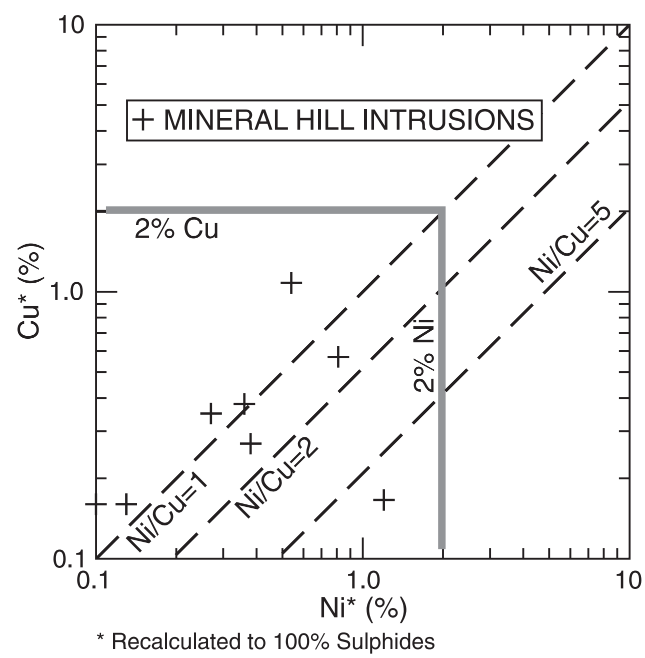


Figure 31. *Variation of Ni and Cu in the sulphides of the Mineral Hill intrusions. Recalculation of sulphide metal contents after Kerr (2001, 2003b).*

drilling located over 1 km to the northeast (*see* Figures 11 and 14); as discussed previously, these two zones may actually represent separate, 'stacked', sill-like intrusive bodies. At the main surface showing, mineralized rocks appear mostly to be medium-grained, homogeneous olivine gabbros, containing interstitial and patchy sulphide, and there is relatively little sign of composite gabbro. Leopard-textured gabbro is also present at the main showing and in other areas of exposure. The contact between the fine- to medium-grained (mineralized) gabbro and the overlying massive coarse-grained leucogabbro is sharp but uninformative with regard to their mutual relationship (Plate 34B).

At the main showing, the mineralized sequence is only about 14 m thick, and it is dominated by medium-grained, homogeneous olivine gabbro containing interstitial to patchy sulphide, and scattered resorbed gneissic fragments (Plate 35A). Generally, this rock resembles the lower (homogeneous) part of the mineralized sequence in the North intrusion, but is somewhat coarser grained. There is a very thin (<1 m) zone of composite gabbro located at the top of the mineralized sequence, and this closely resembles its counterparts in the North intrusion. In the area to the northwest, several holes (including hole SVB-96-36, described previously by Kerr, 1998a) are dominated by relatively homogeneous, fine- to medium-grained gabbro containing evenly dispersed magmatic sulphide. These rocks sit beneath coarse-grained massive leucogabbro. The mineralized zone is over 40 m thick in hole SVB-96-36. Texturally, the mineralized rocks resemble the fine-grained olivine gabbro in the North intrusion, and contain euhedral to granular cumulus olivine (Plate 35B). Clinopyroxene oikocrysts, and typical leopard-texture, are developed sporadically. The mineralized olivine gabbros also contain scattered gneissic fragments, which exhibit the green spinel rims seen elsewhere. Locally, spinel forms inclusions in all igneous phases, and strained metamorphic plagioclase masquerades as an igneous mineral. Holes SVB-96-45, -48 and -49 all contain thin sequences of heterogeneous sulphide-bearing rocks with fine- and coarse-grained domains, sitting above the main mineralized zone. These

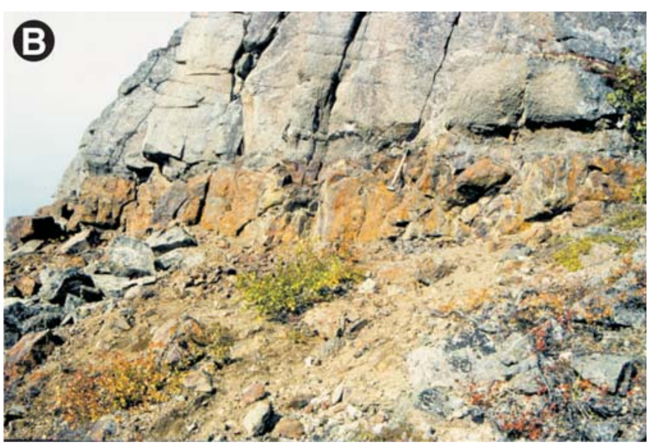
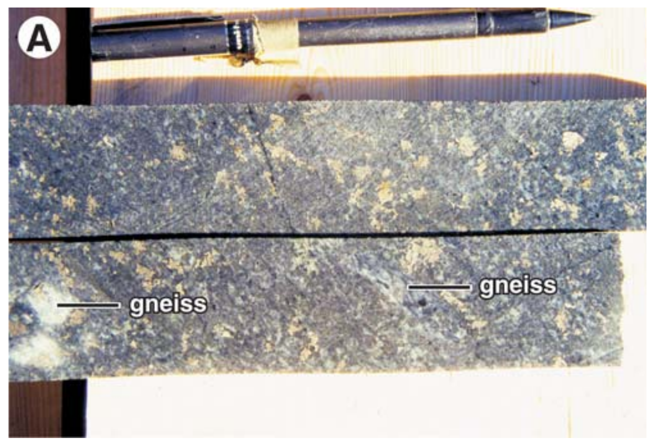


Plate 34. *A. Aerial view of the Mineral Hill prospect, showing massive leucogabbro overlying sulphide-bearing rocks. B. Sharp but uninformative contact between mineralized fine-grained olivine gabbro and overlying massive leucogabbro.*



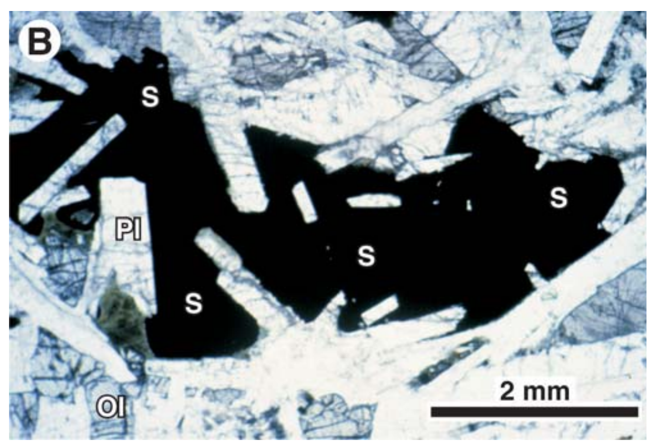


Plate 35. *A. Typical homogeneous sulphide-bearing gabbro from the Mineral Hill prospect; note digested gneissic fragments in the lower core sample. B. Interstitial sulphide in mineralized gabbro from Mineral Hill, intergrown with plagioclase and clinopyroxene, lesser olivine. Both samples from drillhole SVB-96-36 (s–sulphide, pl–plagioclase, ol–olivine).*

rocks appear to represent composite gabbros akin to those documented in the North intrusion, but they have not been examined in the same level of detail. Overall, there appear to be some similarities between the mineralization at Mineral Hill and the typical sequence of the North intrusion, but composite gabbro is nowhere as well developed as in the North intrusion.

Assay Results and Metal Contents

Despite fairly high sulphide contents, locally >20%, mineralized samples from the Mineral Hill intrusions tend to have low grades, typically less than 0.3% combined Ni and Cu (Table 3). Recalculation of disseminated mineralization to 100% sulphides indicates low sulphide metal contents of 0.2 to 0.8% Ni and 0.1 to 0.6% Cu (Figure 31). These grades resemble those obtained from the lower part of the mineralized sequence in some parts of the North intrusion. The sulphide metal contents in the thin composite gabbro sequences of the Mineral Hill area are unknown.

MINERALIZATION ELSEWHERE IN THE PANTS LAKE INTRUSIONS

A few small sulphide-bearing zones are exposed around the northern end of the Worm intrusion, but there is relatively little surface evidence of mineralization in the southern part of this body. Drillhole intersections in the north indicate a mineralized sequence akin to that of the North intrusion, and particularly similar to that of the adjacent Happy Face lobe. The mineralized sequence at the north end of the Worm intrusion is thin, generally <10 m in total. At the south end of the Worm intrusion (*e.g.*, hole SVB-96-31) composite gabbro is well-developed, but the underlying homogeneous subsequence appears to be relatively thin. Assay data are sparse for this area, but generally resemble those from the Happy Face lobe. The similarities support the idea that the Worm intrusion is a continuation of the North intrusion, although the actual physical connection between the two may have been disrupted.

Table 3. Summary of assay results from Mineral Hill intrusions mineralization

Sample ID	From (m)	To (m)	Length (m)	Co (ppm)	Ni (ppm)	Cu (ppm)	S (%)
Drillhole SVB-96-33							
28656	36.70	37.70	1.00	123	618	3333	1.65
28657	37.70	38.80	1.10	229	5842	13503	2.81
Avg. (2.1 m)	36.70	38.80	2.10	178	3354	866	2.26
Drillhole SVB-96-36							
28724	115.00	116.10	1.10	280	1055	1171	6.90
28725	116.10	117.10	1.00	281	1072	1413	6.93
28726	117.10	118.10	1.00	325	955	900	7.67
28727	118.10	119.20	1.10	339	919	857	8.17
28728	119.20	120.20	1.00	312	807	778	7.76
Avg. (5.2 m)	115.00	120.20	5.20	307	963	1023	7.49
Drillhole SVB-98-110							
11020	63.30	64.50	1.20	244	1280	1150	3.86
11021	64.50	66.00	1.50	217	1130	1110	3.26
11022	66.00	67.50	1.50	223	1290	1460	3.66
11023	67.50	69.00	1.50	252	1300	1290	4.06
11024	69.00	70.50	1.50	252	1260	1160	4.22
11025	70.50	72.00	1.50	319	1460	1260	5.58
11026	72.00	73.50	1.50	319	1460	1370	5.40
Avg. (10.2 m)	63.30	73.50	10.20	261	1312	1260	4.30

NOTES
Data from Fitzpatrick *et al.* (1998, 1999) assessment reports; sample numbers correspond to those listed in the assessment reports

The smaller, outlying component bodies of the PLI have not been explored in any detail. Minor surface mineralization occurs in two bodies adjacent to Pants Lake, and appears to be localized at their base. These are probably continuations of the North intrusion. Trivial amounts of sulphide were also noted in one locality at the base of the Cartaway intrusion. The Slingshot Gabbro has not been examined in detail, but Fitzpatrick *et al.* (1999) do not report any surface mineralization.

GEOCHEMISTRY

INTRODUCTION

Overview

Outcrops and drillcore were sampled systematically for geochemical analyses and studies during this project. The total database now consists of over 400 analyses, of which some 350 represent the PLI. About 100 of these samples come from the mineralized sequence near the base of the intrusions, but the remainder provide systematic coverage of all geological units within the intrusions from all geographic areas. These geochemical data for unmineralized and mineralized rocks are discussed separately. This section focuses mostly upon the regional data, which characterize the rock types and document their petrological evolution. A following section focuses in detail on the data from the mineralized sequences, and provides information on processes related to the development of magmatic sulphide mineralization. This section represents a considerable expansion of previous discussions of PLI geochemistry by Kerr *et al.* (2001) and Kerr (2003a).

Overview of Database

Outcrop and core samples were analyzed for major and trace elements at the Department of Natural Resources laboratory in St. John's. Major and trace elements were analyzed by inductively-coupled-plasma–emission spectroscopy (ICP-ES), except for Rb, which was analyzed by atomic absorption spectrometry (AAS). A subset of samples was also analyzed for an extended suite of trace elements, including the rare-earth elements (REE), at Memorial University of Newfoundland. These samples were splits of original powders prepared at the Department of Natural Resources laboratory, and were analyzed by inductively-coupled-plasma–mass spectrometry (ICP-MS). Sulphur was analyzed for a subset of mineralized samples, using the Leco furnace method. Full details of sample preparation and quality-control procedures, including estimates of analytical precision and accuracy, are presented by Finch (1998) for the Department of Natural Resources laboratory.

Records in the database are classified primarily on the basis of geographic area, geological unit, and rock type. For unmineralized rocks, the first two parameters provide the most relevant subdivisions. Additional classification information includes the sample type (outcrop or drillcore) and the drillhole number and meterage, where applicable. The digital geochemical database and a related database containing sample location and drillhole information are available as a companion open file, which also includes complete information on database structure.

Other Relevant Geochemical Studies

Some geochemical analyses, including several from the rocks now included within the PLI, were presented and discussed by Thomas and Morrison (1991). On the basis of the descriptions and analyses, most of these analyses appear to represent the coarse-grained massive leucogabbro unit.

During the current exploration program, hundreds of mineralized samples, mostly from drill intersections, were assayed for Co, Ni, Cu and S. However, there were relatively few major- and trace-element analyses of unmineralized gabbro or other regional rock types. Fitzpatrick *et al.* (1999) present a total of 77 analyses, but only about 20 of these were from the PLI. The main objective of their geochemical work was to enable discrimination of rocks belonging to the PLI from superficially similar mafic rocks assigned to other members of the NPS, or to the HLIS. The most comprehensive previous geochemical study was that of MacDonald (1999). This was based on systematic sampling from three key diamond-drill holes (SVB-97-75, -77 and -79) and, in addition to providing whole-rock data, the study investigated mineral compositions, notably of olivine. MacDonald (1999) concluded that there were compositional differences between the South and North intrusions, strong similarities between some PLI gabbros and troctolites of the Voisey's Bay intrusion, and evidence for widespread chalcophile element depletion. All three of these conclusions are supported and amplified by the results of the current project.

In the early stages of the exploration project, geochemical studies, including analyses of Ni in olivine, were conducted by Dr. M.R. Wilson at Memorial University of Newfoundland, under contract to Donner Resources. These studies were based mostly on samples from early 1996 drillholes, which were located around the major surface showings in the area. Some of the petrographic work from this study was summarized by Hodder (1997). A more detailed study of the mineralized sequence was completed by Smith (2006).

SUMMARY OF ANALYTICAL DATA FROM UNMINERALIZED ROCKS

Analyses were grouped on the basis of geographic area and geological unit, and average compositions were calculated. The first-order geographic divisions were the South intrusion, the North intrusion, and the Mineral Hill intrusions. The South intrusion was divided into upper and lower sections, and the North intrusion was further subdivided into its three main lobes. The Worm and Cartaway intrusions are represented by only a few samples, and are not discussed in any detail here. The five main geological units described in previous sections were used as a secondary subdivision:

1) Fine-grained, layered olivine gabbro;
2) Melagabbro and peridotite;
3) Coarse-grained, massive leucogabbro;
4) Black olivine gabbro; and
5) Diabase and related rock types.

Each of these units is discussed separately below.

Fine-grained, Layered Olivine Gabbro

Table 4 lists the average compositions and standard deviations for this unit in various geographic areas. Note that the South intrusion is divided into upper and lower sections; the former includes material sitting above discontinuous mineralized horizons and/or gneiss screens at around 200 to 250 m depth in holes SVB-97-79 and -86. As suggested by MacDonald (1999) and also discussed previously, these are inferred to represent a separate (earlier?) component. The NDT lobe of the North intrusion contains the thickest sequence of this unit and is thus represented by the largest number of analyses (n=34); all other areas are represented by 10 analyses or less.

The average major-element compositions of this unit in different areas are generally similar, and the low standard deviations suggest that its composition does not vary widely. Mean SiO_2 ranges only from 45.2% (Taheke Lake lobe) to 47.6% (South intrusion), and Al_2O_3 and Fe_2O_3 are high in all areas. There appear to be some differences in MgO content and Mg/(Mg+Fe), as Taheke Lake lobe samples average over 15% MgO compared to 10% MgO or less elsewhere. The Taheke Lake samples also show the lowest mean Na_2O and K_2O contents (<2% and <0.2% respectively), results that also

Table 4. Average compositions for fine-grained olivine gabbro unit, in various areas

		South Intrusion Lower Section		South Intrusion Upper Section		Mineral Hill Intrusion		North Intrusion NDT Lobe		North Intrusion Happy Face Lobe		North Intrusion Taheke L. Lobe	
		Mean n=7	S.D	Mean n=4	S.D	Mean n=9	S.D	Mean n=34	S.D	Mean n=4	S.D	Mean n=5	S.D
SiO_2	%	47.64	1.14	47.13	0.71	47.37	1.32	46.16	1.38	47.35	0.66	45.22	1.22
TiO_2	%	1.57	0.25	1.98	0.58	1.4	0.42	0.89	0.33	1.08	0.11	0.53	0.16
Al_2O_3	%	18.54	1.67	16.07	1.61	16.44	1.49	17.79	2.68	17.82	1.35	15.21	1.85
Fe_2O_3	%	11.3	1.69	13.67	1.88	14.02	1.98	12.97	2.52	12.96	1.27	14.04	1.48
MnO	%	0.14	0.03	0.18	0.02	0.18	0.03	0.17	0.03	0.17	0.01	0.17	0.02
MgO	%	8.29	1.46	8.25	1.69	8.43	1.27	9.98	3.21	8.16	0.9	15.19	3.08
CaO	%	8.64	0.32	8.25	0.56	8.66	0.43	9.03	0.98	9.69	0.61	7.65	1.02
Na_2O	%	3.37	0.18	3.12	0.5	2.89	0.15	2.65	0.46	2.82	0.17	1.94	0.37
K_2O	%	0.52	0.13	0.65	0.16	0.49	0.18	0.29	0.1	0.32	0.04	0.16	0.05
P_2O_5	%	0.32	0.04	0.37	0.19	0.19	0.09	0.09	0.03	0.11	0.01	0.06	0.02
LOI	%	0.25	0.2	0.79	0.41	0.58	0.34	0.74	1.13	0.5	0.2	0.61	0
Total		100.48		100.06		100.45		100.28		100.74		100.29	
Li	ppm	4	1.3	6.5	0.3	6.2	1.9	5.2	2.7	6.2	0.9	3.8	0.5
Be	ppm	0.4	0.1	0.5	0.1	0.4	0.1	0.3	0.1	0.3	0.1	0.1	0
Sc	ppm	14.6	8.7	23.3	1.8	23.2	7.8	17.6	6.5	25.1	5.8	13.2	2.8
Ti	ppm	9726	1347	12062	3423	8702	2516	5495	1984	6699	754	3295	990
V	ppm	101	46	161	20	152	46	105	36	152	18	74	20
Cr	ppm	102	32	104	35	71	15	60	20	64	14	84	8
Mn	ppm	1043	244	1304	173	1372	222	1268	238	1214	160	1235	127
Co	ppm	55	5	60	14	72	23	76	20	71	19	100	16
Ni	ppm	102	43	61	20	91	79	108	53	121	115	186	42
Cu	ppm	19	12	21	4	66	100	25	9	98	116	13	3
Zn	ppm	85	16	109	15	112	23	94	18	100	8	93	5
Ga	ppm	18	0			19	3	21	4	23	0		
Rb	ppm	4	3	7	1	7	3	4	2	5	2	2	0
Sr	ppm	426	48	354	77	299	56	291	67	292	15	244	35
Y	ppm	15	6	22	1	22	6	16	6	21	4	9	3
Zr	ppm	82	21	113	17	93	35	55	23	70	7	33	11
Nb	ppm	6	2	9	2	5	3	3	1	4	1	2	1
Mo	ppm	1	0	1	0	1	0	1	0	1	0	1	0
Ba	ppm	270	61	309	59	244	91	146	37	160	24	96	24
La	ppm	11	4	13	3	10	5	5	2	6	1	2	1
Ce	ppm	24	7	28	6	24	9	14	5	15	2	8	2
Dy	ppm	2.6	1.1	3.8	0.1	3.5	1.1	2.4	1	3.5	0.5	1.8	0.4
Pb	ppm	1	0	1	0	2	2	1	0	1	0	1	0

indicate a less evolved composition. Olivine gabbros in the South intrusion (both upper and lower sections) have higher mean TiO_2, K_2O and P_2O_5 contents than their counterparts elsewhere, but show no other clear major-element distinctions. The mean compositions of fine-grained olivine gabbro in the NDT lobe and the Happy Face lobe of the North intrusion are almost identical. The Mineral Hill intrusions share some of the characteristics of the South intrusion, but their enrichment in TiO_2 and P_2O_5 is less marked.

Mean trace-element compositions for this unit are similar for many elements, but some contrasts are shown by Ti (noted above), Co, Ni, Sr, Ba, La and Ce. Most areas show consistent Ni (88 to 120 ppm) and Co (55 to 71 ppm) contents, but samples from the Taheke Lake area are the richest in Ni (186 ppm) and Co (100 ppm), consistent with their higher MgO and generally less evolved composition. Olivine gabbros from the South and Mineral Hill intrusions contain about twice as much Ba as those from other areas, and those from the South intrusion are also higher in Sr. Lanthanum and Ce are also enriched twofold in the South intrusion and Mineral Hill intrusions compared to other areas, as noted previously by MacDonald (1999).

Melagabbro and Peridotite

Table 5 lists average compositions and standard deviations for melagabbro and peridotite, represented by 5 samples from the South intrusion and a single sample from the NDT lobe of the North intrusion. As might be expected from the petrology analysis, this unit has a relatively primitive composition, with mean SiO_2 of about 41%, and high mean Fe_2O_3 (17.8%) and MgO (21.6%) contents. The South intrusion samples are all enriched in TiO_2 (mean 1.5%) relative to the

Table 5. Average compositions for melagabbro and peridotite unit, in various areas

		South Intrusion Mean n=5	S.D.	North Intrusion NDT Lobe Value n = 1
SiO_2	%	41.16	1.16	41.06
TiO_2	%	1.5	0.2	0.55
Al_2O_3	%	8.44	1.47	7.24
Fe_2O_3	%	17.77	1.13	21.24
MnO	%	0.19	0.01	0.265
MgO	%	21.63	1.84	22.47
CaO	%	4.18	0.58	4.13
Na_2O	%	1.72	0.4	1.07
K_2O	%	0.44	0.08	0.15
P_2O_5	%	0.34	0.05	0.08
LOI	%	3.05	0.75	1.71
Total		100.41		99.96
Li	ppm	5.7	1.3	6.6
Be	ppm	0.3	0.1	0.1
Sc	ppm	8.7	1.3	19.5
Ti	ppm	9059	978	3394
V	ppm	81	8	84
Cr	ppm	130	10	74
Mn	ppm	1437	122	2093
Co	ppm	149	27	146
Ni	ppm	940	228	220
Cu	ppm	405	200	15
Zn	ppm	116	2	125
Ga	ppm			
Rb	ppm	2	0	2
Sr	ppm	166	33	128
Y	ppm	12	1	13
Zr	ppm	79	9	38
Nb	ppm	4	1	2
Mo	ppm	1	0	1
Ba	ppm	188	38	92
La	ppm	8	1	2
Ce	ppm	22	2	15
Dy	ppm	2.4	0.3	2
Pb	ppm	5	2	3

single sample from the North intrusion (0.55%). This contrast in TiO_2 contents resembles that noted above for the fine-grained olivine gabbro from these two areas. The South intrusion samples have elevated Co, Ni and Cu, but this partly reflects the presence of minor interstitial sulphide in all of these rocks, whereas the North intrusion sample (with about 200 ppm Ni) is sulphide-free, and is probably more representative of the mean Ni content for unmineralized rocks. Differences in Sc content are also apparent, consistent with the presence of more clinopyroxene in the North intrusion sample. There are also some differences in Ba, La and Ce contents between South and North intrusion samples. All samples of this unit are cumulate rocks, and their compositions are thus controlled largely by the proportion of olivine and plagioclase and the amount of trapped liquid. Consequently, it is difficult to assess trace-element variations on the basis of a small number of samples. However, for a rock containing 60% olivine or more, the mean Ni content of about 200 ppm suggested by the North intrusion example is anomalously low.

Coarse-grained Massive Leucogabbro

The average compositions and standard deviations of this unit in various areas are listed in Table 6. Note that this unit does not occur in the South intrusion, aside from a thin coarse-grained unit intersected in the upper part of hole SVB-97-79, which is interpreted as a younger sheet. The leucogabbro unit is thickest and best-known in the Happy Face lobe (17 samples), but is very poorly represented in the Taheke Lake lobe (only 3 samples).

Average major-element compositions for all areas are similar although there is some subtle variation in SiO_2, Al_2O_3, MgO and CaO. Samples from the main North intrusion have slightly more SiO_2-rich and Al_2O_3-rich compositions. This suggests that they are more plagioclase-rich than their counterparts from the Mineral Hill and Worm intrusions. There are no apparent differences between leucogabbros from the Mineral Hill intrusions and those in other areas, unlike the fine-grained olivine gabbro unit. Mean trace-element compositions are also similar in all areas. Cobalt, Ni and Cu contents are generally very low, typically <50 ppm for each element. The standard deviations for major and trace elements are similar in magnitude to those listed for the fine-grained layered olivine gabbro unit (Table 4), but likely incorporate a larger ‘noise’ component due to the difficulty of obtaining representative samples from these coarse-grained units in drillcore. Compositional variation in this unit is thus less indicative of variations in magma chemistry than in the fine-grained, olivine gabbro unit, for which the analogous sampling errors are relatively small. Nevertheless, the massive leucogabbro is richer in Al_2O_3 and CaO, and poorer in Fe_2O_3 and MgO, than the fine-grained olivine gabbro unit (Table 4). Such differences are consistent with petrographic data indicating that it is a plagioclase cumulate.

Black Olivine Gabbro

Average compositions and standard deviations of the black olivine gabbro unit are listed in Table 7, representing only the Taheke Lake lobe (44 samples) and the Happy Face lobe (2 samples) in the North intrusion. Major-element com-

Table 6. Average compositions for coarse-grained leucogabbro unit, in various areas

		Mineral Hill Intrusion Mean n=5	S.D	Worm Intrusion Mean n=6	S.D	North Intrusion NDT Lobe Mean n=8	S.D	North Intrusion Happy Face Lobe Mean n=17	S.D	North Intrusion Taheke L. Lobe Mean n=3	S.D
SiO_2	%	47.54	0.39	47.86	0.33	48.99	1.23	48.51	1	48.7	0.58
TiO_2	%	1.3	0.32	1.49	0.62	0.9	0.3	1.06	0.3	0.69	0.2
Al_2O_3	%	19.01	1.71	17.32	2.87	21.88	3.1	20.41	1.3	23.04	0.7
Fe_2O_3	%	11.83	1.44	13.73	2.63	9.23	2.98	10.76	1.3	8.33	0.72
MnO	%	0.16	0.02	0.19	0.04	0.12	0.05	0.14	0.03	0.11	0.01
MgO	%	5.81	1.01	6.4	0.99	4.66	1.14	4.93	1.03	4.55	0.08
CaO	%	9.86	0.67	9.39	0.79	10.6	1.38	10.2	0.49	11.1	0.36
Na_2O	%	3.13	0.18	3.27	0.23	3.4	0.27	3.27	0.2	3.27	0.05
K_2O	%	0.42	0.12	0.45	0.12	0.39	0.21	0.4	0.14	0.25	0.03
P_2O_5	%	0.13	0.05	0.14	0.04	0.09	0.04	0.12	0.05	0.07	0.02
LOI	%	0.84	0.43	0.26	0.32	0.59	0.81	0.51	0.49	0.24	0.07
Total		100.02		100.46		100.79		100.31		100.39	
Li	ppm	5.7	1.6	6.4	1.6	9	10.8	6.8	2.5	3.9	0.2
Be	ppm	0.5	0	0.4	0.2	0.3	0.1	0.4	0.1	0.2	0.1
Sc	ppm	22.8	4.7	31	16.1	17.8	10	20.1	3.9	14.7	1.4
Ti	ppm	8202	1691	9256	3783	5540	1648	6752	1570	4364	1277
V	ppm	145	31	207	145	109	51	118	34	95	12
Cr	ppm	50	14	39	10	50	57	35	12	40	20
Mn	ppm	1250	149	1406	277	934	314	1115	127	815	134
Co	ppm	51	7	56	6	40	9	45	8	39	2
Ni	ppm	44	23	32	11	30	5	39	13	30	0
Cu	ppm	35	8	42	21	24	6	34	8	20	8
Zn	ppm	104	17	107	21	75	26	92	12	67	7
Ga	ppm	22	2	23	2	21	1	23	2	22	0
Rb	ppm	9	0	5	3	4	2	8	2	5	0
Sr	ppm	334	28	291	42	360	44	349	25	377	3
Y	ppm	22	3	25	7	16	5	23	6	13	4
Zr	ppm	76	20	91	32	58	16	75	31	40	13
Nb	ppm	3	2	5	1	4	1	4	2	3	1
Mo	ppm	1	0	1	0	1	0	1	0	1	0
Ba	ppm	192	51	211	55	157	39	191	53	128	20
La	ppm	8	3	8	3	6	2	8	3	4	1
Ce	ppm	18	5	20	6	14	5	17	5	10	3
Dy	ppm	3.3	0.6	3.9	1.3	2.4	0.9	3.4	1.2	2	0.3
Pb	ppm	3	3	1	0	1	0	1	0	1	0

positions are similar in both areas, and generally resemble that of the coarse-grained, massive leucogabbro (Table 6) aside from slightly higher MgO and variably lower Al_2O_3 and Fe_2O_3 in the black olivine gabbro. Trace-element compositions differ only slightly between the Taheke Lake and Happy Face lobes, and most closely resemble those of the massive leucogabbro unit. However, Ni content of the black olivine gabbro (55 to 82 ppm) is generally higher than that of the massive leucogabbro.

Diabase and Related Rock Types

This unit is represented only by a few samples, but these data are very important, because rapidly cooled rocks are more likely to represent liquid compositions, and may thus provide information about parental magma compositions. The average compositions and representative analyses of diabase units that can be physically linked to the PLI are listed in Table 8. Several other diabase samples, mostly representing

Table 7. Average compositions for black olivine gabbro unit, in various areas

		North Intrusion Taheke Lake Lobe Mean n=44	S.D	North Intrusion Happy Face Lobe Mean n=2	S.D
SiO_2	%	48.17	1.37	47.47	0.33
TiO_2	%	0.94	0.27	1.17	0.02
Al_2O_3	%	20.11	2.69	17.19	1.2
Fe_2O_3	%	11.03	2.53	13.53	0.52
MnO	%	0.15	0.03	0.18	0
MgO	%	6.77	2.97	8.76	0.98
CaO	%	10	1.25	9.04	0.48
Na_2O	%	3.02	0.39	2.67	0.13
K_2O	%	0.33	0.1	0.33	0.03
P_2O_5	%	0.1	0.03	0.12	0
LOI	%	0.34	0.42	0.1	0
Total		100.82		100.5	
Li	ppm	5.6	1.4	6.5	0.6
Be	ppm	0.3	0.1	0.3	0
Sc	ppm	19.2	6.5	23.5	0.4
Ti	ppm	5844	1569	7329	231
V	ppm	121	38	154	6
Cr	ppm	45	25	55	9
Mn	ppm	1070	242	1311	14
Co	ppm	54	19	70	7
Ni	ppm	55	40	82	18
Cu	ppm	23	8	46	18
Zn	ppm	87	15	105	3
Ga	ppm	22	1		
Rb	ppm	5	2	4	2
Sr	ppm	328	44	283	9
Y	ppm	17	4	21	1
Zr	ppm	60	20	77	3
Nb	ppm	4	1	5	1
Mo	ppm	1	0	1	0
Ba	ppm	153	34	163	6
La	ppm	6	2	6	0
Ce	ppm	13	4	16	1
Dy	ppm	2.8	0.7	3.3	0.1
Pb	ppm	1	0	1	0

dykes observed outside the boundaries of the PLI, have not been included here, because their setting and age are unknown, and they may not actually belong to the PLI.

Viewed as a group, diabase samples display a similar range of SiO_2 contents to other PLI units (45.6 to 52.0%), but they have more variable major- and trace-element compositions. The analyses from the South intrusion represent diabase that appears to intrude the upper section of hole SVB-97-86, and a basal chilled zone located beneath the mineralized zone in hole SVB-97-79. Both are distinct in terms of their high TiO_2 contents (3.4 to 3.8%) and P_2O_5 contents (1 to 1.6%) compared to diabase samples from other areas, and to fine-grained olivine gabbro from the South intrusion. Four samples from basal chill zones in the North intrusion (NDT and Taheke Lake lobes) are all very similar, but exhibit much lower TiO_2 (0.4 to 1.6%) and P_2O_5 (<0.2%) than the South intrusion samples. A basal chill zone from the Mineral Hill area (hole SVB-96-36) shows higher TiO_2 than the North intrusion samples, but is not as enriched as chilled rocks associated with the South intrusion. One analysis of a chilled zone, gradational with coarse-grained leucogabbro, at the upper contact of the PLI (Happy Face lobe), is almost identical to the composition of the basal chill zones associated with the fine-grained olivine gabbro unit elsewhere in the North intrusion.

Trace-element compositions of the diabase samples show no significant differences for most elements, but there are contrasts in Zr, Nb, La and Ce, all of which are strongly enriched (by factors of 3 to 5) in diabase samples associated with the South intrusion relative to those from other areas. The Mineral Hill intrusions show some enrichment in these elements also, but not to the same extent. Their trace-element compositions seem to lie somewhere between the South and North intrusions, as do their major-element compositions. There may also be some systematic variation in Ba, which shows more variable enrichment in the samples from the South intrusion.

Diabases from the NDT lobe of the North intrusion have the lowest Zr, Nb and REE contents. The high Ni and Cu contents in sample AKC1193 are due to small amounts of sulphide; if this sample is excluded, diabase Ni contents are variable, but generally low (13 to 53 ppm). Compared to spatially associated fine-grained olivine gabbros, the diabases have higher Rb and Ba contents and (in the South intrusion and Mineral Hill intrusions) higher La, Ce and Y. In summary, aside from the NDT lobe, diabases have generally more evolved compositions than associated fine-grained olivine gabbros.

Inter-unit Comparisons

Table 9 lists the average major- and trace-element compositions of the principal units within the PLI. Some of these averages duplicate those presented in previous tables, but others represent combined averages from more than one area; the amalgamation of data was predicated on the strong intra-unit similarities noted above.

Table 8. Average and representative compositions for diabase and related rock types, in various areas

		South Intrusion			Mineral Hill Intrusions		North Intrusion Area				
		Hole 97-86 Upper Section Mean n=2	S.D	Hole 97-79 Basal Chill AKC-825	Hole 96-48 Basal Chill Zone Mean n=2	S.D	NDT Basal Chill AKC-1193	NDT Basal Chill AKC-1208	NDT Basal Chill AKC-1191	Taheke L. Basal Chill AKC-1131	Happy Face Upper Chill AKC-705
SiO_2	%	47.00	0.61	45.56	49.92	0.75	52.01	52.12	49.12	48.41	49.31
TiO_2	%	3.42	0.03	3.77	1.72	0.06	0.37	0.81	1.22	1.58	1.06
Al_2O_3	%	13.84	0.03	16.57	14.96	0.30	18.16	17.57	16.84	16.81	16.69
Fe_2O_3	%	15.17	0.39	14.48	14.59	0.00	9.91	10.88	13.91	13.45	12.35
MnO	%	0.18	0.01	0.17	0.18	0.01	0.14	0.16	0.19	0.18	0.16
MgO	%	4.22	0.20	6.22	5.68	0.43	7.48	6.56	7.51	6.45	6.30
CaO	%	7.52	0.36	7.84	8.29	0.50	7.54	7.46	8.43	9.19	8.58
Na_2O	%	3.89	0.09	3.77	2.86	0.12	2.92	3.01	3.00	2.77	2.96
K_2O	%	1.11	0.26	0.89	0.75	0.08	0.94	1.18	0.58	0.55	0.58
P_2O_5	%	1.59	0.01	0.99	0.23	0.03	0.04	0.03	0.16	0.16	0.15
LOI	%	2.88	0.82	0.19	0.97	0.66	0.71	0.98	n/a	1.79	0.91
Total		100.82		100.45	100.15		100.22	100.76	100.96	101.34	99.05
Li	ppm	5.8	1.2	9.5	6.1	0.2	18.3	30.5	12.7	8.5	3.5
Be	ppm	1.5	0	0.8	0.8	0.1	0.3	0.4	0.4	0.5	0.5
Sc	ppm	24	0.1	18.6	35.6	0.6	15.3	23.8	25.4	33.7	27.4
Ti	ppm	21168	6	22860	11234	650	2276	4939	7342	9468	6994
V	ppm	161	1	153	191	1	87	148	151	212	155
Cr	ppm	37	1	59	64	8	81	71	53	87	97
Mn	ppm	1348	105	1251	1417	84	1031	1151	1374	1233	1285
Co	ppm	44	1	52	49	3	80	55	57	61	53
Ni	ppm	26	1	50	17	3	203	42	13	49	53
Cu	ppm	28	0	25	33	3	236	129	18	53	35
Zn	ppm	124	2	118	127	6	76	80	113	117	108
Ga	ppm			24	1						
Rb	ppm	16	4	8		23	34	23	8	23	
Sr	ppm	266	18	448	297	2	294	277	294	270	309
Y	ppm	42	1	28	33	1	8	8	8	28	23
Zr	ppm	290	5	195	123	8	29	23	29	94	76
Nb	ppm	22	0	17	7	1	1	3	1	5	5
Mo	ppm	2	0	1	1	0	1	1	1	1	1
Ba	ppm	708	124	455	411	57	174	256	174	198	311
La	ppm	60	1	26	18	3	4	4	4	9	17
Ce	ppm	103	1	54	35	4	9	9	9	19	31
Dy	ppm	7	0	5.1	5	0.1	1.1	1.1	1.1	4.9	3.4
Pb	ppm	4	1	1	2	1	2	2	2	1	2

Not surprisingly, the melagabbro and peridotite unit shows the most primitive major-element composition, and the highest contents of compatible trace elements. It is clearly distinct from all other units. Although of generally very constant composition, the fine-grained, layered olivine gabbro unit contains at least two subgroups, as outlined above on the basis of TiO_2, P_2O_5, La and Ce contents, and (to a lesser extent) Sr and Ba variations. Spatially associated diabase samples define exactly the same subgroups. This suggests that these contrasts are indeed related to primary magma composition variations. However, the diabase samples are compositionally distinct from the spatially associated fine-grained olivine gabbro units. In general, they are higher in TiO_2, K_2O and P_2O_5, and locally higher in SiO_2 and CaO; conversely, they are poorer in MgO, and, locally, poorer in Al_2O_3. In terms of trace elements, they show higher Rb and Ba contents, and lower Ni contents. In the South and Mineral Hill intrusions, the diabases also exhibit higher Y, Nb, La and Ce than associated fine-grained olivine gabbros. Overall, diabase samples have more evolved compositions than the associated fine-grained olivine gabbros. Many of the latter are plagioclase–olivine cumulates, and these compositional contrasts with possible parental magmas are, to some extent, expected. The accumulation of plagioclase and olivine, from which most of the above-noted elements are excluded, will inevitably reduce the overall abundances of such elements.

Major-element contrasts between the fine-grained, layered olivine gabbro and the coarse-grained massive leucogabbro exist, but are very subtle. The latter has slightly higher SiO_2, Al_2O_3, CaO, Na_2O and K_2O, coupled with lower Fe_2O_3 and MgO. Among the trace elements, the leucogabbro is dis-

Table 9. Comparison of average compositions for the Pants Lake intrusions to the average compositions of the Voisey's Bay and Mushuau intrusions; comparative data from Li *et al.* (2000)

		Melagabbro	Fine-grained, layered olivine gabbro			Lcgabbro	Black gabbro	Voisey's Bay Intrusion				Mushuau intrusions	
		All Areas Mean n=6	South Intrusion Mean n=10	North Intr. NDT / HF Mean n=38	North Intr. Taheke L. Mean n=5	North Intrusion Mean n=28	North Intrusion Mean n=46	Normal Troctolite Mean n=102	Variable Troctolite Mean n=48	Conduit Rocks Mean n=11	Mela-troctolite Mean n=21	Mela-troctolite Mean n=10	Variable Troctolite Mean n=8
SiO_2	%	41.14	47.5	46.29	45.22	48.67	48.14	46.79	45.18	41.26	43.46	41.57	48.9
TiO_2	%	1.34	1.75	0.91	0.53	0.97	0.95	1.32	1.08	2.14	0.75	0.63	0.88
Al_2O_3	%	8.24	18.04	17.79	15.21	21.11	19.98	19.38	18.94	16.72	7.34	9.41	18.7
Fe_2O_3	%	18.35	11.71	12.97	14.04	10.06	11.14	9.28	11.3	18.89	13.83	19.33	12.2
MnO	%	0.20	0.15	0.17	0.17	0.13	0.15	0.1	0.1	0.12	0.18	0.21	0.11
MgO	%	21.77	7.99	9.79	15.19	4.81	6.86	9.71	9.61	6.69	23.23	21.47	7.98
CaO	%	4.17	8.62	9.10	7.65	10.41	9.96	8.78	8.22	7.16	5.95	4.18	6.9
Na_2O	%	1.61	3.37	2.67	1.94	3.31	3.00	2.91	2.86	2.79	0.84	1.52	3.4
K_2O	%	0.39	0.57	0.29	0.16	0.38	0.33	0.37	0.34	0.62	0.36	0.18	0.33
P_2O_5	%	0.30	0.35	0.09	0.06	0.11	0.10	0.24	0.2	0.29	0.13	0.08	0.11
LOI	%	2.83	0.43	0.71	0.61	0.50	0.33	0.01	0.4	2.02	2.63	0.6	0.35
Total		100.34	100.29	100.33	100.29	100.46	100.81	99.01	98.3	98.69	98.78	99.3	99.86
Li	ppm	5.8	4.8	5.3	3.8	7.1	5.6						
Be	ppm	0.3	0.4	0.3	0.1	0.4	0.3						
Sc	ppm	10.5	17.1	18.4	13.2	18.9	19.4	11	9	9.6	23.2	12.8	15.3
Ti	ppm	8115	10752	5622	3295	6150	5909						
V	ppm	82	120	110	74	113	122	73	65	97	122	71	105
Cr	ppm	121	106	60	84	40	45	121	150	119	2113	267	311
Mn	ppm	1546	1104	1262	1235	1031	1080						
Co	ppm	148	55	75	100	43	55	53	111	223	102	131	119
Ni	ppm	820	90	109	186	35	56	244	1948	3067	1287	684	1104
Cu	ppm	340	21	33	13	30	24	36	847	1570	146	42	721
Zn	ppm	118	90	95	93	84	88	67	77	107	97	107	101
Ga	ppm	0	18	21		22	21	15	15	16	9	10	16
Rb	ppm	2	5	4	2	7	5	4	4	14	13	2	4
Sr	ppm	160	414	291	244	355	326	530	539	498	102	189	341
Y	ppm	12	17	17	9	20	17	9	8	10	11	9	14
Zr	ppm	72	93	57	33	66	61	64	51	67	45	55	4
Nb	ppm	4	7	3	2	4	4	3	3	5	3	2	4
Mo	ppm	1	1	1	1	1	1						
Ba	ppm	172	286	147	96	175	153	212	184	265	93	99	189
La	ppm	7	12	5	2	7	6	7	6	9	5	5	8
Ce	ppm	21	25	14	8	15	13	17	15	22	12	11	18
Dy	ppm	2.3	2.9	2.5	1.8	3.0	2.8	1.7	1.5	1.9	1.9	1.5	2.3
Pb	ppm	5	1	1	1	1	1	2	11	22	7	1	5

tinguished by lower Cr, Co and Ni, and weak enrichment in Y, Zr, Ba, La and Ce. The black olivine gabbro has a major-element composition similar to that of the coarse-grained leucogabbro, but has higher MgO relative to Fe_2O_3. The average trace-element composition of the black olivine gabbro is not readily distinguishable from either of the other gabbro units.

Comparisons with Mafic Rocks from elsewhere in Labrador

Table 9 lists key average compositions from the PLI, and compares them with the mean compositions of Mesoproterozoic mafic rocks from various parts of Labrador, including the Voisey's Bay and Mushuau intrusions of the Voisey's Bay district.

The mean major-element composition of the fine-grained, layered olivine gabbro unit is very similar to that of the 'normal troctolite' (NT) and 'variably-textured troctolite' (VTT) units at Voisey's Bay (Li *et al.*, 2000). The only obvious differences in trace-element composition are the higher Ni, Cu and Sr contents of the Voisey's Bay rocks compared to the PLI olivine gabbro. However, the high Ni and Cu values in the VTT average (Table 10) are due to the presence of minor sulphide mineralization in most of these samples and are not indicative of magmatic concentrations. The fine-grained olivine gabbro of the PLI shows higher MgO and

Table 10. Average REE compositions of unmineralized rocks in the Pants Lake intrusions

(all data are in ppm) Unit	N	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Normalization Factors used in REE Charts (from Sun and McDonough, 1989)															
Chondrite		0.237	0.612	0.095	0.467	0.153	0.058	0.205	0.037	0.254	0.057	0.165	0.025	0.17	0.025
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	0.4

lower SiO_2 than the variable troctolite of the Mushuau intrusions, suggesting that its composition is more primitive than the Mushuau intrusion rocks. Melagabbro from the PLI more closely resembles the melatroctolite of the Mushuau intrusions than melatroctolite inclusions from the Voisey's Bay intrusion, which are significantly more magnesian. However, it is difficult to compare trace-element compositions because of the presence of sulphides in some of the rocks from Voisey's Bay. More rigorous comparisons are also seriously hampered by the lack of publically available numerical data from Voisey's Bay; Li *et al.* (2000) present only average compositions and selected variation diagrams.

Compared to the calculated bulk composition of the Kiglapait intrusion (Scoates and Mitchell, 2000) and the average composition of its fine-grained marginal phases, the gabbros of the PLI are poorer in SiO_2, and richer in MgO and Fe_2O_3. However, PLI diabase analyses (Tables 8 and 9) resemble the presumed Kiglapait parental compositions, and, in some cases, appear more fractionated. They also resemble the mean compositions of high-Al gabbros from the HLIS and the Harp Dykes. Amongst other mafic suites in Labrador, these are the only rocks that show high TiO_2 contents akin to those reported here from the South intrusion. Trace-element comparisons with these examples are hampered by the limited trace-element data currently available from outside the Voisey's Bay area, and the lack of raw numerical data for the average compositions given by Li *et al.* (2000).

MAJOR-ELEMENT VARIATION TRENDS IN UNMINERALIZED ROCKS

Tabular listings provide a great deal of information about general compositions of units, but they do not adequately convey details of variation trends. This section presents and discusses geochemical variation diagrams that summarize inter-element correlations and variations. The effects of magmatic differentiation are most commonly assessed by plotting components against a chemical index of fractionation. For mafic rocks such as the PLI, MgO is generally preferred over the conventional choice of SiO_2 in intermediate and felsic rocks. Unlike SiO_2, MgO is a generalized inverse measure of magmatic fractionation.

Description of Variation Trends

Major-element oxides, excluding Fe_2O_3, are all negatively correlated with MgO. For many elements (*e.g.*, Al_2O_3 and CaO, in Figure 32), this correlation is generally linear, and all of the samples lie upon a single common trend irrespective of geological unit or geographic area. These trends are anchored at the high-Mg (unfractionated) end by the melagabbro–peridotite unit, and at the low-Mg (fractionated) end by the coarse-grained, massive leucogabbro unit and parts of the black olivine gabbro unit. Generally, the massive leucogabbro is characterized by higher Al_2O_3 and CaO contents, and lower MgO, compared to the fine-grained, layered olivine

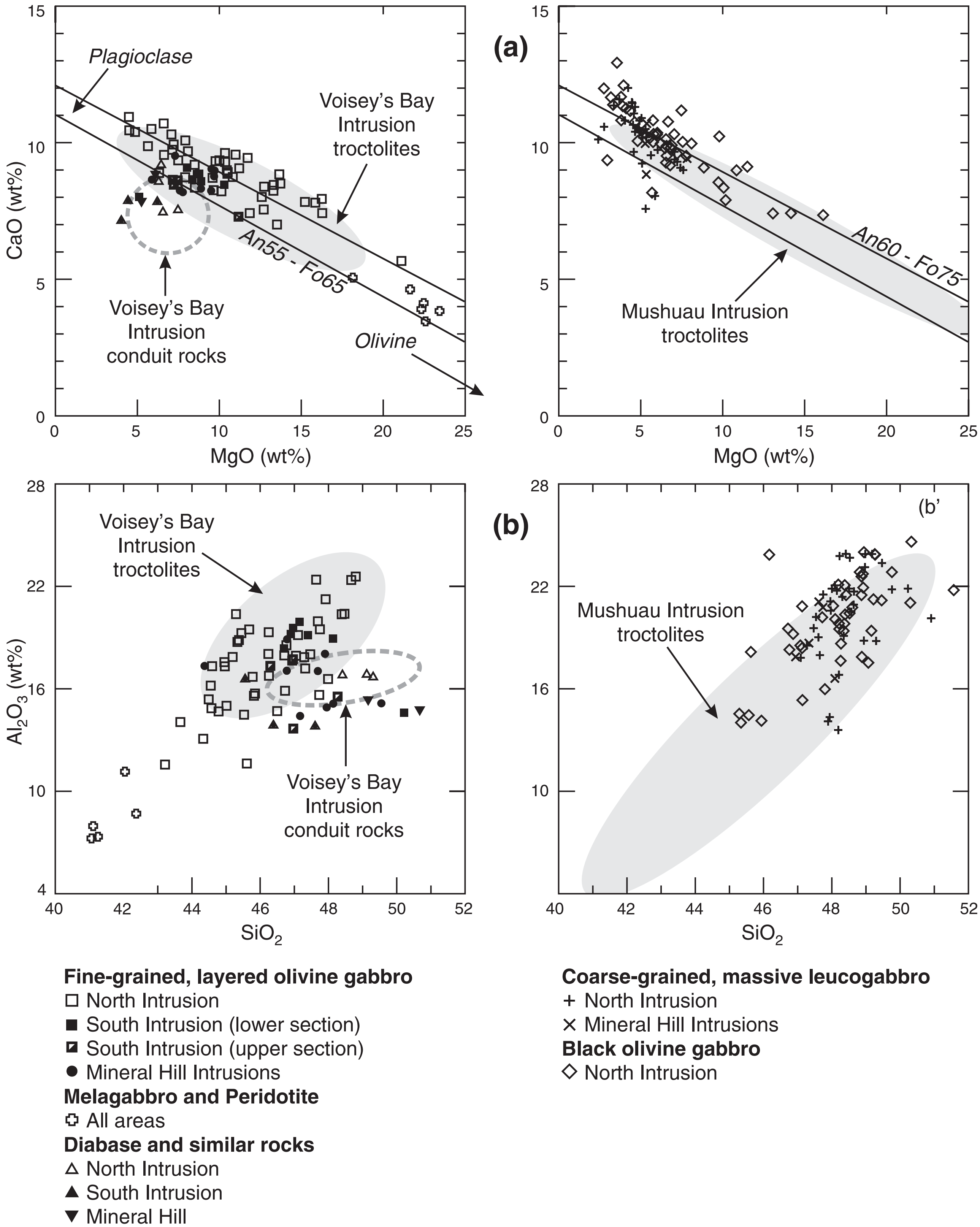


Figure 32. *Selected major-element variation trends in the Pants Lake intrusions. a) CaO vs MgO. b) Al_2O_3 vs SiO_2. Fields for the Voisey's Bay and Mushuau intrusions constructed from Li* et al. *(2000). Each diagram is shown as two plots in order to represent different units without excessive 'clutter'.*

gabbro unit, but there is considerable overlap between them, and with the black olivine gabbro unit. Diabase samples are characterized by lower CaO and Al_2O_3 at a given MgO content (Figure 32), largely reflecting the absence of cumulus plagioclase in these rocks. The black olivine gabbro unit overlaps both the fine-grained, layered olivine gabbro unit and the massive leucogabbro unit, but has a much wider range of MgO contents than the latter.

Other major-element oxides, such as TiO_2 and Na_2O (Figure 33) discriminate the fine-grained olivine gabbro unit from different areas. Samples from the South and Mineral Hill intrusions are characterized by high TiO_2, as are related diabase and melagabbro samples from the South intrusion. South intrusion diabase samples have, by far, the highest TiO_2 (>3%). Similar trends against MgO are shown by P_2O_5 (not illustrated), which is also strongly enriched in diabase sam-

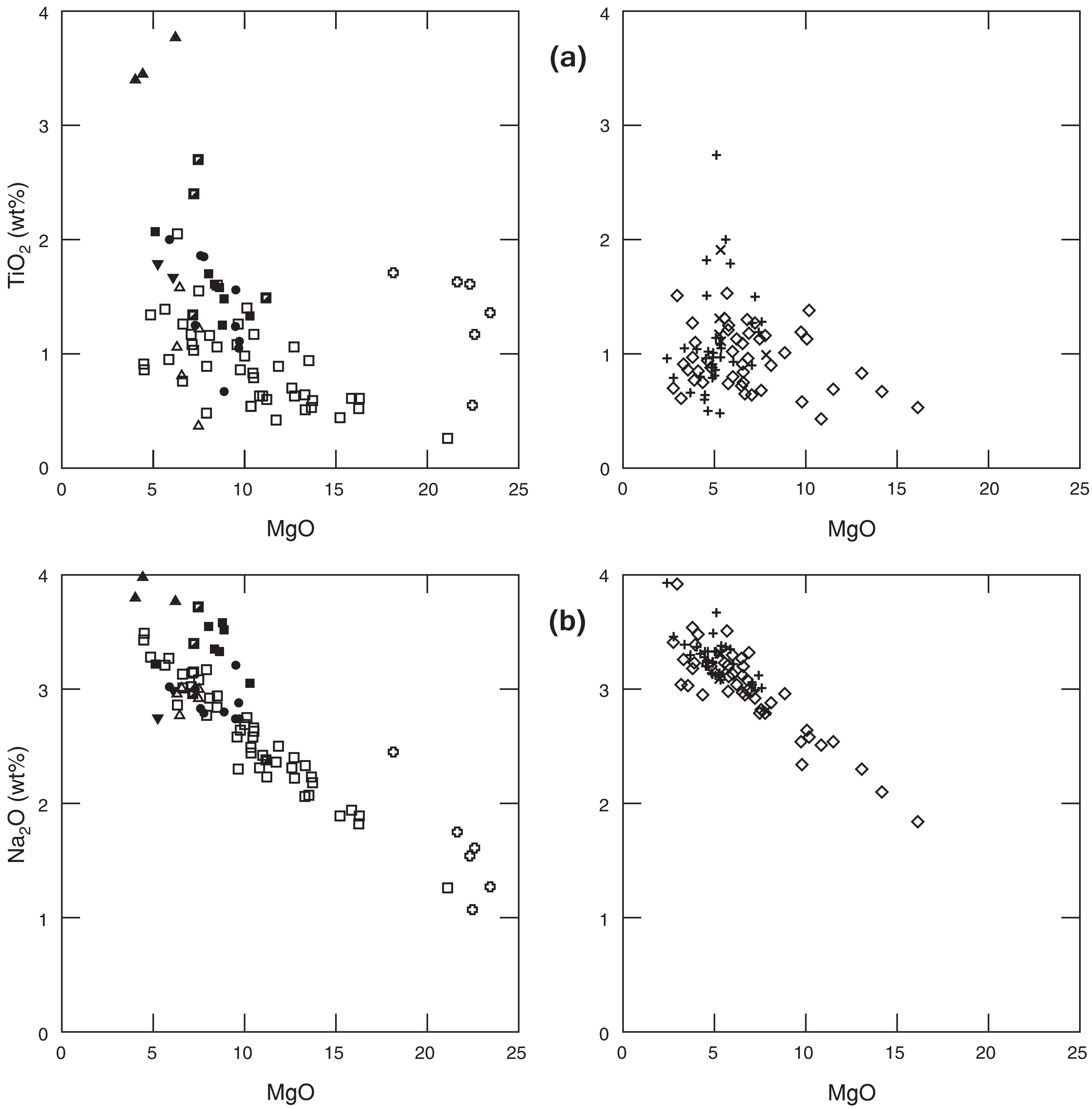


Figure 33. *Selected major-element variation trends in the Pants Lake intrusions. a) TiO_2 vs MgO. b) Na_2O vs MgO. Fields for the Voisey's Bay and Mushuau intrusions constructed from Li* et al. *(2000). Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

ples. In the Na_2O–MgO diagram (Figure 33), there are clearly two subparallel trends; an upper (elevated Na_2O) trend defined largely by the South intrusion samples, and a lower (depressed Na_2O) trend defined by the remainder of the data, including most samples from the Mineral Hill intrusions. These contrasts in Na_2O contents are much less evident in tabular listings. A similar, but less striking, double trend is revealed by K_2O contents (not illustrated).

The subalkaline nature of most PLI mafic rocks is illustrated well by the (Na_2O+K_2O)–SiO_2 plot (Figure 34a), but there is a tendency for higher alkali-element contents in fine-grained olivine gabbro and diabase from the South intrusion, as well as most melagabbro samples that plot partially in the alkaline field. However, no such contrast in alkali-element contents is visible in data from the coarse-grained, massive leucogabbro unit (Figures 33b and 34a). Magnesium numbers (*i.e.*, molecular MgO/[MgO+FeO]) decline from almost 75 in melagabbro to about 30 in massive leucogabbro, with considerable overlap (Figure 34b). There is a progressive decrease in Mg number from melagabbro, through fine-grained olivine gabbro, to black olivine gabbro and massive leucogabbro, coupled with a slight increase in SiO_2. The black olivine gabbro unit is relatively Mg-rich (Mg number generally >50) compared to the massive leucogabbro unit (Mg number generally <50). Most diabase samples have Mg numbers <50.

The PLI mafic rocks exhibit tholeiitic (*i.e.*, Fe-enrichment) major-element trends in the AFM ternary plot (Figure 35) and in the Al_2O_3–(FeOt + TiO_2)–MgO plot (Figures 35 and 36), but neither projection provides any useful unit distinctions, aside from separating melagabbro samples by virtue of their high MgO content. Note that the field names in Figures 35 and 36 are designed for volcanic rocks, and do not necessarily apply to cumulate rocks such as those of the PLI. Nonetheless, the bulk of the data for the fine-grained olivine gabbro unit lie within the high-Mg tholeiite field.

Comparisons with Mafic Rocks of the Voisey's Bay Area

Relatively little published major-element geochemical data is available from the Voisey's Bay area, but some comparisons can be made with the results of Lightfoot and Naldrett (1999) and Li *et al.* (2000). In the CaO–MgO diagram, most of the data form a well-defined array that lies between tie lines joining plagioclase (An60–An55) and olivine (Fo65–Fo75), reflecting the dominance of olivine and plagioclase in the gabbros. However, measured olivine compositions in PLI gabbros are generally less than Fo60 (MacDonald, 1999). The more calcic composition of the massive leucogabbro and black olivine gabbro units probably indicates a larger contribution of CaO from clinopyroxene, and diabase samples all lie below the main data array. The overall distribution of data is remarkably similar to that shown by the Voisey's Bay intrusion (Li *et al.*, 2000; fields indicated on Figure 32). The chilled marginal rocks and the 'feeder olivine gabbro' (labelled 'conduit rocks' in Figure 32b, considered to represent the closest approach to initial liquid compositions at Voisey's Bay, have compositions analogous to the Pants Lake diabase samples. A similar correspondence is seen in a plot of the Al_2O_3 vs. SiO_2 diagram (*see* Kerr *et al.*, 2001) although the points are less tightly grouped than for the Voisey's Bay intrusion data of Li *et al.* (2000). Lightfoot and Naldrett (1999) and Li *et al.* (2000) also provide information on the Mushuau intrusions, which shows a much greater compositional range than the Voisey's Bay intrusion or the PLI. In terms of major-element trends, the PLI more closely resemble the Voisey's Bay intrusion than the Mushuau intrusions.

TRACE-ELEMENT VARIATION TRENDS IN UNMINERALIZED ROCKS

Many trace elements show either no systematic variation, or poor discrimination between units and areas, and are thus not discussed in detail. However, others show systematic trends against MgO or other indices, and provide useful distinction among units. The following discussion is conveniently subdivided by element groupings.

Transition Elements

The transition elements Sc, V, Mn and Zn show either flat trends against MgO, or poor correlations, and do not provide any useful unit discrimination. Chromium shows a positive correlation with MgO, which is to be expected, but South intrusion samples show higher Cr at relatively low MgO compared to other areas (Figure 37a). Cobalt shows a very good positive correlation with MgO, suggesting that it is mostly controlled by olivine, and the low-Co end of the data array is anchored by diabase samples (Figure 37b). However, some coarse-grained leucogabbro and black olivine gabbro samples have lower Co contents than these, suggesting that they contain larger amounts of cumulus plagioclase. Nickel also shows a positive correlation with MgO, which is to be expected in sulphide-free rocks, and indicates control by olivine (Figure 38a). Note that melagabbro samples from the South intrusion have high Ni contents (>1000 ppm) because they are sulphide-bearing, and therefore are excluded from the diagram. As in the case of Co, diabase samples anchor the low-Ni end of the data array. The highest Ni contents are shown by the fine-grained olivine gabbro unit and some samples of the black olivine gabbro, but most of the samples contain less than 150 ppm Co and 200 ppm Ni (Figures 37b and 38a). In contrast, Cu shows no systematic variation against MgO, and is low (commonly <50 ppm) in all units (Figure 38b). Some diabase samples from the North intrusion, however, have elevated Cu contents above 150 ppm, but these contain minor

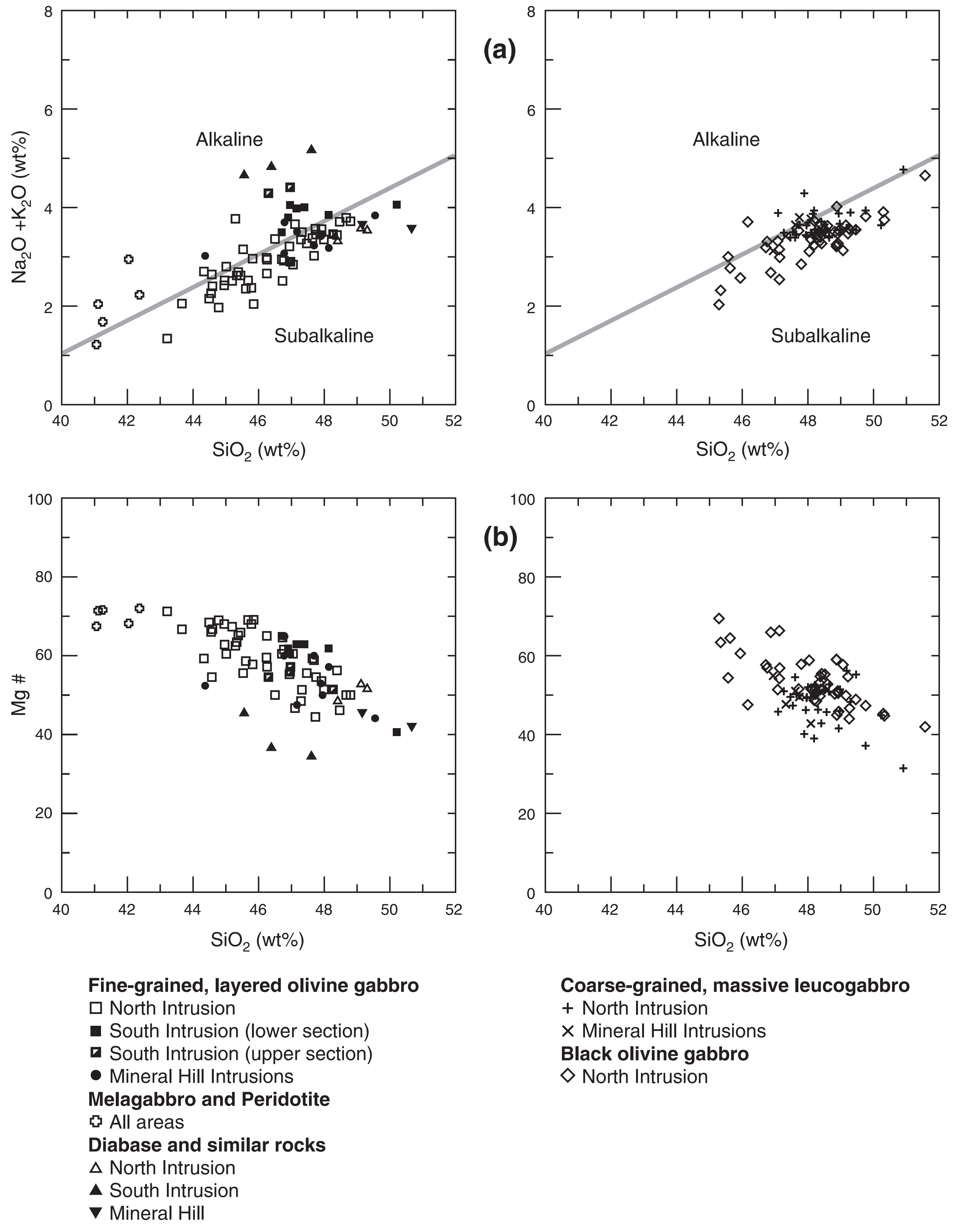


Figure 34. *Selected major-element variation trends in the Pants Lake intrusions. a)* $Na_2O + K_2O$ *vs* SiO_2*. b) Magnesium Number [molecular (MgO/MgO + FeO)] vs* SiO_2*. Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

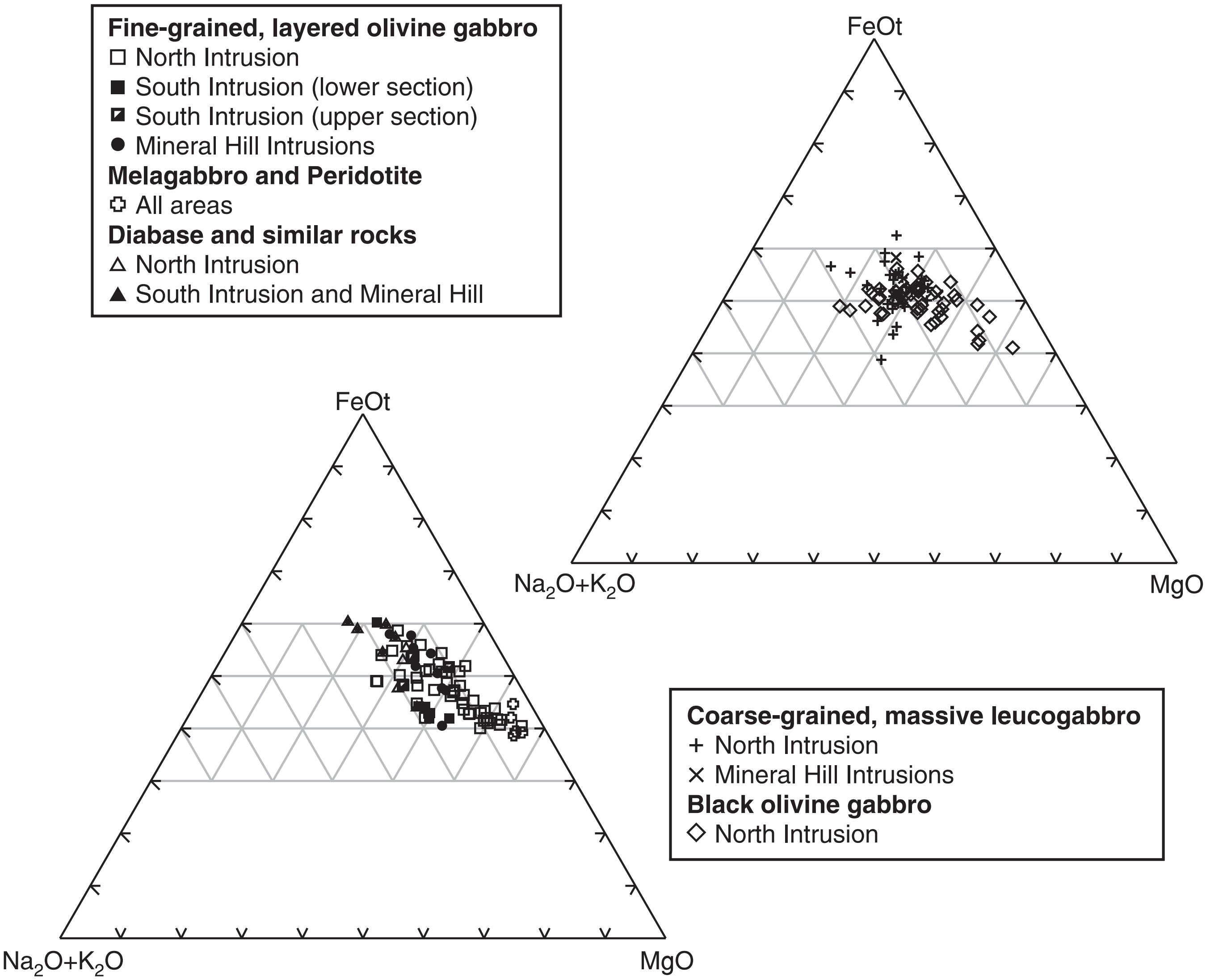


Figure 35. *Selected major-element variation trends in the Pants Lake intrusions. AFM ternary diagram. Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

amounts of sulphide, and are therefore excluded from the diagram (Figure 38d).

Lithophile Elements

Rubidium is low (<10 ppm) in almost all samples in which it was analyzed for, and shows no useful variation patterns. Strontium shows a good inverse correlation against MgO, as is to be expected for it behaves incompatibly during olivine fractionation (Figure 39a). Fine-grained olivine gabbros from the South intrusion are, in part, distinguished by higher Sr contents at a given MgO content, but some of these data lie within the main data array, as do most samples from Mineral Hill (Figure 39a). Barium provides a similar (but steeper) inverse trend, also indicating incompatibility, and South intrusion samples show distinctly higher Ba at a given MgO content (Figure 39b). The differences in the Sr and Ba trends suggest that Sr is compatible in plagioclase, whereas Ba is not; consequently, the presence of cumulus plagioclase in samples introduces a more significant noise component to the Sr data.

High-field-strength (HFS) and Rare-earth-elements (REE)

Of the HFS elements, Nb probably shows the clearest pattern, and is characterized by a negative correlation against MgO (Figure 40a) that closely resembles the pattern for the lithophile element Ba (Figure 39b). South intrusion samples and some Mineral Hill intrusion samples show elevated Nb compared to the North intrusion; most diabase samples also show Nb enrichment. Zirconium patterns (not

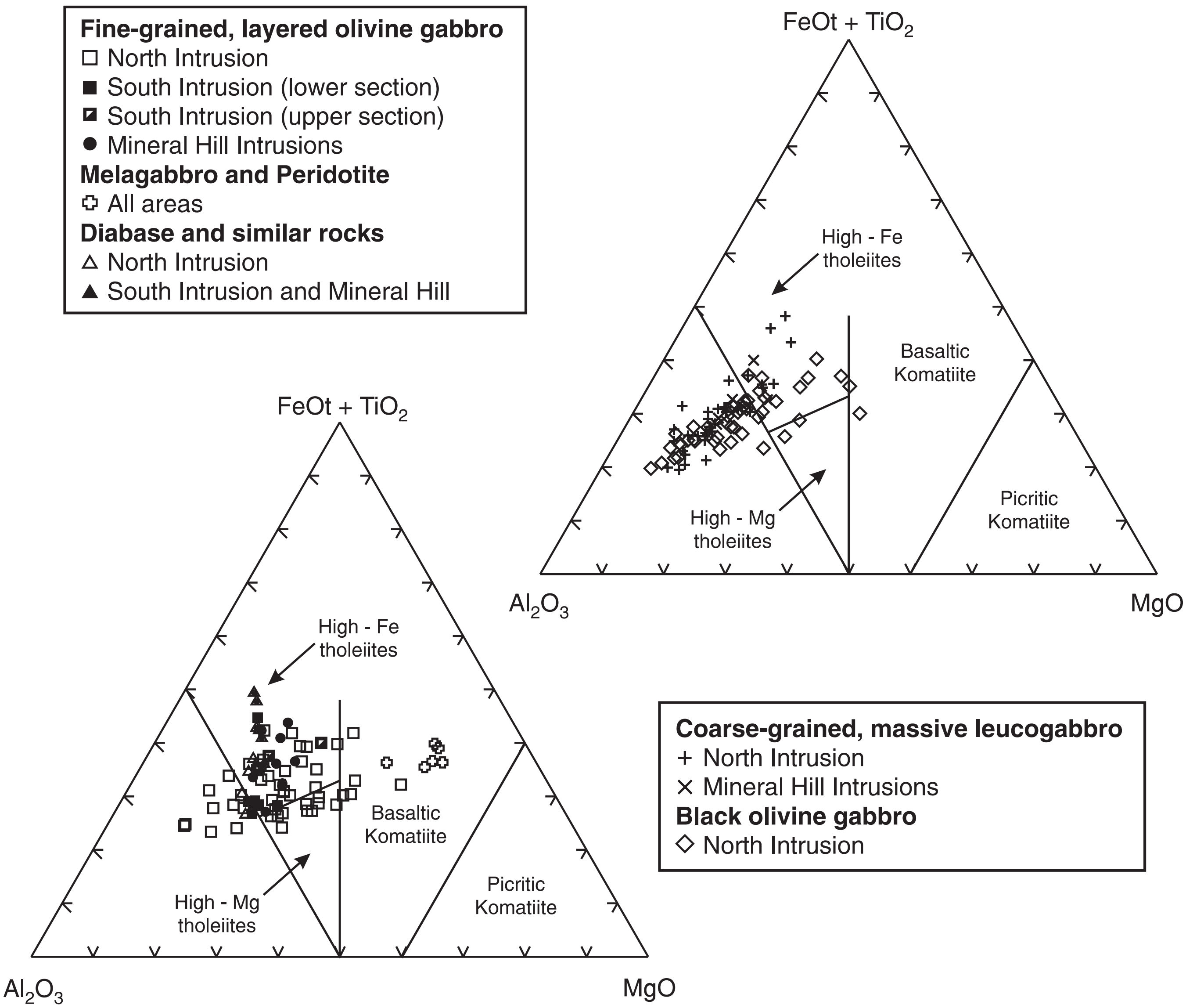


Figure 36. *Selected major-element variation trends in the Pants Lake intrusions. Al_2O_3 - (FeO_t+ TiO_2) - MgO ternary diagram. Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

illustrated) resemble the Nb trends, but show more scatter. Yttrium data (not illustrated) exhibit the same generally negative correlation against MgO, but do not show any clear distinction among different areas, although diabase samples exhibit relatively high Y contents. The pattern for Ce (Figure 40b) is shared by other REE such as La and Dy and, in general, resembles the pattern for Nb (Figure 40a). South intrusion samples and some Mineral Hill intrusion samples again show enrichment in all these elements relative to the North intrusion.

Trace-element Ratios

Trace-element ratios are, in many cases, more informative than raw trace-element data. A plot of Ni vs. Cu shows a rather disorganized pattern in which Ni/Cu ratios range from a low of about 0.5 to over 20 (Figure 41a). This variation contrasts with the strong covariant pattern for Ni and Cu shown by mineralized samples (*see* Figures 26, 28, and 31; also Kerr, 1999) in which Ni/Cu remains almost constant at just over 1. This wide range of Ni/Cu in sulphide-free samples indicates the effects of cumulus olivine, which concentrates Ni, but not Cu; effects from olivine are 'drowned' in mineralized samples, where both elements are controlled by sulphides. However, the diabase samples, which likely represent the closest approach to liquid compositions, have Ni/Cu ratios between 0.5 and 2, with an average value close to 1.0, similar to the average Ni/Cu of mineralized rocks. The Ni/Co ratios change in a similar manner, from 0.25 to 1.0 in diabase samples, to >4.0 in olivine-rich melagabbro samples (Figure 41b).

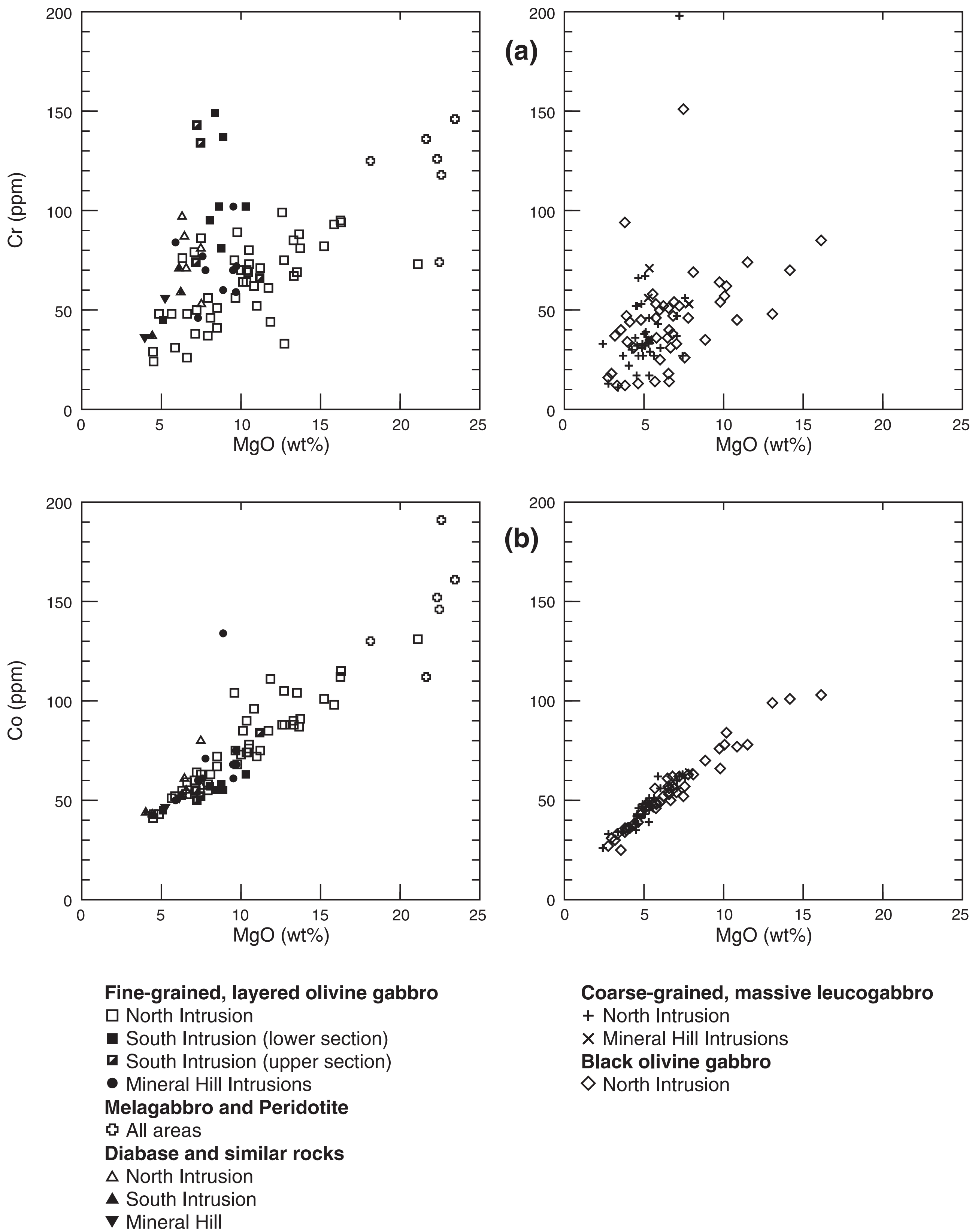


Figure 37. *Selected trace-element variation trends for transition elements in the Pants Lake intrusions. a) Cr vs MgO. b) Co vs MgO. Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

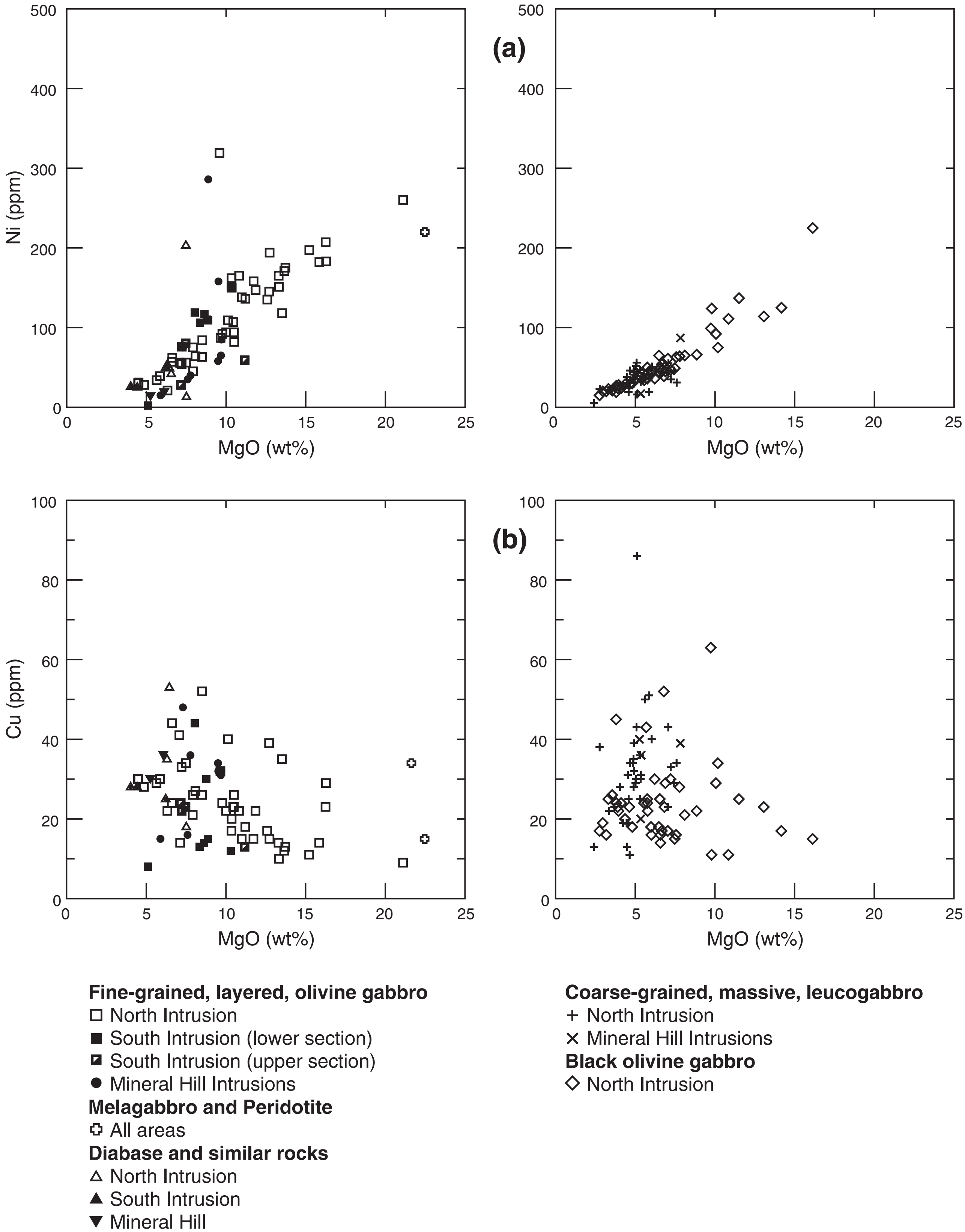


Figure 38. *Selected trace-element variation trends for transition elements in the Pants Lake intrusions. a) Ni vs MgO. b) Cu vs MgO. Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

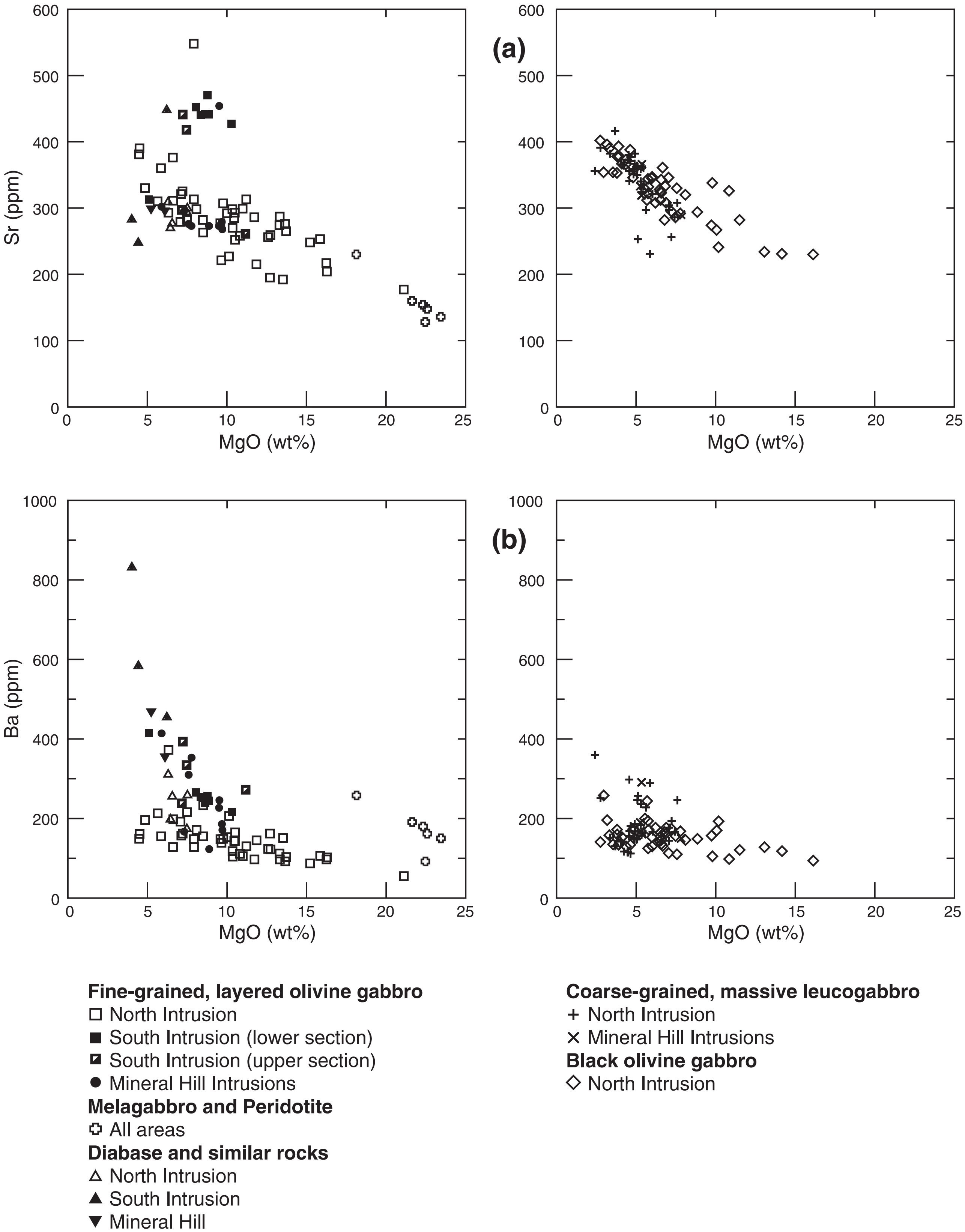


Figure 39. *Selected trace-element variation trends for lithophile elements in the Pants Lake intrusions. a) Sr vs MgO. b) Ba vs MgO. Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

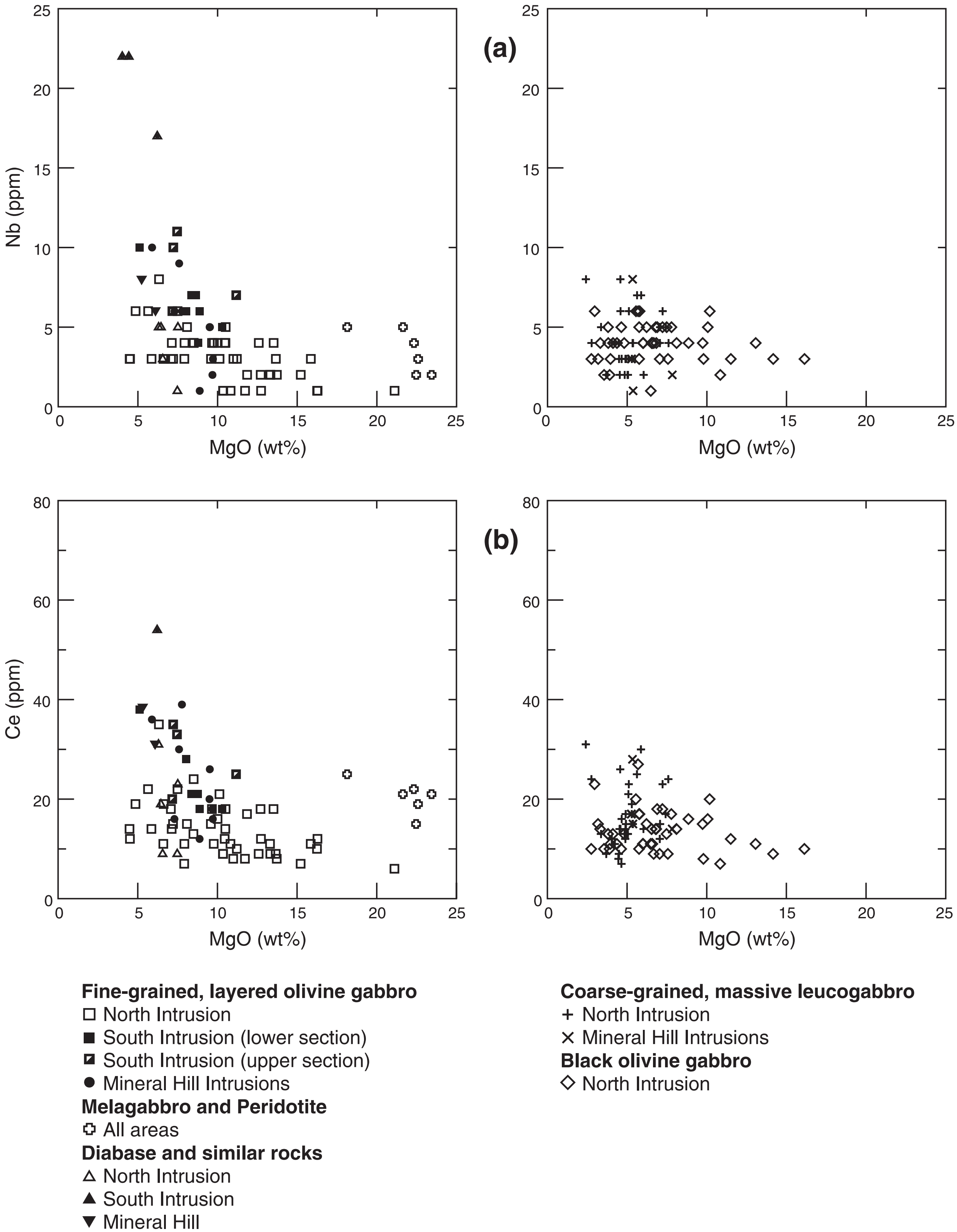


Figure 40. *Selected trace-element variation trends for HFSE and REE in the Pants Lake intrusions. a) Nb vs MgO. b) Ce vs MgO. Each diagram is shown as two plots to represent different units without excessive 'clutter'.*

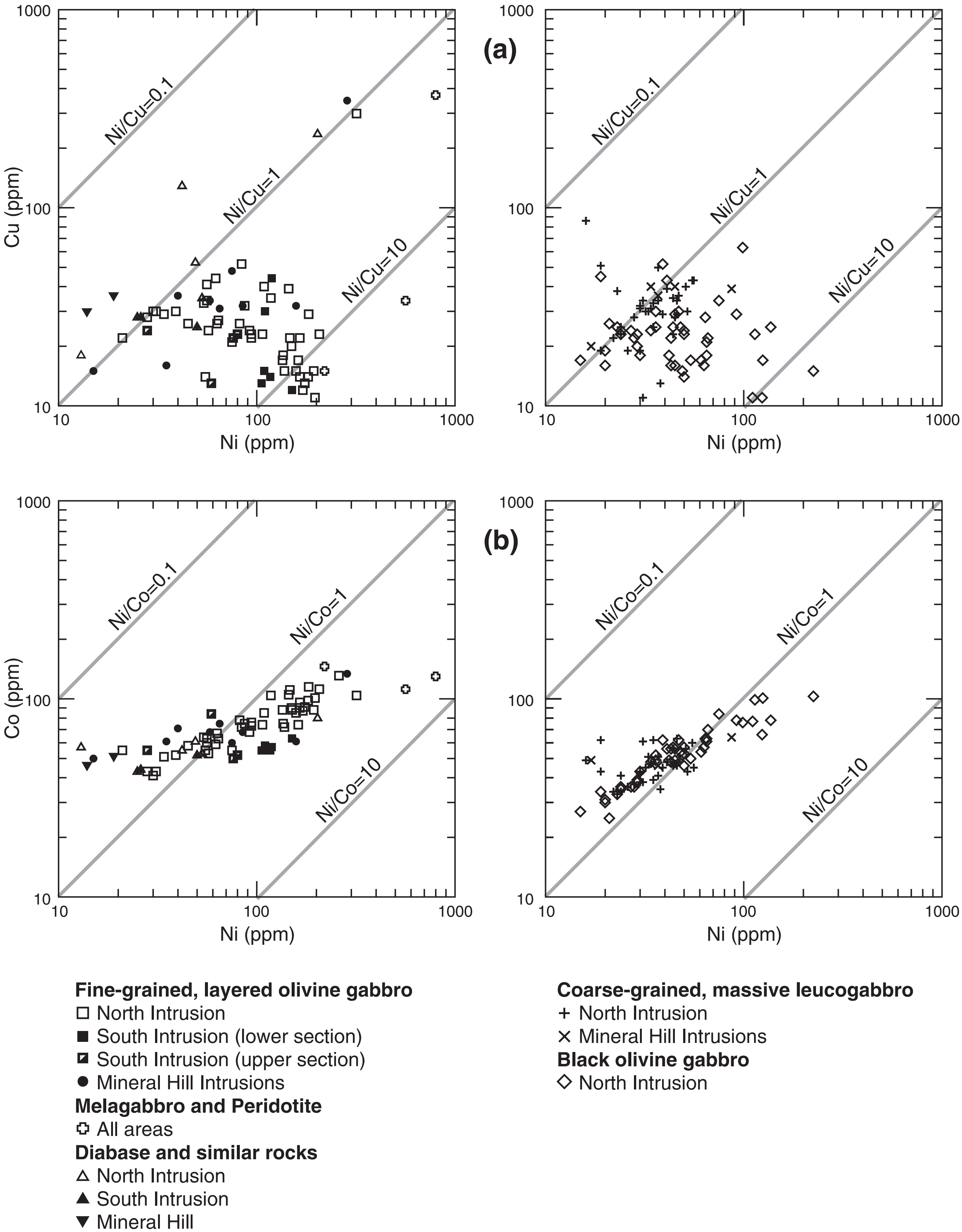


Figure 41. *Selected trace-element variation trends for inter-element ratios in the Pants Lake intrusions. a) Cu vs Ni. b) Co vs Ni. Note that mineralized rocks are excluded from these plots.*

Nickel/cobalt ratios in the sulphide-free rocks are much lower than those observed in mineralized samples where the average Ni/Co is about 8, albeit with a wide range of values (Figure 30; Kerr, 1999).

Copper/zirconium ratios have been suggested as a potentially valuable indicator of metal depletion caused by sulphide segregation because the two elements are normally covariant and incompatible, and unaffected by accumulation of either olivine or plagioclase. Virtually all sulphide-free samples from the PLI show low Cu/Zr ratios (<1), and there appears to be little or no correlation between Cu/Zr and Ni (Figure 42a). Values of <1 are generally considered to record the effects of sulphide removal, which affects Cu, but not Zr (*e.g.*, Lightfoot *et al.*, 1994).

Cerium/yttrium ratios are another useful measure, as they provide a good indication of the slope of the REE profile. Although Y is not (strictly) a rare-earth element, it has normalized abundances similar to those of heavy REE such as Yb or Lu. The contrasts in Ce/Yb ratios previously noted by MacDonald (1999) imply that Ce/Y should separate South and North intrusions. This ratio provides an effective discriminant (Figure 42b) when plotted against [Sr + Ba]. Fine-grained gabbros from the South intrusion are separated by virtue of high Ce/Y and elevated [Sr + Ba], and melagabbro samples from the South intrusion are also well distinguished by high Ce/Y. However, coarse-grained, massive leucogabbro and black olivine gabbro from the North intrusion have identical Ce/Y ratios, similar to the fine-grained olivine gabbro from that area.

Rare-earth-element Patterns

Rare-earth-element data were acquired for a subset of samples representing unmineralized rocks; average REE compositions of the various units are listed in Table 10. All REE profiles are normalized to the chondritic values of Sun and McDonough (1989).

The REE patterns for fine-grained olivine gabbro of the North intrusion (NDT lobe) are simple, and show gentle slopes, with normalized La/Lu of 2-3 (Figure 43a). Most samples show a positive Eu anomaly, which is a signature of cumulus plagioclase, and the amplitude of this anomaly is inversely correlated with the total REE abundance. This is a common pattern in mafic igneous rocks containing cumulus plagioclase, which hosts Eu but excludes the other REE; the plagioclase in the rock essentially dilutes all the remaining REE (and many other trace elements). A troctolitic sample resembles the gabbroic rocks. Diabase samples associated with the North intrusion have higher REE abundances than most gabbros and troctolites, and also show slightly steeper REE patterns, due to slight relative enrichment in light REE (elements La to Eu). Their REE abundances resemble those of the most REE-enriched, fine-grained olivine gabbros.

South intrusion fine-grained olivine gabbro samples have rather different REE and trace-element patterns. The REE profile (Figure 43b) is distinctly steeper, and the normalized La/Lu ratio is >6, as opposed to about 2 to 3 for the North intrusion. However, the overall shape of the pattern is similar, and most samples show modest positive Eu anomalies. The sample that lacks such a feature is, predictably, the one with the highest REE abundances, implying that REE abundances are again mostly controlled by the amount of dilution from cumulus plagioclase. Aside from their Eu anomalies, profiles from the upper and lower sections of the South intrusion are identical. Diabase samples associated with South intrusion gabbros show overall REE enrichment (up to La = 200 x chondrite), slightly steeper LREE profiles compared to the gabbros, and lack Eu anomalies. However, their profiles remain similar to those of associated fine-grained olivine gabbro.

Fine-grained olivine gabbro samples from the Mineral Hill intrusion have gently sloping REE patterns that resemble those from the North intrusion, but show somewhat higher REE abundances (Figure 43c). They clearly do not resemble the South intrusion fine-grained olivine gabbro. Chilled diabase samples that are gradational with fine-grained barren olivine gabbro below the mineralized sequence at Mineral Hill have the highest REE abundances (up to 80 x chondrite) and lack Eu anomalies. The REE data suggest correlation of the Mineral Hill intrusion with the North intrusion, despite their spatial proximity to the South intrusion.

Melagabbro samples from the South intrusion have a REE profile that is identical to the fine-grained, layered, olivine gabbros, but show very small negative Eu anomalies (Figure 43d). These patterns imply a slight deficiency of cumulus plagioclase, rather than an excess, which is to be expected in rocks that are mafic mineral cumulates.

Coarse-grained, massive, leucogabbro from the Happy Face and NDT lobes of the North intrusion have REE patterns that are essentially identical to those from the fine-grained olivine gabbro in this area (Figure 44A). Although there is significant overlap, the leucogabbro tends to have slightly higher REE abundances than the fine-grained gabbro. As noted previously, the amplitude of the positive Eu anomaly is inversely correlated with the overall REE abundance. A diabase sample from a chilled zone at the upper contact of the leucogabbro unit (Happy Face lobe) is slightly LREE-enriched, but its profile from Eu to Lu is identical to that of the coarse-grained leucogabbro. Light rare-earth-element enrichment probably reflects the presence of country-rock fragments. Two samples of coarse-grained

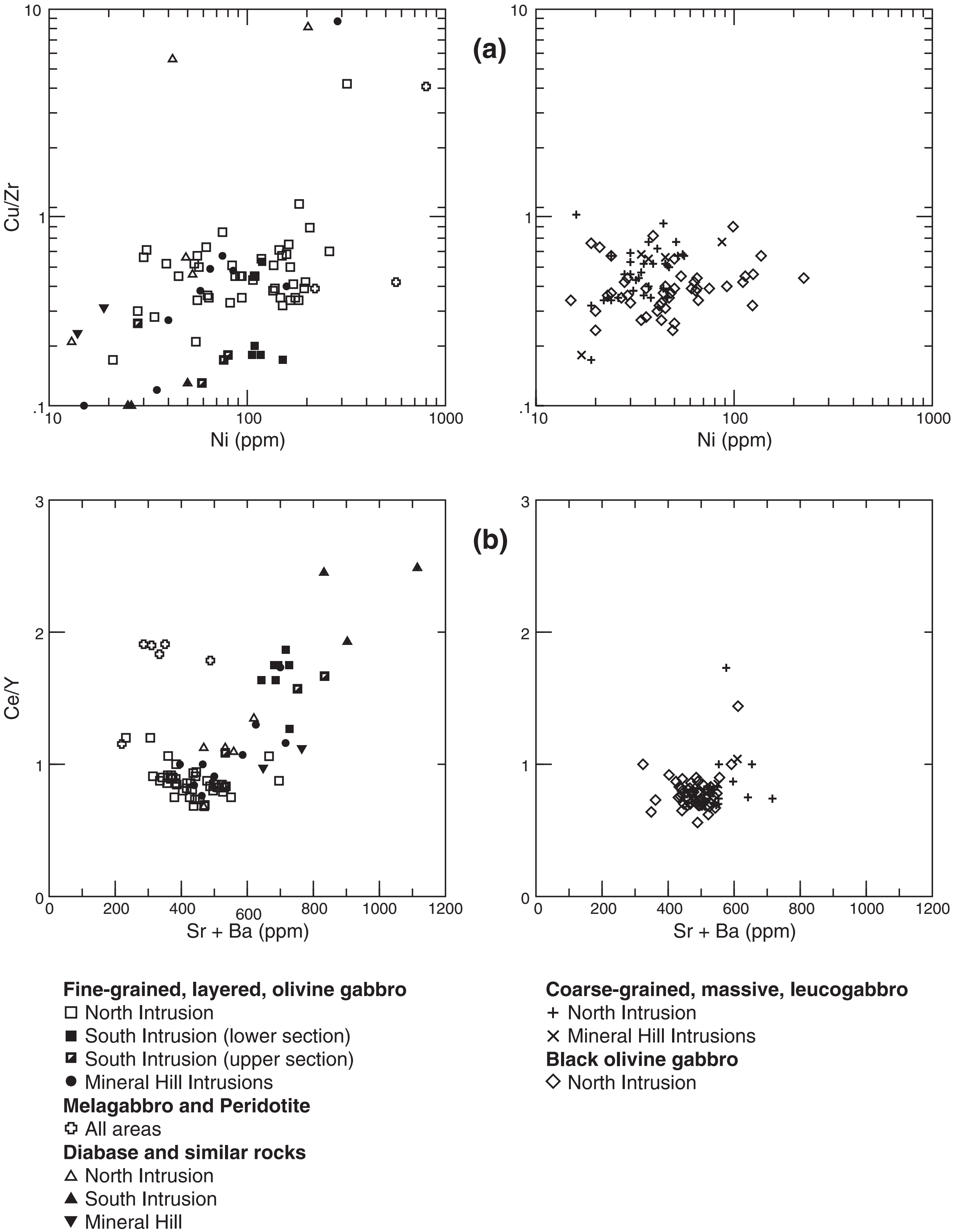


Figure 42. *Selected trace-element variation trends for inter-element ratios in the Pants Lake intrusions. a) Cu/Zr vs Ni. b) Ce/Y vs Sr+Ba. Note that mineralized rocks are excluded from these plots.*

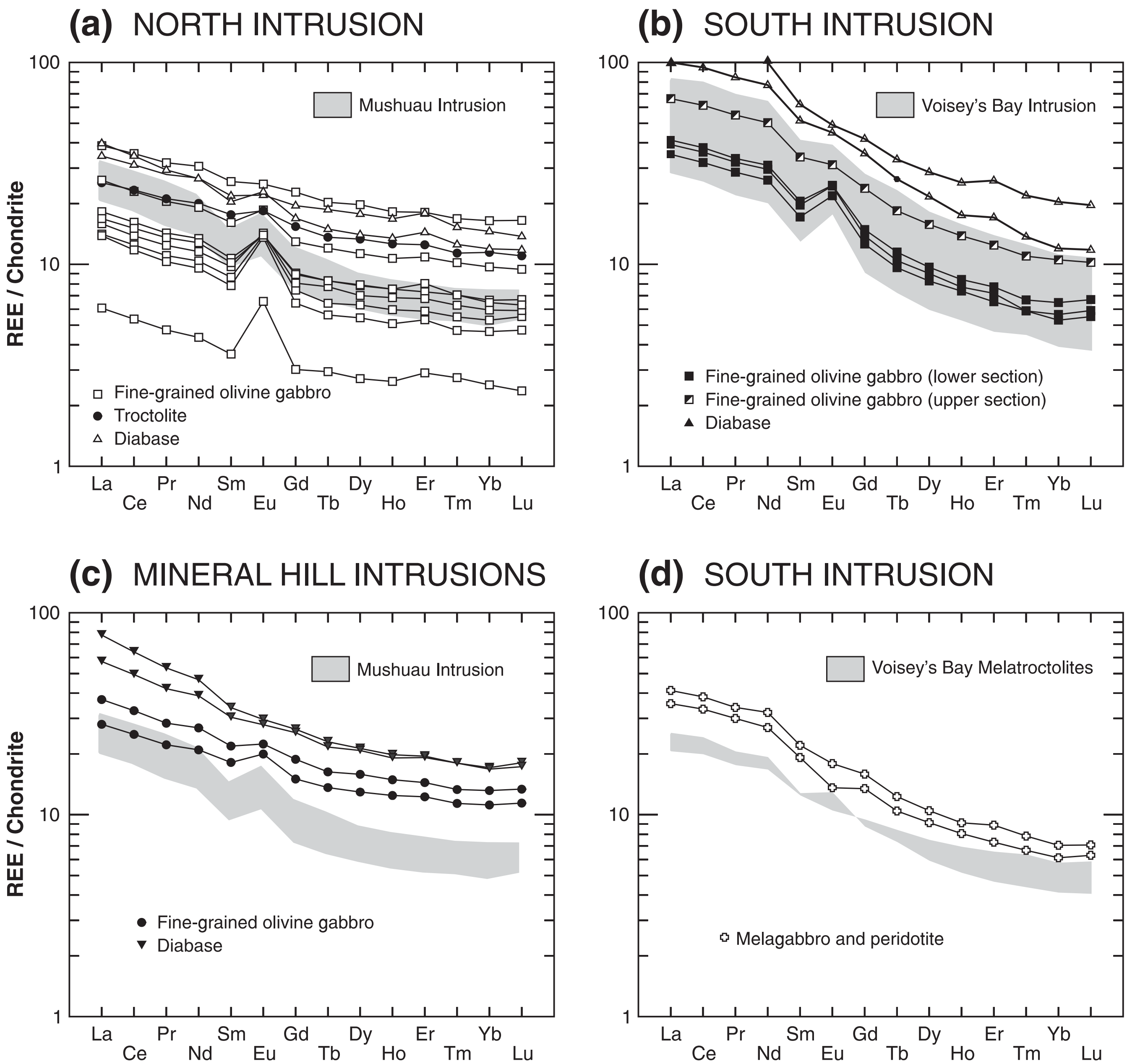


Figure 43. *Chondrite-normalized REE profiles for fine-grained olivine gabbro, melagabbro and diabase units. a) North intrusion. b) South intrusion. c) Mineral Hill intrusions. d) Melagabbro from the South intrusion. Chondritic normalization factors from Sun and McDonough (1989). Fields for the Voisey's Bay and Mushuau intrusions constructed from Li* et al. *(2000).*

leucogabbro from the Mineral Hill intrusion are essentially identical to those from the North intrusion (Figure 44B). The black olivine gabbro unit has a REE profile that closely resembles the other units in the North intrusion, and its overall REE abundances are intermediate between those of the fine-grained olivine gabbro and the coarse-grained leucogabbro, but overlap both (Figure 44C).

Overall, the REE data indicate a close genetic relationship between all of the units in the North intrusion. There are differences in REE abundance ranges between fine-grained gabbro and coarse-grained leucogabbro, but they remain difficult to separate on a single-sample level. The black olivine gabbro cannot be distinguished confidently from either of the other units on the basis of REE content or patterns.

Comparisons with Mafic Rocks of the Voisey's Bay Area

The REE profiles for the PLI can be compared with those from the Voisey's Bay and Mushuau intrusions (Emslie, 1996;

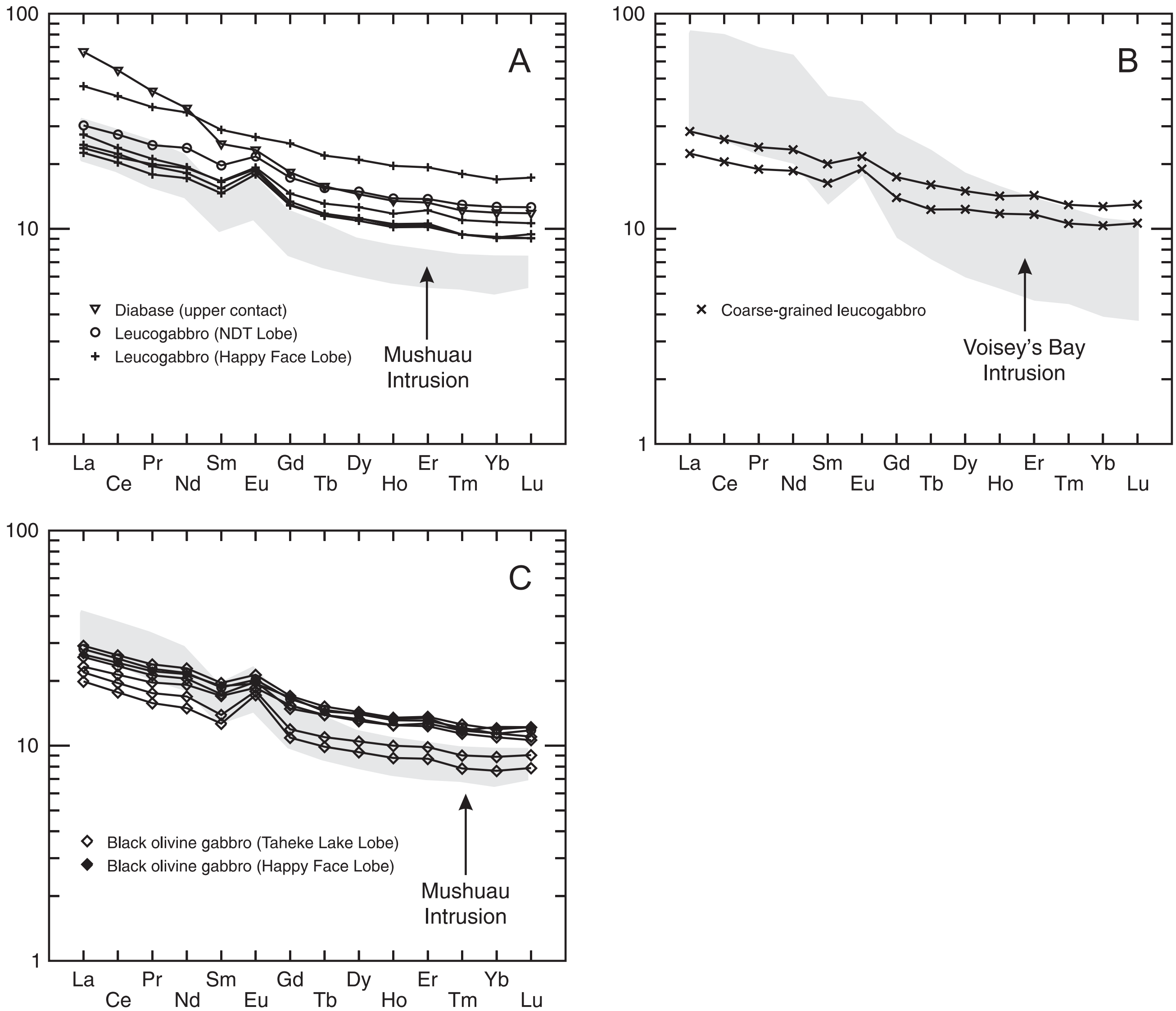


Figure 44. *Chondrite-normalized REE profiles for massive leucogabbro and black olivine gabbro units. A. North intrusion. B. Mineral Hill intrusions. C. Black olivine gabbro from the North intrusion. Chondritic normalization factors from Sun and McDonough (1989). Fields for the Voisey's Bay and Mushuau intrusions constructed from Li* et al. *(2000).*

Lightfoot and Naldrett, 1999; Li *et al.*, 2000). Troctolites from the Voisey's Bay intrusion (Figure 43b) have distinctly steeper REE profiles than the North intrusion gabbros (Figure 43a), but show the same inverse correlation between their Eu anomalies and total REE content. In contrast, the Voisey's Bay REE profiles are very similar to those from the South intrusion (Figure 43b), as noted initially by MacDonald (1999). Rare-earth-element profiles of melagabbro–peridotite from the South intrusion resemble those of melatroctolite inclusions in the Voisey's Bay area (Li *et al.*, 2000), but the PLI have higher REE contents (Figure 43d). The gabbros of the North intrusion and the Mineral Hill intrusions, regardless of unit, more closely match the patterns from the Mushuau intrusion (Figures 44A, C and 45).

Trace-element data from Voisey's Bay have commonly been depicted in the form of primitive-mantle-normalized extended trace-element plots (also known as 'spidergrams'). Here, trace-element data are far better normalized to chondritic values and a summary comparison between the PLI and the Voisey's Bay area using this method is illustrated in Figure 45. This diagram also emphasizes the strong similarities between South intrusion fine-grained olivine gabbro and troctolites of the Voisey's Bay intrusion, and the more general similarities between the North intrusion and the Mushuau intrusion. There are, however, some differences, notably the deeper negative Ta and Nb anomalies of the PLI rocks. The absence of both U data and reliable Rb and Pb data for PLI samples complicates exact comparisons of the lithophile ele-

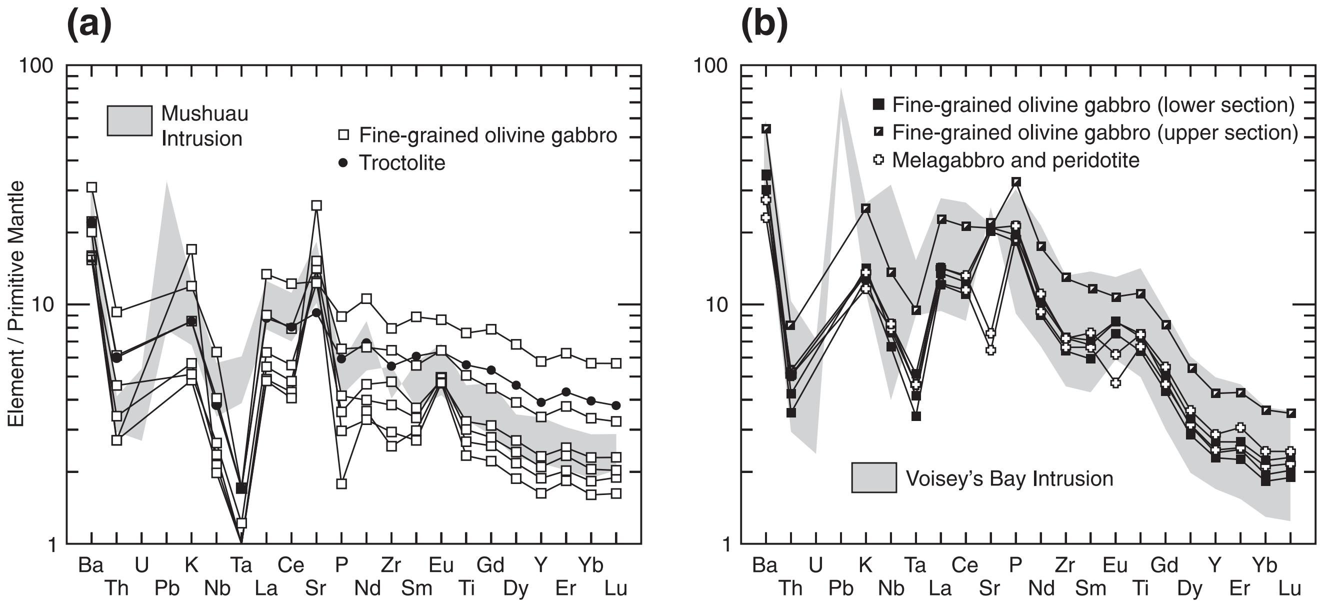


Figure 45. *Multi-element plots comparing REE and trace-element profiles of the Pants Lake intrusions and troctolitic rocks of the Voisey's Bay area. a) North intrusion. b) South intrusion. Charts use 'primitive mantle' normalization factors from Sun and McDonough (1989). Fields for the Voisey's Bay and Mushuau intrusions constructed from Li* et al. *(2000).*

ment (Ba to K) profiles, but data from holes SVB-97-77 and 97-79 presented by MacDonald (1999) suggest that these elements are also generally depleted compared to the Voisey's Bay troctolites.

GEOCHEMISTRY OF MINERALIZED SEQUENCES

This section examines major- and trace-element patterns among the mineralized rocks of the PLI, and is mostly focused upon those of the North and South intrusions. The Ni, Cu, and Co contents of sulphide mineralization, and calculated sulphide metal contents were previously discussed in conjunction with descriptions of mineralization in the section entitled '*Magmatic Sulphide Mineralization*'.

Overview

Mineralized rocks in the PLI include melagabbro and peridotite containing disseminated sulphides in the South intrusion, and the complex and varied sulphide-rich gabbros of the mineralized sequence in the North intrusion. Most of the data discussed here come from the latter group. The complete major- and trace-element database consists of about 100 samples, but a large amount of additional data for Ni, Cu, Co, and S is available in assessment reports (*e.g.*, Fitzpatrick *et al.*, 1998; *see* also discussion in Kerr, 1999; Kerr *et al.*, 2001). For the purposes of discussion, the mineralized sequence of the North intrusion is divided into four principal and two subordinate units:

1) Sulphide-poor composite gabbro;
2) Sulphide-rich composite gabbro;
3) Leopard-textured gabbro; and
4) Undivided, mineralized, fine-grained gabbro.

The two subordinate units are

5) Poikilitic olivine diabase (a fine-grained, variably mineralized, rock that resembles black olivine gabbro); and
6) Barren or weakly mineralized gabbro, variably present in the lowermost part of the Mineralized sequence or, more rarely, as thinner units just below the basal contact of the main body.

The distinction between the two varieties of composite gabbro is visual and subjective; in most cases, increased sulphide content accompanied by an increase in the proportion of digested gneiss fragments (Kerr, 1999).

The interpretation of geochemical data in mineralized rocks is inherently more difficult than for sulphide-free samples. Mineralized samples have high iron contents purely as a consequence of pyrrhotite-dominated sulphides, which, in turn, depress percentage values of all other oxides. Trace elements that are not concentrated in sulphides are also diluted in sulphide-rich samples. The ideal approach would be to normalize all data to a sulphide-free state, and correct for the excess iron. Unfortunately, this is not possible because only some of the samples have been analyzed for sulphur.

Summary of Numerical Data

Table 11 lists the average compositions of rock types in the mineralized sequences of the South and North intrusions; the mineralized mafic cumulates from the South intrusion

Table 11. Average compositions of mineralized rocks in the Pants Lake intrusions

		Composite Gabbro (sulphide-poor) Mean n=19	S.D	Composite Gabbro (sulphide-rich) Mean n=17	S.D	Leopard-textured Gabbro Mean n=8	S.D	Sulphide-bearing Gabbro Mean n=37	S.D	Poikilitic Olivine Diabase Mean n=5	S.D	Barren Lower Gabbro Mean n=3	S.D
SiO2	%	45.86	2.67	44.66	2.44	37.91	6.15	45.82	5.65	44.28	7.07	49.48	1.61
TiO2	%	1.03	0.27	0.98	0.26	0.73	0.17	1.01	0.36	0.84	0.39	1.54	0.19
Al2O3	%	18.18	1.82	18.85	2.56	13.28	2.03	15.98	2.06	16.85	3.42	15.37	0.75
Fe2O3	%	14.78	3.58	15.28	4.24	29.06	9.97	16.89	5.83	19.06	12.45	14.88	1.20
MnO	%	0.17	0.02	0.16	0.02	0.17	0.01	0.16	0.04	0.17	0.02	0.19	0.01
MgO	%	7.05	1.43	6.88	1.06	6.56	1.30	7.45	1.96	7.00	1.16	6.51	1.18
CaO	%	9.04	0.78	9.24	0.90	6.89	1.34	7.76	1.87	8.38	1.66	8.28	0.39
Na2O	%	2.77	0.23	2.61	0.31	2.03	0.41	2.56	0.38	2.58	0.59	2.77	0.09
K2O	%	0.42	0.13	0.33	0.06	0.25	0.09	0.57	0.70	0.36	0.13	0.73	0.10
P2O5	%	0.10	0.02	0.09	0.03	0.07	0.03	0.11	0.06	0.09	0.05	0.20	0.07
LOI	%	1.16	1.19	1.04	0.97	2.69	1.69	1.73	1.85	1.23	0.23	0.69	0.18
Total		100.32		100.12		99.65		99.71		100.85		100.42	
Li	ppm	8.1	3.1	6.1	1.1	4.6	1.4	6.8	4.6	8.7	4.1	7.1	0.9
Be	ppm	0.3	0.1	0.3	0.1	0.2	0.1	0.5	0.6	0.2	0	0.6	0.1
Sc	ppm	21.8	4	20.6	5.2	17.5	6.8	20	6.9	20.9	9.2	31.1	3.5
Ti	ppm	6403	1593	6271	1702	4563	1050	6444	2230	5094	2158	9636	1057
V	ppm	145	32	147	27	143	34	145	58	145	52	176	16
Cr	ppm	62	33	93	41	128	63	82	31	71	23	64	10
Mn	ppm	1293	161	1233	187	1439	439	1261	315	1363	379	1470	45
Co	ppm	119	86	152	96	539	327	159	129	225	262	65	13
Ni	ppm	546	813	1031	1649	2757	1474	662	965	1351	2231	56	36
Cu	ppm	560	795	908	1079	2062	600	698	1067	1480	2438	72	52
Zn	ppm	106	19	111	16	139	19	118	28	123	51	122	15
Ga	ppm	13	10	23	3	16	2	20	3			25	2
Rb	ppm	7	3	6	3	4	3	14	16	7	3	12	0
Sr	ppm	296	28	284	25	221	36	263	52	266	50	295	4
Y	ppm	18	3	18	5	14	3	19	5	16	6	29	4
Zr	ppm	65	13	63	17	50	14	72	27	54	19	110	28
Nb	ppm	3	1	2	1	1	0	3	3	3	1	5	2
Mo	ppm	1	1	1	0	1	0	2	4	1	0	1	0
Ba	ppm	164	15	149	27	132	35	198	94	142	37	360	94
La	ppm	5	1	6	3	3	1	9	7	5	2	15	5
Ce	ppm	15	3	15	4	16	2	22	14	15	4	30	9
Dy	ppm	2.8	0.6	2.9	0.8	2.6	1.1	3	0.9	2.5	1.1	4.5	0.7
Pb	ppm	4	7	5	5	15	4	9	12	19	35	3	2

are also represented by analyses previously presented in Table 5.

Average compositions of sulphide-poor and sulphide-rich composite gabbro in the North intrusion differ little, aside from higher Fe_2O_3 (total) and lower SiO_2 in the latter, due to sulphides. Higher mean Al_2O_3 in sulphide-rich varieties may reflect the presence of more digested gneiss fragments, which are dominated by plagioclase and spinel, although the contrast in chemistry is small, given the large standard deviation. The average trace-element compositions are identical, aside from differences in Ni, Cu and Co, due to sulphides. The average compositions of both varieties of composite gabbro are broadly similar to those of unmineralized gabbros from the North intrusion (Tables 4, 6 and 7), aside from those differences related to sulphides. The Al_2O_3 contents of composite gabbro are intermediate between those of the fine-grained olivine gabbro and coarse-grained leucogabbro units, but there are no clear differences in Na_2O or K_2O, or in lithophile trace-element contents. Thus, it appears that there is no obvious geochemical signature from digested gneiss fragments in composite gabbros, although it should be noted that extremely fragment-rich examples were deliberately avoided during sampling.

The average composition for leopard-textured gabbro includes sulphide-rich samples, as indicated by very high Fe_2O_3, Ni, Cu and Co, and it is, therefore, difficult to compare this to unmineralized units. However, the average composition of undivided, mineralized fine-grained gabbro (generally poorer in sulphides than leopard-textured gabbro) is similar to that of its unmineralized counterpart (accounting for differences related to sulphides), but has slightly lower Al_2O_3 and a notably higher K_2O content (Tables 4 and 11). As the K_2O content is diluted by sulphides, this difference may be important. The barren fine-grained gabbro from the lowermost part of the mineralized sequence also has higher TiO_2 and K_2O than typical unmineralized, fine-grained gabbro, and also has a twofold relative enrichment in La, Ce and Dy (Tables 4 and 11). In this respect, it resembles diabase samples that are commonly more evolved than the fine-grained unit. Poikilitic olivine diabase, interpreted as a fine-grained, variably mineralized variety of black olivine gabbro, is also sulphide-rich, and, therefore, difficult to compare rigorously to its unmineralized counterpart.

Geochemical Variation Trends

Attempts to investigate geochemical trends in the mineralized rocks using variation diagrams were unsuccessful. All show rather variable compositions, which are, in part, due to the presence of sulphides. The Al_2O_3 and SiO_2 are also particularly variable, despite a relatively small range in MgO. The mineralized rocks cannot be distinguished from unmineralized gabbros with confidence on the basis of major elements, although a tendency toward higher K_2O, particularly at lower MgO contents, is present among the mineralized gabbros.

Differences in trace-element variation trends are mostly connected to the effects of sulphides. In contrast to unmineralized gabbros, Ni and Co are no longer correlated with MgO (Figure 46a, b), but there are strong correlations between Ni and Cu (Figure 46c) and Ni and Co (Figure 46d). Nickel/copper is constant at about 1, as previously indicated (Kerr, 1999; *see* also the much larger database including company assay data discussed in the section on *Magmatic Sulphide Mineralization*). Nickel/copper shows a curved trend, from Ni/Co ~ 1 in weakly mineralized rocks, to Ni/Co ~ 8 in Ni-rich samples. Note that samples containing more than 10 000 ppm (1%) Ni or Cu have been excluded from these diagrams to avoid compression of the remaining data. These patterns reflect the control of chalcophile elements by the sulphides in mineralized rocks, and the 'drowning' of any variation due to silicate minerals (largely olivine). The differences between the Ni/Cu and Ni/Co trends reflect the smaller differences in the Co contents of olivine and sulphides compared to those for Ni. The Ni/Cu and Ni/Co ratios indicated by the mineralized rocks resemble those in unmineralized rocks that have low MgO contents, *i.e.*, those that are least affected by cumulus olivine (compare Figures 46c, d; 37a, b). Other trace elements do not yield useful information, although they do show that sulphide-bearing gabbros and the barren gabbro in the lowermost part of the mineralized sequence tend to have higher REE and Nb contents than their unmineralized counterparts.

Rare-earth-element distributions provide a more effective comparison method because their shapes are not affected by sulphides. The average REE contents of mineralized units are listed in Table 12. Composite gabbro samples echo the shapes of REE profiles from unmineralized fine-grained olivine gabbros in the North intrusion but tend to have higher REE abundances; they most closely resemble the patterns for the black olivine gabbro. One sulphide-poor composite gabbro sample shows LREE enrichment that may be a contamination signature from gneissic debris (Figure 47a). Sulphide-bearing gabbros (including leopard-textured rocks) have patterns that resemble those of unmineralized fine-grained olivine gabbro (Figure 47c, d). Generally, REE profiles from the mineralized sequence resemble those of unmineralized rocks in the North intrusion. A mineralized gabbro from the base of hole SVB-97-79 in the South intrusion shows the steeper REE pattern characteristic of all rocks from this area, including the sulphide-bearing mafic cumulates (Figure 47d).

MINERAL CHEMISTRY STUDIES

No mineral analyses were conducted as part of this project, but important data of this type were collected by Hodder (1997), MacDonald (1999) and Naldrett (1999; included within the report of Fitzpatrick *et al.*, 1999). Small amounts of olivine data were reported by Smith (2006). This section summarizes these data and the main conclusions of these studies. Hodder (1997) analyzed olivines, clinopyroxenes and plagioclases from several short drillholes completed during the 1996 season. Olivines display a range of compositions from Fo41 to Fo67, and most clinopyroxenes prove to be augitic. Plagioclase has a wide range of compositions, corresponding to An44 to An71, and larger plagioclase crystals (in the massive leucogabbro unit) are zoned, with calcic cores containing up to An77. MacDonald (1999) completed a more detailed study of olivine compositions from three key drillholes, but did not report any Ni analyses. Naldrett (1999) provided olivine composition data, including Ni, for these holes, and several other drillholes.

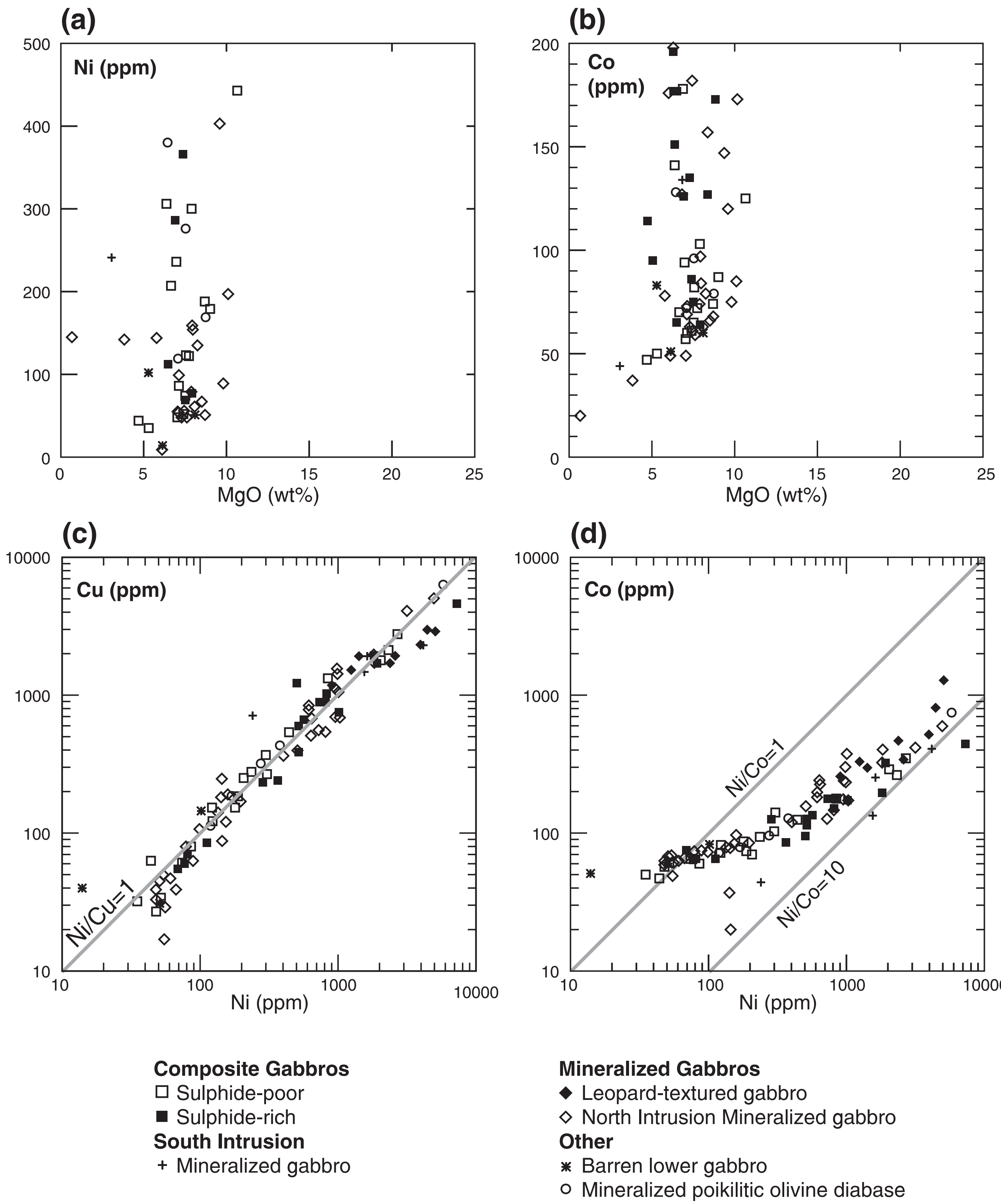


Figure 46. *Selected trace-element variation trends in mineralized rocks from the Pants Lake intrusions. a) Ni vs MgO. b) Co vs MgO. c) Cu vs Ni. d) Co vs Ni.*

Table 12. Average REE analyses of mineralized rocks in the Pants Lake intrusions

(all data are in ppm) Unit	N	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Normalization factors used in REE Charts (from Sun and McDonough, 1989)															
Chondrite		0.237	0.612	0.095	0.467	0.153	0.058	0.205	0.037	0.254	0.057	0.165	0.025	0.17	0.025
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	0.2	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 dbs	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

Variations in the Major-element Composition of Olivine

The MgO content of olivine, expressed as the molecular proportion of the magnesium end-member forsterite (Fo content), provides a valuable index of fractionation for mafic magmas, which most commonly evolve to more Fe-rich compositions. MacDonald (1999) systematically sampled three key drillholes; SVB-97-75 (North intrusion, Taheke Lake lobe, containing high-grade sulphide intersections in footwall gneisses), SVB-97-77 (North intrusion, NDT lobe, near its thickest point), and SVB-97-79 (deep hole in the South intrusion). These holes were sampled at 10 to 20 m intervals and provide the most complete information on olivine compositions and their relationship to igneous stratigraphy. In the following account, the term ‘normal trend’ is used to describe a decrease in Fo content related to stratigraphic height within the intrusion, and ‘reverse trend’ is used to describe an increase in Fo content with stratigraphic height. A normal trend is characteristic of closed-system fractionation where a magma chamber crystallizes in place, cumulates develop, and remaining magma becomes more Fe-rich. Reverse trends can be produced in several situations, but are most commonly related to open-system behaviour, where fresh magma enters the chamber, and counteracts the iron-enrichment due to fractionation. Reverse trends, however, also can be related to variations in the amount of trapped residual liquid that has reacted with cumulus olivine.

Hole SVB-97-77 contains one of the most complete sections through the North intrusion, including some 300 m of fine-grained, layered olivine gabbro. Forsterite content variations (Figure 48; after MacDonald, 1999) show very clear depth-related variations. There is a clear reversal in Fo content variation that corresponds to the upper boundary of the mineralized sequence just above 400 m depth. Most of the overlying fine-grained olivine gabbro unit shows a progressive upward increase in Fo content from about Fo45 to Fo67, *i.e.*, it shows a reverse fractionation trend. Above about 200 m, Fo content decreases steadily to about Fo58, which occurs immediately below the contact with coarse-grained, massive leucogabbro. Within the lower reversed-fractionation interval, there are some small intervals where Fo content decreases, before increasing again. The coarse-grained, massive leucogabbro contains large interstitial olivines that tend to be strongly zoned, and the range of compositions measured in a single sample is much greater, as indicated by the width of the compositional envelope in Figure 48. Nevertheless, the average values from the leucogabbro suggest an overall normal trend toward lower Fo contents. A nearby hole intersecting a similarly thick sequence of fine-grained olivine gabbro (hole SVB-97-59) was examined in less detail (Naldrett, 1999) and shows essentially the same features, *i.e.*, a lower interval with a reverse fractionation trend, and an upper interval with a normal fractionation trend. However, hole SVB-97-82, in the western part of the NDT lobe, shows only the reverse fractionation trend within the fine-grained olivine gabbro unit (Naldrett, 1999).

Hole SVB-97-75 is dominated by black olivine gabbro, in which olivines show wide variations in Fo content suggesting zonation, as seen in the coarse-grained massive leucogabbro unit from hole SVB-97-77. It is difficult to define trends, but the upper part of the hole seems to show two intervals that have reversed fractionation trends. The profile (Figure 49;

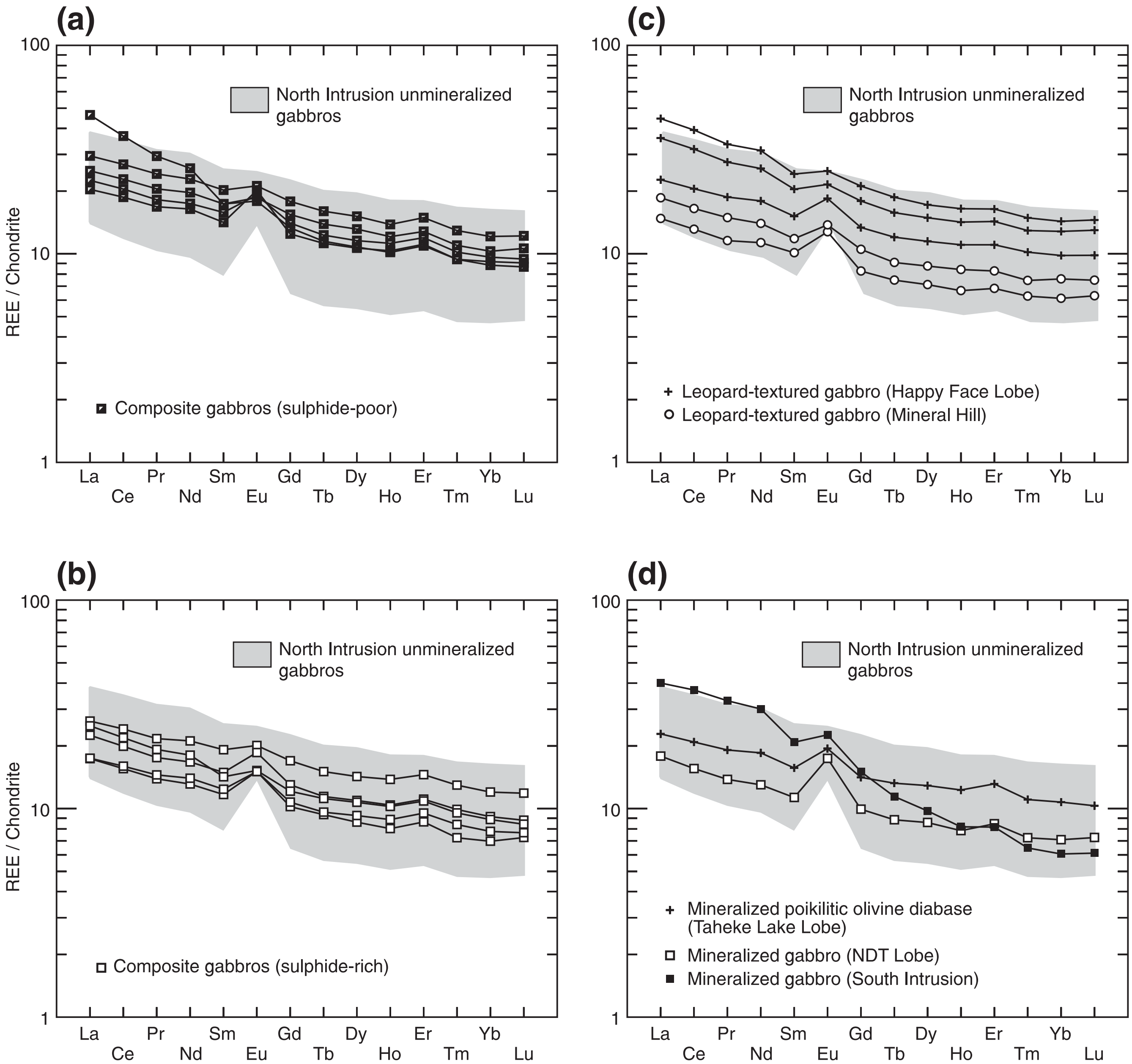


Figure 47. *Chondrite-normalized REE patterns for mineralized rocks of the Pants Lake intrusions. a) Sulphide-poor composite gabbros, North intrusion. b) Sulphide-rich composite gabbros, North intrusion. c) Leopard-textured gabbros, North intrusion. d) Other mineralized gabbroic rocks from the North and South intrusions. Shaded field shows range of fine-grained, layered olivine gabbros from the North intrusion (*see *Figure 43).*

after MacDonald, 1999) shows no obvious break corresponding to the top of the mineralized sequence, but there is a reverse trend in a thin sequence of fine-grained olivine gabbro sitting above it. However, the exact boundary between black olivine gabbro and the mineralized sequence is hard to position. There are no olivine analyses from other holes in this part of the Taheke Lake lobe, so it is not known how representative this pattern is.

Hole SVB-97-79, in the South intrusion, shows perhaps the most complex pattern (Figure 50; after MacDonald, 1999). The lowermost part of the hole has modest Fo contents (around Fo55), which increase rapidly to Fo65 to Fo75 in the sulphide-bearing melagabbro and peridotite of the mineralized sequence. In the overlying fine-grained olivine gabbro unit, there is initially a normal fractionation trend from 650 to 500 m depth, followed by a short interval in which Fo increases

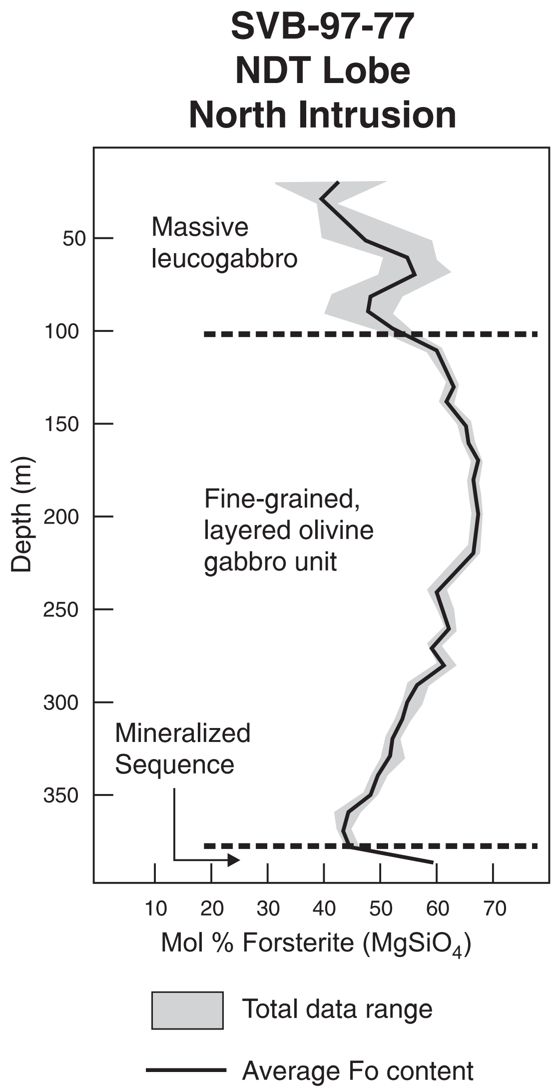


Figure 48. *Variations in forsterite content of olivines in hole SVB-97-77 (North intrusion, NDT lobe). After MacDonald (1999).*

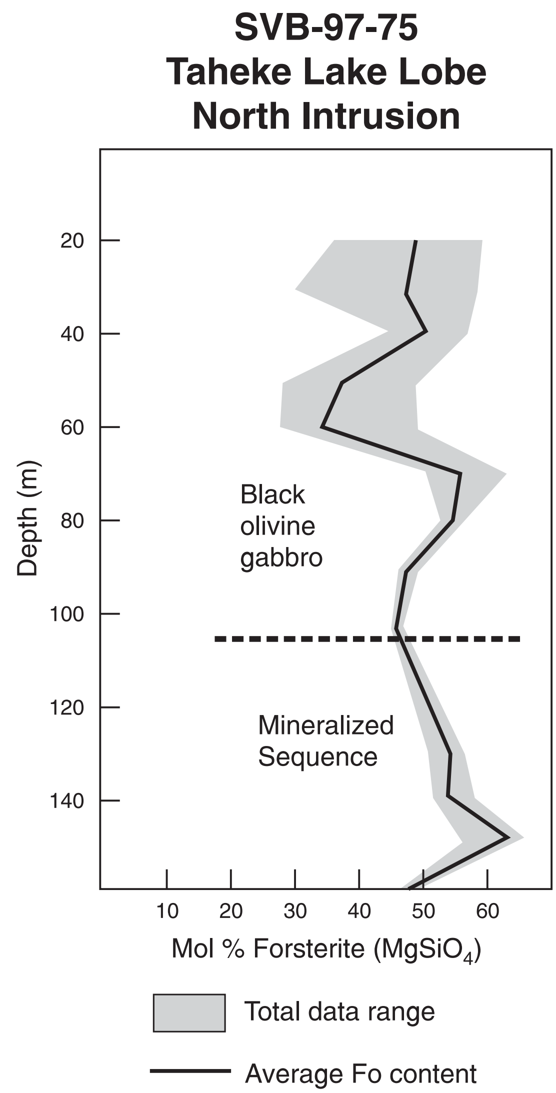


Figure 49. *Variations in forsterite content of olivines in hole SVB-97-95 (North intrusion, Taheke Lake lobe). After MacDonald (1999).*

slightly. This is overlain by another long section displaying a normal fractionation trend, which terminates below the thin zone of mineralized rocks at about 250 m. The upper section of the South intrusion shows a rather erratic pattern, with no clear trend. The adjacent hole SVB-97-86 was sampled in less detail (Naldrett, 1999) and shows essentially the same pattern, *i.e.*, it is dominated by normal fractionation trends.

Naldrett (1999) also analyzed olivines from long intervals of coarse-grained anorthositic gabbro intersected in holes adjacent to both South and North intrusions. This work was intended to verify the interpretation that these rocks are older NPS or HLIS anorthosites, and to disprove any connection between them and the PLI. Olivine compositions from the anorthositic gabbros are very iron-rich (typically Fo25 to Fo10), and are completely distinct from those of the PLI, which are typically more magnesian than Fo40.

Variations in the Nickel Contents of Olivine

The Ni content of olivine is a very important parameter in the assessment of mafic rocks for their potential to host magmatic sulphides. Nickel is strongly correlated with Fo content, but this relationship is disrupted in the presence of sulphides, for which Ni has a strong preference. Anomalously low Ni contents at a given Fo content are, in many instances, indicative of metal depletion caused by sulphide segregation. The Ni content of olivines can also be used to derive general estimates of the metal contents of associated sulphide liquids (*e.g.*, Li and Naldrett, 1999; Li *et al.*, 2000).

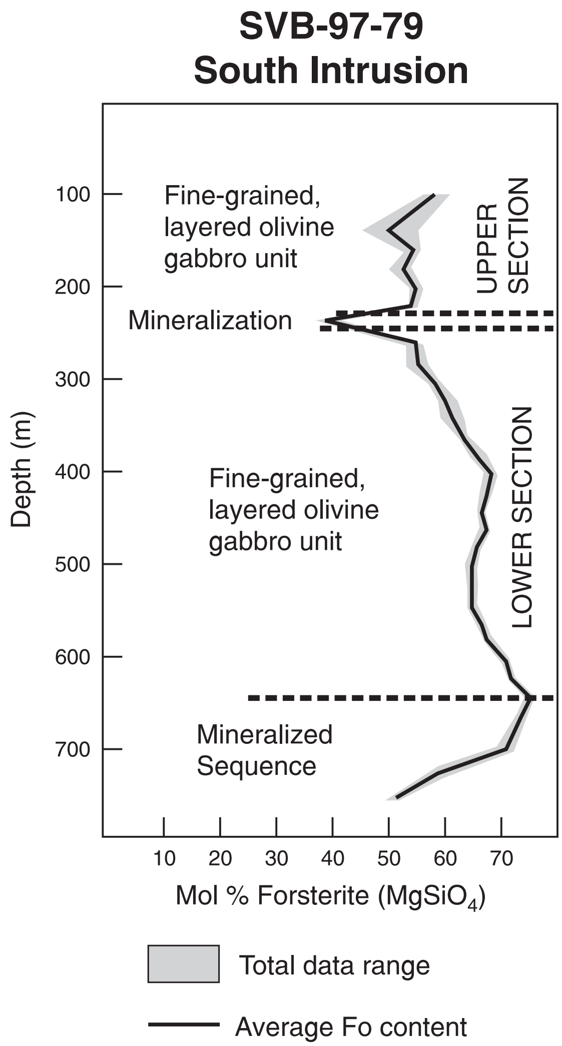


Figure 50. *Variations in forsterite content of olivines in hole SVB-97-79 (South intrusion). After MacDonald (1999).*

Hodder (1997) attempted to obtain Ni values through microprobe analyses, but found that most were close to the detection limit for the instrument calibration and hence unreliable. Nickel was analyzed by MacDonald (1999) but the data were not reported. Naldrett (1999) provided a discussion of available data from a wide range of drillholes, including those examined by MacDonald (1999). The co-variation of Ni with Fo content in olivines is predictable from a knowledge of partition coefficients and major-element compositions; this provides a relatively narrow envelope of Ni concentrations, within which variation depends on the proportion of other phases (plagioclase, orthopyroxene and clinopyroxene) crystallizing with the olivine (Figure 51a; after Li and Naldrett, 1999). If sulphide liquid is also present, it will very quickly remove Ni from the magma, and olivines that subsequently crystallize from the magma will have anomalously low Ni contents. Thus, magma fractionation in the presence of sulphide defines a very different trend, well below the normal fractionation envelope (Figure 51a).

Olivines from the PLI display strong correlation of Ni and Fo content, and have generally low Ni contents, from <100 to about 1200 ppm Ni, with most samples containing less than 500 ppm. Virtually all fall below the 'normal fractionation' envelope for magmas of this general composition (Figure 51b). The data conform to the expected pattern for fractionation in the presence of sulphides, which appear to have started to separate from the original magma before about 10 % crystallization (Naldrett, 1999). The data imply that virtually all of the PLI gabbros crystallized from magmas that had lost Ni through removal of sulphide liquids, and are consistent with the generally low whole-rock Ni values and the low Cu/Zr ratios. The information presented by Naldrett (1999) does not permit comparison of different PLI units, but the highest Ni values are reported from the melagabbro and peridotite unit, and most of the olivines containing >600 ppm Ni are reported to come from the South intrusion.

In comparison with results from Voisey's Bay, olivines from the PLI resemble those from the 'olivine gabbro' (OG) and 'feeder olivine gabbro' (FOG) units, which fall along the same Ni-depleted trend, and are interpreted to have lost metals to sulphide liquids (Li and Naldrett, 1999; Figure 51a). However, most troctolitic rocks from Voisey's Bay have significantly higher Ni contents at a given Fo content, and thus plot mostly in the field of 'normal' fractionation - *i.e.*, they have not suffered noticeable metal depletion. Olivines from rocks directly associated with mineralization at Voisey's Bay (*i.e.*, basal and feeder breccias, and leopard troctolite) show a diffuse pattern that overlaps both the normal and the depleted trends. In general, the Ni contents of olivines from the PLI indicate more pervasive depletion effects from sulphide liquids than at Voisey's Bay, where many rocks show little or no evidence of such effects.

There appears to be a fairly simple relationship between the Ni content of olivines and sulphide liquids that have equilibrated with them, such that the Ni content of the sulphides

Figure 51 (opposite). *Variations of Ni and Fo contents of olivines from the Pants Lake intrusions and the Voisey's Bay area. a) Summary of data from Voisey's Bay, after Naldrett (*in *Fitzpatrick* et al.*, 1999) and Li and Naldrett (1999); fractionation paths show the differences between systems that develop sulphide liquids and those that do not. b) Data from the Pants Lake intrusions compared to the evolution of sulphide-bearing and sulphide-free systems, after Naldrett (*in *Fitzpatrick* et al.*, 1999). Ol– olivine, Pl– plagioclase. Points on curve refer to % crystallization of the magma.*

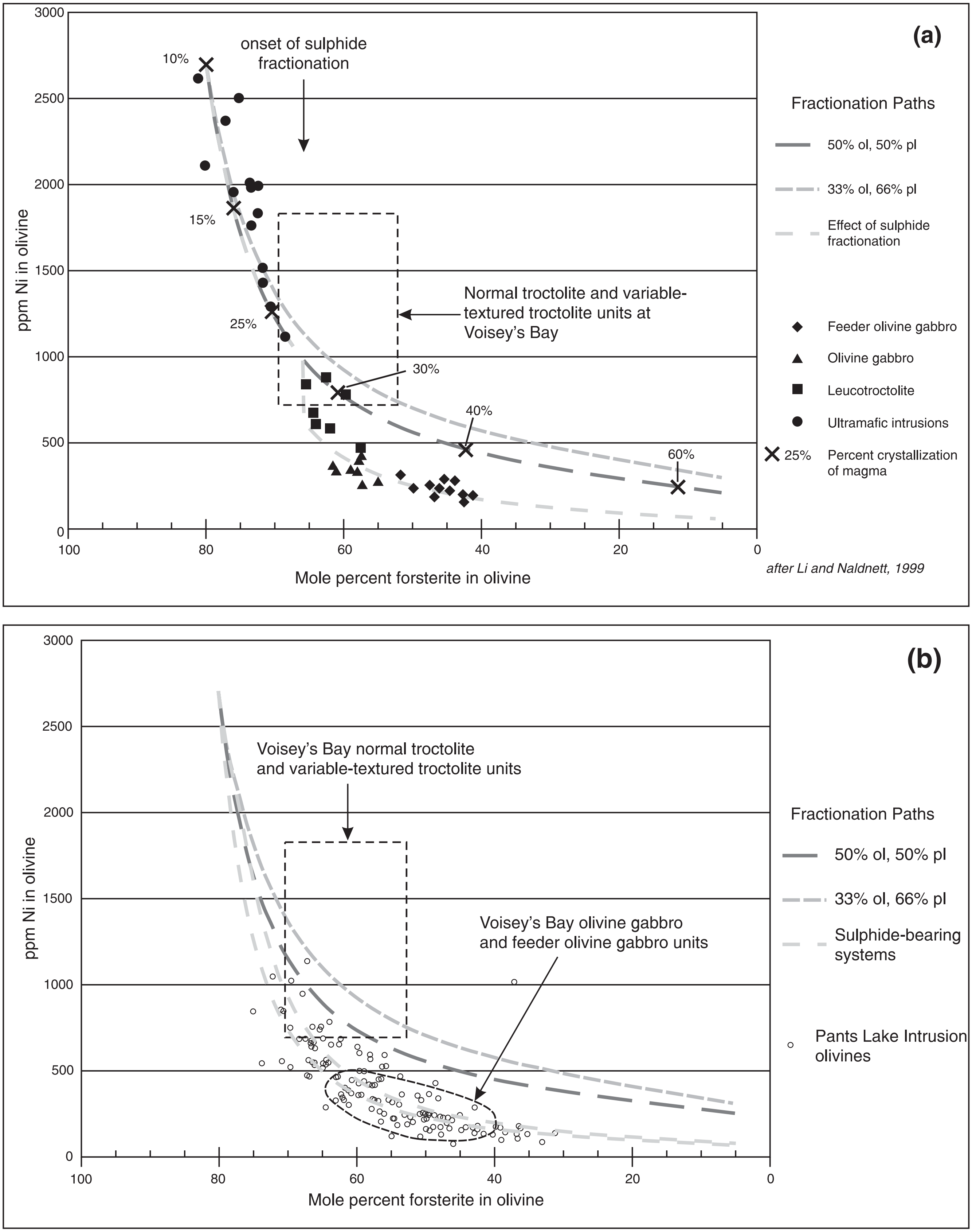


Figure 51. *Caption on page 104.*

is approximately 60 times greater than that of olivine (Li and Naldrett, 1999). On this basis, olivines with 200 to 400 ppm Ni imply that associated sulphide liquids should contain 1.2% to 2.4% Ni (Figure 52), which is consistent with much of the data for sulphide Ni contents summarized in the chapter describing magmatic sulphide mineralization. Applying the same reasoning to data from Voisey's Bay (Li and Naldrett,1999), three groupings of sulphide Ni contents are recognized. Olivine data from the olivine gabbro and feeder olivine gabbro units suggest modest Ni contents (<2%) that are akin to the values calculated from most of the PLI data. However, most of the Voisey's Bay olivines correspond to significantly higher sulphide Ni contents, ranging up to 6% Ni or more in the 'variable troctolite' (VTT) unit. Calculated values from rock types most closely associated with sulphide mineralization at Voisey's Bay cluster around 4% Ni, which is consistent with assay results from massive sulphides (Figure 52; *see* also Figure 30). Olivines with Ni contents consistent with >4% Ni in sulphides are rare in the PLI, although calculated sulphide metal contents of this order are present, notably in the South intrusion (Figure 26) and the Taheke Lake lobe of the North intrusion (Figure 28). Smith (2006) also completed some analyses of nickel in olivine, but this study used Laser Ablation–Inductively Coupled Plasma-Mass Spectrometry (LA–ICP-MS), rather than the conventional electron-microprobe analyses used by MacDonald (1999) and

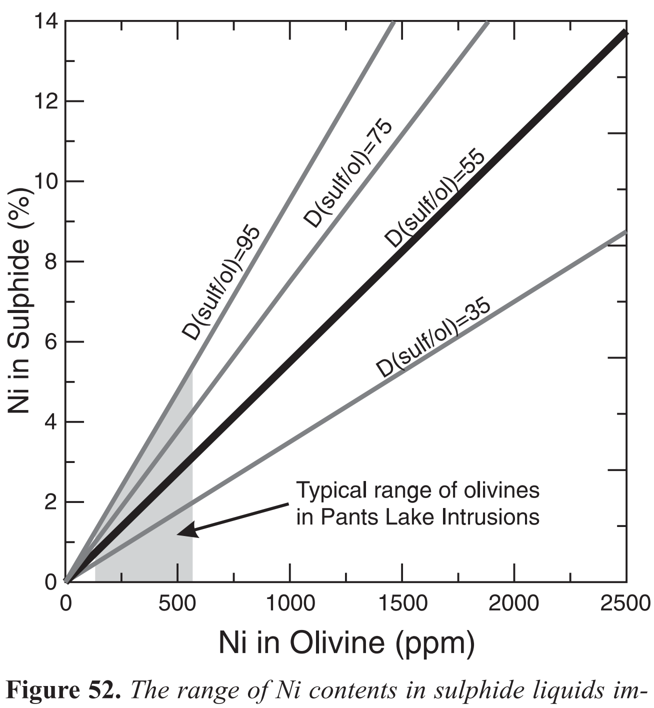


Figure 52. *The range of Ni contents in sulphide liquids implied by compositional data from olivines in the Pants Lake intrusions. The various lines in the plot show different values for the sulphide/olivine partition coefficient for Ni between coexisting sulphide and olivine; a value of approximately 55 is favoured by Naldrett (*in *Fitzpatrick* et al.*, 1999).*

Naldrett (1999). The results from the drillholes (SVB-96-04, 96-09, 97-91 and 98-102) were variable in terms of Ni contents, and cannot be compared with the earlier data, which came from different drillholes. Only a few samples were analyzed from each hole, and it is not possible to construct profiles from these data; however, the expected correlation between MgO content and Ni content exists within the data. Smith (2006) suggested that locally high Ni contents in some olivines (up to 900 ppm) indicate the possibility of higher grade sulphide liquids, a conclusion with which the author would agree, based on other types of data. (This is discussed further in the final chapter of the report.)

Plagioclase Compositions

No systematic study of plagioclase compositions has been conducted. However, MacDonald (1999) investigated the dark-coloured, turbid plagioclase of the black olivine gabbro unit in an attempt to discover the causes of the unusual colour. Naldrett (personal communication, 1999) had previously suggested that this might be due to submicroscopic inclusions of graphite, perhaps derived from metasedimentary gneisses. Using a scanning electron microscope, MacDonald (1999) attempted to analyze tiny dark inclusions within the plagioclase, but could not obtain conclusive data due to the small size of the inclusions relative to the electron beam. However, analyses did indicate a higher Fe content when the beam was centred on the inclusions. These results suggest, but do not prove, that the distinctive dark colour of the plagioclase is related to numerous inclusions of iron oxide, presumably formed through exsolution processes.

ISOTOPE GEOCHEMISTRY

There have been few isotopic studies of the Pants Lake intrusions. This section discusses some Sm–Nd isotopic data acquired by the GSNL, and also sulphur isotope data reported by Li *et al.* (2001) and Smith *et al.* (2001); the analytical data from the latter source are contained within the thesis by Smith (2006), but are listed in this section.

Sm–Nd Isotopic Analyses

The Sm–Nd isotopic analyses were conducted at Memorial University of Newfoundland, using whole-rock powders. The analytical procedures correspond to those outlined by Kerr and Wardle (1997) for an earlier study of basement intersections from offshore drilling near Makkovik. The samples analyzed include gabbros and diabases from both the South and North intrusions, composite gabbros associated with sulphide mineralization, and two samples of country-rock gneisses. The data are listed in Table 13, which shows Sm and Nd contents, $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios, and calculated parameters (Nd, and depleted-mantle model ages).

Table 13. Sm–Nd isotopic data from the Pants Lake intrusions and associated rock types

Sample Number	Comments	Age (Ma)	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Epsilon Nd (CHUR)	Model Age (Ma)
Churchill Province paragneisses								
6340971	quartzofeldspathic gneiss	1330	31.2	5.2	0.1002	0.511230	-11.1	2430
6340864	quartzofeldspathic gneiss	1330	36.0	7.3	0.1224	0.511604	-7.5	2400
South Intrusion								
6340987	melagabbro (ol-cumulate)	1330	15.0	3.0	0.1333	0.512015	-1.4	1940
6340983	fine-grained gabbro	1330	12.6	2.7	0.1313	0.512004	-1.2	1910
6340928	diabase from chilled zone	1330	39.7	8.4	0.1273	0.511986	-0.9	1850
North Intrusion								
6340913	fine-grained gabbro	1330	6.5	1.7	0.1604	0.512260	-1.2	2240
6341060	duplicate of 6340913	1330	5.5	1.5	0.1620	0.512264	-1.4	2602
6340933	fine-grained gabbro	1330	9.7	2.7	0.1669	0.512326	-1.0	2330
6340915	fine-grained gabbro	1330	9.8	2.6	0.1622	0.512258	-1.5	2320
6341044	fine-grained gabbro	1330	7.0	2.0	0.1684	0.512295	-1.9	2530
6340849	coarse-grained leucogabbro	1330	9.3	2.4	0.1576	0.512195	-2.0	2300
6341036	diabase from chilled zone	1330	15.7	4.4	0.1702	0.512334	-1.4	2500
6341053	composite gabbro	1330	12.1	2.7	0.1273	0.511854	-3.5	2090
6340939	composite gabbro	1330	6.8	1.9	0.1661	0.512293	-1.5	2400

NOTES
For details of analytical procedures, *see* Kerr and Wardle (1997).
Model ages are calculated with reference to the depleted-mantle evolution model of De Paolo (1988).
Sample 6341053 contains recognizable fragments of partially digested paragneiss.
Errors are less than ± 0.000025 for ^{143}Nd, and less than ± 0.0005 for $^{147}Sm/^{144}Nd$.

The εNd values are calculated using a common value of 1330 Ma, representing an average of the 1322 and 1338 Ma U–Pb ages, because the differences in εNd induced by age differences of 16 Ma are negligible. The εNd is expressed with reference to a chondritic undepleted reservoir (CHUR), with $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios of 0.1696 and 0.512638, respectively. The depleted-mantle ages were obtained using the depleted-mantle evolution curve developed by DePaolo (1988).

The most obvious feature of the data in Table 13 is that the samples of country-rock paragneiss have strongly negative εNd values (-7.5 to -11.1) compared to all other samples. This reflects the fact that they are significantly older, having formed prior to 1860 Ma. Most other samples, representing mafic rocks of the PLI, have a narrow range of εNd values, from -1.0 to -2.0; given that the estimated uncertainty in εNd values (from all sources including age uncertainty) is about 0.4 εNd units, many of these values are identical within respective errors. The only exception to this pattern is one sample of composite gabbro, rich in gneiss fragments, which has εNd (1330 Ma) of -3.5. The data from the South intrusion exhibit higher Nd contents, and thus lower $^{147}Sm/^{144}Nd$ ratios, than data from the North intrusion. This is consistent with the differences in REE patterns noted in the preceding section.

The analyses were not conducted for the purposes of geochronology, but they do provide some age information. Samples from the PLI, with the exception of sample 6341053 (composite gabbro rich in gneissic fragments) define a linear array that yields an age of 1256 ± 50 Ma (2σ), with an initial $^{143}Nd/^{144}Nd$ ratio of 0.510922 ± 0.000051 (Figure 53). This is younger than the U–Pb zircon ages of 1338 and 1322 Ma, but is close to them within errors. Note that this is not an isochron, but an 'errorchron', because several samples lie off the regression line. The data from the South intrusion (3 samples) cannot define an age as there is so little variation in their $^{147}Sm/^{144}Nd$ ratios. The data from the North intrusion also have a limited range in $^{147}Sm/^{144}Nd$, and exhibit scatter, such that they define an imprecise errorchron age of 1472 ± 276 Ma, which is not considered geologically meaningful. The samples of country-rock gneisses clearly lie off the errorchron array(s), as does the composite gabbro that contains abundant gneiss fragments (Figure 53). Absence of isochron behaviours

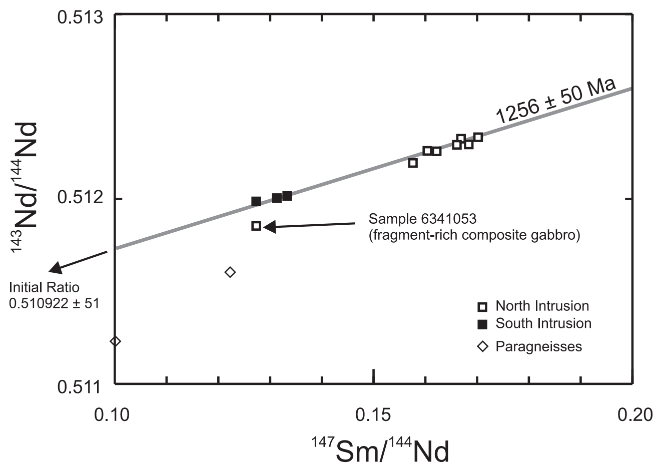


Figure 53. *The Sm–Nd isochron plot for data from the Pants Lake intrusions and country-rock gneisses. Regression method after York (1969).*

is most likely related to variations in the initial $^{143}Nd/^{144}Nd$ ratios of the individual samples, in turn, because individual samples have different degrees of contamination by the country-rock gneisses (*see* below).

The Sm/Nd isotopic data for the PLI samples are, in general, very consistent, with εNd between -1 and -2. These values represent the εNd of the parental magmas to the intrusions, and are intermediate between the εNd projected for a depleted-mantle reservoir (+5.0) at *ca.* 1330 Ma, and the εNd of samples from country-rock gneisses (-7.5 to -11.0). The simplest interpretation of such a pattern is that it records the contamination of mantle-derived mafic magma (with εNd of around +5) by more ancient country-rock gneisses. Some constraints can be imposed on the degree of contamination by using simple two-component isotopic mixing models. The contaminant end-member is represented by the average of the data from the gneisses (εNd = -9 and 34 ppm Nd), and the magmatic end-member is assumed to be of high-Mg gabbroic (picritic) composition (εNd = +5, and 5 ppm Nd). The results of mixing calculations using these assumptions indicate that between 10 and 13% of the Nd in the PLI parent magmas was derived from older crustal material; the projected 'mixed' Nd content of some 9–10 ppm corresponds well with the range of values observed in both mineralized and unmineralized rocks (Tables 10 and 12). Note that this does not necessarily mean that the parent magmas assimilated 10 and 13% of older crust, because such contamination could be selectively accomplished by extraction of much smaller amounts of anatectic melt or a hydrothermal fluid from the country rocks.

Rocks from the mineralized sequences provide abundant evidence for the presence of this older material on a more local scale. The low εNd (-3.5) of the fragment-rich composite gabbro is probably due to the gneissic fragments in the sample. In the same way, scatter amongst gabbro samples (Figure 53) is interpreted to reflect the presence of smaller amounts of such older material within them, which may not be detectable to the eye. The contamination of the PLI mafic magmas is thus interpreted to have taken place in two stages, *i.e.*, an initial deep-level process that led to uniform contamination, followed by more local effects close to the present level of erosion, by which older material was physically incorporated into the magmas.

The Sm–Nd isotopic data for the plutonic rocks of the NPS in the area around Voisey's Bay are reported by Emslie *et al.* (1994), and Amelin *et al.* (2000) report both Sm/Nd and Rb/Sr data from mineral separates from the Voisey's Bay and Mushuau intrusions. The mafic intrusions of the NPS have variable εNd at the time of their emplacement, from -3 to -6 (Emslie *et al.*, 1994). The subsequent study of Amelin *et al.* (2000) confirmed that the Mushuau intrusions has εNd from -3 to as low as -10, and indicated that the Voisey's Bay intrusion has εNd of 0 to -4, with most values in the range of -1 to -2. Tasiuyak gneisses analyzed by Amelin *et al.* (2000) had similar Nd isotopic compositions to the samples reported here, *i.e.*, εNd of -8 to -10. 'Breccias' analyzed by Amelin *et al.* (2000) had εNd values between typical magmatic rocks and the gneisses, like the composite gabbro in Table 13.

The data reported here from the PLI are similar to those reported from the Voisey's Bay intrusion. Amelin *et al.* (2000) suggested that there was minor contamination (8-13%) of a mantle-derived mafic magma by Tasiuyak gneiss; this estimate is consistent with the interpretation offered above. The association of mineralized, nickeliferous intrusions with such relatively primitive Nd isotopic compositions may be significant. If the development of sulphide liquids is indeed a function of country-rock contamination, more extensive deep-level contamination may be a negative influence if it leads to sulphide liquid formation at lower crustal depths. Any deposits formed at such levels are well beyond the limits of feasible exploration. Conversely, less-contaminated mafic intrusions are more likely to retain their inventory of nickel until they ascend to higher levels in the crust, where external sources of sulphur may exist, and any magmatic sulphide deposits would lie at feasible exploration depths.

Sulphur Isotope Analyses

Sulphur isotope analyses of mineralized samples from the PLI were completed by Smith (2006) and preliminary results from these were reported by Smith *et al.* (2001). Li *et al.* (2000) also report some sulphur isotope analyses from one of the earlier drillholes in the project area.

Sulphur isotope compositions from several drillholes in the PLI (*see* Table A-2) range from -1.93 to -5.25, expressed as $\delta^{34}S$ (per mil units). Sulphides from the country-rock gneisses had $\delta^{34}S$ from -1.32 to -4.91, *i.e.*, they cover essentially the same range of isotopic compositions. A similar correspondence was noted by Li *et al.* (2000). Smith (2006) also analyzed some minor sulphides hosted in older anorthositic rocks intersected in hole SVB-97-92; these had $\delta^{34}S$ from -0.99 to -6.43. The results are indicated in Figure 54, as data histograms. As mantle-derived 'magmatic' sulphur is inferred to have neutral to slightly positive $\delta^{34}S$, these results suggest that a large proportion of the sulphur in the mineralization was not of mantle origin, but derived from crustal sources. The correspondence between magmatic sulphides and those in the country rocks strongly suggests that the latter were the source for much of the sulphur. Naldrett *et al.* (2000) reached similar conclusions for the sulphides in hole SVB-98-96, based upon a consideration of sulphide mineral assemblages, notably the presence of troilite (FeS) rather than pyrrhotite ($Fe_{1-x}S$). The sulphur isotope compositions from Pants Lake fall in the same general range as those from Voisey's Bay, but the latter are distinctly more variable, as are sulphur isotope data from the Tasiuyak gneiss (Ripley *et al.*, 1999). Consequently, the data from Voisey's Bay are ambiguous compared to those from Pants Lake.

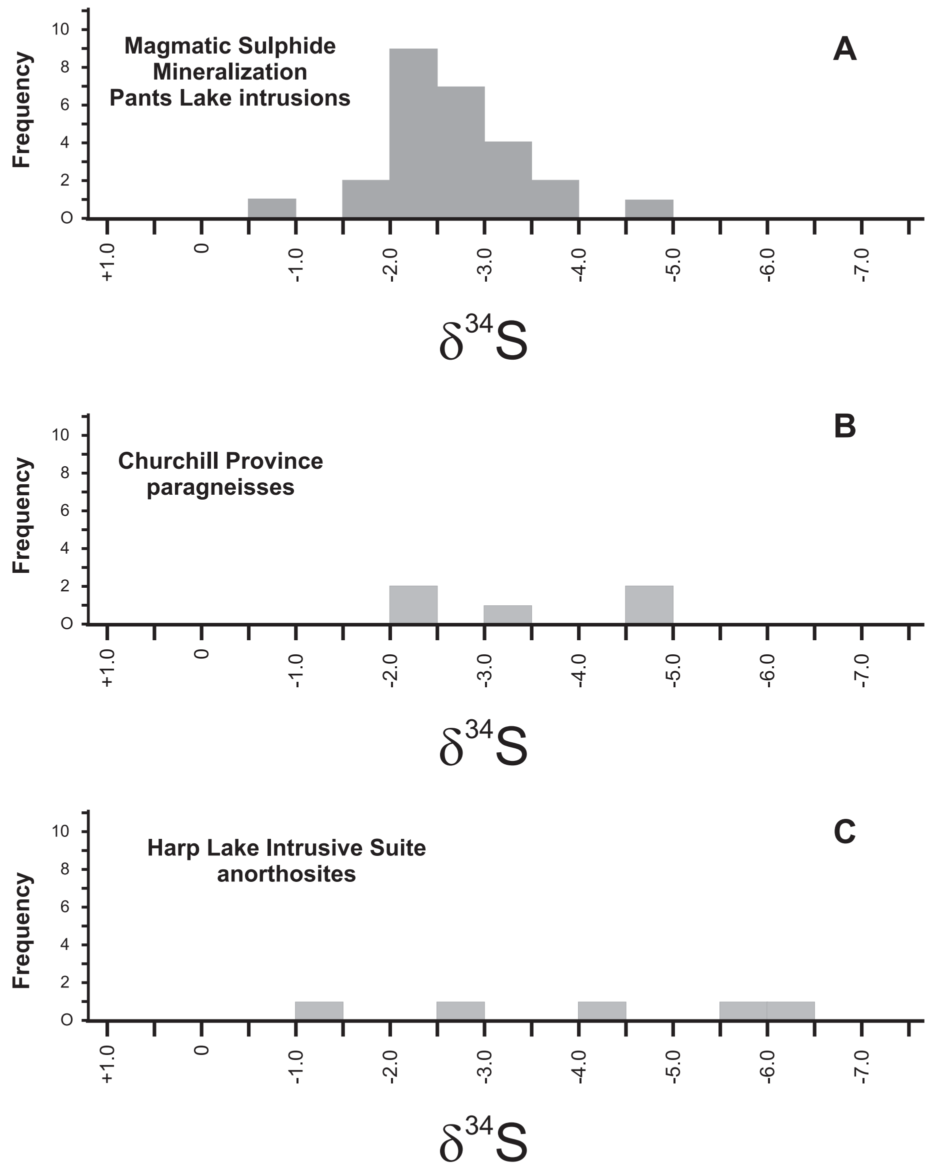


Figure 54. *Data histograms indicating the variation in sulphur isotopic compositions measured using sulphide separates from the Pants Lake Intrusions country rocks. Data from Smith (2006).*

MINERAL GEOCHEMISTRY

Trace-element Geochemistry of Sulphide Minerals

The only study of the geochemistry of the sulphide minerals at Pants Lake was conducted by Maddigan (2008) using Secondary Ion Mass Spectrometry (SIMS). The objective of the study was to compare the minor-element geochemistry of sulphides (mostly chalcopyrite and pentlandite) from Pants Lake and Voisey's Bay. The results indicated that the Pants Lake sulphides are richer in Co, Zn, As and Bi compared to the equivalent minerals at Voisey's Bay. Maddigan (2008) suggested that such differences might reflect a greater contribution of sulphur from the country-rock gneisses at Pants Lake.

SUMMARY, DISCUSSION AND CONCLUSIONS

INTRODUCTION

The final section of this report reiterates the most important findings of this study, and discusses aspects of these results. There are obvious parallels between the mafic rocks and Ni–Cu sulphide mineralization of the Pants Lake and Voisey's Bay areas, noted several years ago (Wares, 1997; Kerr and

Smith, 1997), but there are also some important differences between the two areas. These questions have been summarized and discussed elsewhere (Kerr, 1999, 2003a, b; Kerr and Ryan, 2000; Kerr *et al.*, 2001), but this section provides an expanded treatment. For ease of reference, this section of the report is organized into sub-sections corresponding to the titles of the various preceeding chapters.

REGIONAL GEOLOGICAL FRAMEWORK

Summary

The PLI are nickeliferous mafic plutonic complexes whose extent and importance were unrecognized prior to exploration work in 1995. On the basis of their age and affinity, the PLI are grouped as part of the 1350 to 1290 Ma NPS. Mafic intrusions are a minor but important component of the NPS, which is dominated by anorthositic and granitoid rocks. The best-known NPS mafic intrusion prior to 1995 was the classic 1305-Ma Kiglapait intrusion north of Nain (Figure 6). The 1333-Ma Voisey's Bay intrusion (host to the Ni–Cu sulphide deposits) is certainly the best known from a metallogenetic perspective. The NPS was emplaced across the tectonic boundary between the Archean Nain and Paleoproterozoic Churchill provinces (Figure 6). This crustal-scale boundary between these two structural provinces runs close to the site of the Voisey's Bay deposits, and has been suggested to have influenced their formation (*e.g.*, Naldrett *et al.*, 1996).

The PLI are located some 100 km south of Voisey's Bay (Figures 6 and 7), and are located some 20 km to the west of the Nain–Churchill boundary, within the Churchill Province. In this area, the boundary separates complex orthogneisses of the Nain Province from paragneisses and metagranitoid rocks of the Churchill Province. In the area of the PLI, paragneisses of pelitic to semipelitic composition are dominant; these rocks are compositionally similar to the Tasiuyak gneiss of the Voisey's Bay area, and commonly contain minor sulphide and graphite. The gneisses are intruded by plutonic rocks of the *ca.* 1450 Ma HLIS in the southern part of the study area; these are dominated by anorthosite and rapakivi-textured granite. In the northern part of the study area, the gneisses are intruded by similar plutonic rocks assigned to the NPS, but these remain undated.

The PLI are located at the southern end of the NPS, in a basement inlier dominated by Churchill Province gneisses. They consist of several discrete plutonic bodies, in which the dominant rock type is olivine gabbro, accompanied by lesser amounts of troctolite, melagabbro, and diabase. The PLI were originally considered to be a single entity, but U–Pb geochronology now shows that the two largest intrusions, the North and South intrusions, have ages of 1322 and 1338 Ma, respectively (Smith *et al.*, 1999, 2001; *see* appendix A.1). The intrusions are undeformed and unmetamorphosed, although there is some possible evidence for gentle folding of the North intrusion (*see* section entitled 'Geometry and Stratigraphy'). Disseminated Ni–Cu sulphide mineralization is widespread in the basal sections of the two largest PLI, and is also known from several smaller bodies. Mineral exploration in the area was conducted from 1995 to 1998, and resumed in 2001. This work involved regional mapping, geophysics (notably EM and gravity surveys), and extensive diamond drilling.

Comparisons with the Voisey's Bay Area

There are clear similarities between the geological setting of the PLI and that of analogous mafic rocks in the Voisey's Bay area. Both represent relatively primitive mafic magmas that were, in part, intruded into the sulphide- and graphite-bearing Tasiuyak gneiss. The reacted country-rock fragments closely associated with mineralization in both areas (*see* section on '*Magmatic Sulphide Mineralization*') attest to physical and chemical interaction between magmas and these country rocks. The tectonic boundary between the Nain and Churchill provinces was interpreted to control the conduit that facilitated the rapid ascent of the Voisey's Bay parental magmas (Naldrett *et al.*, 1996), but no such case can be made for the PLI, which lie some 20 km west of the equivalent structure (Figures 7 and 9). However, there are many uncertainties about the exact position of the Nain–Churchill boundary in the Voisey's Bay area itself (Ryan, 1996), and the direct spatial link in that area has been questioned (Ryan, 2000). There may be a general role for the Nain–Churchill boundary (or one of many associated structures) as a channel for magma ascent, but caution is dictated in using the boundary as a direct exploration guide, or in focusing on analogous boundaries in exploration elsewhere.

Most other mafic intrusions forming part of the NPS (Figures 6 and 7) were emplaced into Archean gneisses of the Nain Province, and these appear to lack significant sulphide mineralization (Kerr and Ryan, 2000). The PLI and the Voisey's Bay Intrusion are the only examples emplaced within the Tasiuyak gneiss or equivalent rocks, and the only examples currently known to be widely mineralized. The data from the PLI further support the general concept that the Tasiuyak gneiss played a critical role, either as a direct sulphur source, a contaminant that promoted sulphur exsolution, or through both processes (Naldrett *et al.*, 1996; Li and Naldrett, 1999; Kerr and Ryan, 2000). However, direct evidence for derivation of sulphur from the country rocks at Voisey's Bay remains ambiguous, due to the very wide range of sulphur isotope compositions typical of the Tasiuyak gneiss, which overlaps neutral values typical of mantle-derived magmatic sulphur (Ripley *et al.*, 1999, 2000). Mineralized rocks at Pants Lake have $\delta^{34}S$ values from 0 to -5 per mil, compared to country-rock values of -1 to -5 per mil (Li *et al.*, 2001; Smith *et* *al.*, 2001). These results are consistent with an important contribution of sulphur from the country rocks, but (as at Voisey's Bay) the proportions are not easy to constrain.

Timing of Mafic Magmatism

The ages of 1338 ± 2 Ma and 1322 ± 2 Ma reported for the South and North intrusions, respectively (Smith *et al.*, 1999, 2001; *see* appendix A.1) are similar, but not identical, to the ages of 1333 ± 1 Ma and 1313 ± 1 Ma reported from the Voisey's Bay and Mushuau intrusions (Amelin *et al.*, 1999; Li *et al.*, 2000). Geochemical data also demonstrate that the South and North intrusions are distinct, and resemble the Voisey's Bay and Mushuau intrusions, respectively (*see* section on 'Geochemistry'). There is no reason to suppose that crystallization age is a direct control on mineralization, but the similarity of these patterns is striking. However, the younger Pants Lake North intrusion is extensively mineralized, whereas the Mushuau intrusion, to date, is known to contain only limited basal mineralization. Of course, the Mushuau intrusion sits within Archean orthogneisses of the Nain Province, rather than within the Tasiuyak gneiss. This supports the contention that location and subjacent country rocks are ultimately more important than crystallization age (Kerr and Ryan, 2000).

COUNTRY ROCKS TO THE PANTS LAKE INTRUSIONS

Summary

The country rocks to the PLI are subdivided into the Nain Province basement (largely orthogneisses), the Churchill Province basement (largely paragneisses and metamorphosed granitoid rocks), and Mesoproterozoic intrusive rocks of the NPS and HLIS.

Gneisses of the Nain Province occur only in the eastern part of the area. They are dominated by grey, variably banded, tonalitic to granodioritic gneisses that commonly contain disrupted amphibolitic layers interpreted as transposed mafic dykes. Migmatites are common, and the neosomes of early migmatites have also been extensively transposed – such features suggest that these rocks have a complex history. There is no pervasive straightening or mylonitization associated with the Nain–Churchill boundary, but some local northwest–southeast mylonite zones are developed within the Nain Province. Churchill Province gneisses include paragneisses of pelitic to psammitic composition, and two different types of orthogneiss. The paragneisses are commonly migmatitic, and interlayered with bands of pegmatite and garnetiferous granite; positioning map boundaries between these rocks and 'true' orthogneisses is inherently difficult. The paragneisses commonly consist of quartz, K-feldspar, plagioclase, and biotite, with variable amounts of garnet, sillimanite, and cordierite. Graphite and sulphide (pyrrhotite) are also commonly present. The paragneisses have a complex structural and metamorphic history, in which earlier east–west-trending fabrics have been reoriented into the dominant northwest–southeast foliation trend. Deformation in the paragneisses appears to be particularly intense approaching the Nain–Churchill boundary. The most abundant orthogneiss type in the Churchill Province is a coarse-grained, garnetiferous rock that commonly displays well-preserved relict igneous textures. More deformed variants of this rock type are augen gneisses, and the contacts between orthogneiss and paragneiss are commonly zones of increased deformation. Medium- to coarse-grained orthogneisses of more granular appearance are also present; these are typically orthopyroxene-bearing, and resemble 'charnockites' and 'enderbites' described from areas around Voisey's Bay, and elsewhere. The Churchill Province orthogneisses are interpreted as pre- and syntectonic Paleoproterozoic intrusive rocks emplaced into the paragneisses, but their absolute ages are unknown.

Mesoproterozoic plutonic rocks are undeformed and unmetamorphosed. Those in the north are assigned to the NPS, whereas those in the south are assigned to the HLIS; few of these rocks have been dated, so such assignments are largely geographic. The HLIS in the study area contains two rock types, *i.e.*, coarse-grained anorthosite to leuconorite, and equigranular to porphyritic syenite and granite (Arc Lake granite of Emslie, 1980). The NPS includes very similar rock types, and also some iron-rich mafic to intermediate rocks of the type generally described as ferrodiorite. These Mesoproterozoic plutonic rocks have locally been intersected in deep drillholes, and can be locally difficult to distinguish from the gabbroic rocks of the PLI.

Comparisons with the Voisey's Bay Area

As noted in the preceding section, the dominant country rocks to the PLI resemble the Tasiuyak gneiss, which hosts some parts of the Voisey's Bay deposits, and is inferred to underlie much of the Voisey's Bay area at depth. Metasedimentary gneisses of the Pants Lake area also resemble the Tasiuyak gneiss, in that, they contain significant amounts of sulphide (pyrrhotite) and graphite. As discussed above, there is ample physical evidence for interaction between mafic magmas and these rocks in both areas. Although the sulphur isotope data from Voisey's Bay are equivocal in terms of the sulphur source for the ores, Amelin *et al.* (2000) present Sr, Nd and Pb isotope evidence that collectively point to contamination of the Voisey's Bay intrusions by the Tasiuyak gneiss. The Re–Os data of Lambert *et al.* (2000) also point to this conclusion, although interpretation of these latter data is complex. The Nd isotope data from the PLI are closely similar to those of the Voisey's Bay intrusions, and it seems reasonable to assume that PLI magmas were contaminated by the paragneisses.

Orthogneisses are more abundant in the Churchill Province of the Pants Lake area than at Voisey's Bay. However, the orthopyroxene-bearing orthogneisses are similar in many respects to the 'enderbitic gneiss' that hosts part of the Voisey's Bay deposit, notably the Ovoid and Eastern Deeps zones. Although this enderbitic gneiss is generally considered to be part of the Nain Province, this assumption has been challenged by Ryan (2000) who pointed out that such rocks are also common within the Churchill Province. The garnetiferous granitoid gneiss of the Pants Lake area has no direct equivalent in the Voisey's Bay area, although such rocks do occur elsewhere within the Tasiuyak gneiss in northern Labrador.

Finally, there is some indication from regional map patterns (Figure 9) that the PLI are preferentially sited within the paragneisses, rather than in the orthogneiss units. If this is the case, it is likely because the paragneisses provided less resistance to forceful intrusion and/or were more easily assimilated into the magmas.

GEOLOGY AND PETROLOGY

Summary

The PLI consist of several discrete plutonic bodies, of which the two largest are the South (1338 ± 2 Ma; Smith *et al.*, 2001) and the North intrusions (1322 ± 2 Ma; Smith *et al.*, 1999). There are also several other smaller bodies, of which the best-known are the Worm intrusion and the Mineral Hill intrusions (Figure 9). On the basis of contained rock types and geochemical patterns, the latter (and other minor bodies) are correlated with the North intrusion. However, none of these minor bodies has actually been dated. Although there are demonstrable age differences within the PLI, the mafic rocks from all of these intrusions are petrologically similar. For example, the fine-grained, layered olivine gabbro, which is present in the South and North intrusions, is petrologically identical in both. Previous assumptions of a common age (*e.g.*, Kerr, 1999; Kerr *et al.*, 2001) were entirely justified, even though there are some subtle geochemical contrasts between the South and North intrusions.

Four main rock types are recognized within the PLI. These are:

1) Fine-grained, layered olivine gabbro, present in both South and North intrusions;
2) Melagabbro–peridotite, present mostly in the South intrusion;
3) Massive coarse-grained leucogabbro, present widely in the North intrusion; and
4) Black olivine gabbro, present locally in the North intrusion.

All these rock types have essentially the same primary mineral assemblage, *i.e.*, plagioclase, olivine, clinopyroxene, iron oxide, and biotite, but their textures and modal compositions vary. The fine-grained, layered olivine gabbro contains granular, cumulus olivine and euhedral plagioclase, and typically has subtle layering defined by modal variations. Melagabbro and peridotite are mafic cumulates, dominated by olivine, with intercumulus plagioclase and pyroxene, and these appear to be closely associated with, and gradational with, the fine-grained, layered olivine gabbro. Troctolitic variants of the fine-grained, layered olivine gabbro are similarly interpreted as mafic cumulates. In the South intrusion, the melagabbro and peridotite occur near the base of the body, and there are local occurrences with the lower part of the North intrusion. The mafic cumulates of the South intrusion also contain sulphides.

Massive coarse-grained leucogabbro forms the upper unit of the North intrusion, and is a plagioclase cumulate, containing interstitial to oikocrystic olivine and clinopyroxene. Its textures show that olivine crystallized late, rather than early, because olivine is interstitial to plagioclase. Plagioclase crystals are commonly zoned. Black olivine gabbro of the North intrusion has a rather similar texture, but is distinguished by the acicular habit and dark colour of its plagioclase, apparently caused by very fine inclusions of iron oxide. It was originally thought to be a variant of the massive leucogabbro, but stratigraphic variations indicate that it is a discrete unit, normally located at the base of the North intrusion. Coarse-grained, black olivine gabbro is restricted to the northern part of the North intrusion, but a fine-grained variant (poikilitic olivine diabase) occurs on a wider scale in the North intrusion, and is also found within the mineralized sequence.

Minor rock types found within the PLI include diabase and fine-grained chilled gabbro, most commonly associated with the basal contacts of intrusions, but also seen locally at the upper contact of the North intrusion, where it grades downward into coarse-grained massive leucogabbro. Intrusive breccias are also locally associated with contact regions, and consist of well-preserved angular inclusions of paragneiss and granite in a fine-grained gabbroic matrix. These breccias are distinct from the more complex breccia-like rocks of the North intrusion mineralized sequence.

In addition to the generally unmineralized igneous rocks described above, both the South and North intrusions contain sulphide-bearing mineralized sequences, normally located close to their basal contacts. In the South intrusion, sulphides are mostly hosted by melagabbro and peridotite. In the North intrusion, there is a distinctive package of unusual and complex, sulphide-bearing, mafic rocks that exhibits a consistent internal stratigraphy. These are discussed in more detail in conjunction with sulphide mineralization.

Discussion

Most of the mafic igneous rocks within the PLI can be classified as olivine gabbro, although there are minor occurrences of troctolite, melagabbro, and peridotite. The distribution and textures of these latter two rock types indicate that they are generally mafic cumulates. They appear to be closely linked to the fine-grained, layered olivine gabbro unit. In the Voisey's Bay area, the mafic rocks of the Mushuau and Voisey's Bay intrusions are generally described as 'troctolites' (*e.g.*, Naldrett *et al.*, 1996; Li and Naldrett, 1999; Li *et al.*, 2000), but most of these also contain clinopyroxene, and many would probably be olivine gabbros if classified strictly. The distinctions between 'gabbro' and 'troctolite' are somewhat artificial in that they form a continuum, and there is no doubt that the mafic rocks of the PLI are petrologically similar to those of the Voisey's Bay area. Just as the Mushuau and Voisey's Bay intrusions are petrologically indistinguishable, one cannot distinguish on petrological grounds between the gabbros of the South and North intrusions.

It is important to note that mafic rocks from the PLI show important textural differences that suggest differences in their crystallization sequences. Fine-grained, layered olivine gabbro invariably contains cumulus olivine, as do the associated mafic cumulate rocks. This feature is common to both the South and North intrusions. In contrast, the coarse-grained, massive leucogabbro and the black olivine gabbro of the North intrusion have late, interstitial olivine, whose habit resembles that of intercumulus clinopyroxene. This shows that there were at least two discrete batches of mafic magma within the North intrusion. One of the two crystallized olivine at an early stage, together with plagioclase, but the other did not have olivine on its liquidus until relatively late.

GEOMETRY AND STRATIGRAPHY

Summary

Exploration drilling provides valuable information on the 3-D geometry, anatomy and stratigraphy of the PLI, which would never be available from surface geological data alone. Both the South and North intrusions are sheet-like to slab-like bodies that are present widely in the subsurface, and this general geometry is shared by other minor intrusions in the area.

The South intrusion is a northwest-dipping, slab-like intrusion having a maximum true thickness of 500 to 600 m (Figure 12). It is dominated by fine-grained, layered olivine gabbro, underlain by a basal melagabbro and peridotite sequence up to 80 m in total thickness. This basal mafic to ultramafic cumulate zone is present in every drillhole that penetrated the basal contact of the South intrusion, and the stratigraphy of the South intrusion appears to be very consistent and predictable. There is a discontinuity in the upper part of the South intrusion, at a level where minor sulphides are associated with local screens of gneissic material (Figure 12). Above this level, sheets of fine-grained, chilled gabbro and diabase are more abundant than below, and there are also breaks in mineral composition trends (MacDonald, 1999). The South intrusion is structurally overlain by at least two sill-like bodies that form the Mineral Hill intrusions (*see* below). Kerr (1999) originally suggested that the latter might be genetically related to the South intrusion, and connected to it by a conduit system. The Mineral Hill intrusions, however, contain coarse-grained massive leucogabbro, and their general stratigraphy is more akin to that of the North intrusion. Geochemical patterns also indicate that the Mineral Hill intrusions are likely not related genetically to the South intrusion.

The more complex North intrusion is subdivided into three interconnected lobes (Figures 9 and 15). The NDT lobe consists of a northwest-dipping, slab-like body up to 500 m thick (Figure 16). It is dominated by fine-grained, layered olivine gabbro, which is overlain by a thin cap of massive leucogabbro. Minor mafic cumulate rocks occur in its lowermost section, but these are rare and discontinuous compared to those of the South intrusion. A thin mineralized sequence sits at the base of the intrusion. To the east, across a basement 'high', the Happy Face lobe is a flat-lying to gently northeast-dipping sheet, generally less than 200 m thick, which is dominated by massive leucogabbro (Figures 17 and 18). Fine-grained, layered olivine gabbro forms only a thin unit near the base of the sheet, above the sulphide-bearing rocks of the mineralized sequence. To the north, the NDT and Happy Face lobes both connect with the Taheke Lake lobe, which retains the most complete stratigraphy within the North intrusion (Figure 20). This lobe of the intrusion again has a sheet-like form, having a maximum thickness of about 400 m. It forms a gentle arch, dipping to the northwest in the west, and to the northeast in the east. In the west, it contains fine-grained, layered olivine gabbro akin to that of the NDT lobe, which is locally overlain by massive leucogabbro; however, the basal unit of the intrusion here consists of black olivine gabbro. In the west, the sheet is dominated almost entirely by black olivine gabbro, and the other units are missing. As in all areas of the North intrusion, there is a mineralized sequence at the base of the intrusion. Although the coarse-grained black olivine gabbro is only recognized as a discrete mappable unit in the Taheke Lake lobe, a closely similar rock type and a fine-grained equivalent (poikilitic olivine diabase) occur locally in the Happy Face and NDT lobes. In these areas, rocks considered equivalent to the black olivine gabbro generally occur at the top of the mineralized sequence and also within the mineralized sequence, below the fine-grained olivine gabbro unit (*e.g.*, Figure 19).

The overall geometry of the North intrusion resembles that of a gentle, north-plunging fold, with limbs that dip at only 10 to 15° (Figures 20 and 23). This suggests that there may have been some post-1322 Ma deformation in this part of Labrador. However, the changes in attitude are accompanied by changes in thickness and in stratigraphic anatomy, so it remains possible that this in part reflects the original intrusive geometry. The geometric arrangement of units in the Taheke Lake lobe indicates that the black olivine gabbro sits at the base of the North intrusion, and is a discrete unit, rather than a variant of the upper massive leucogabbro unit. The stratigraphy of the North intrusion can most easily be understood if the black olivine gabbro (and underlying mineralized sequence) of the Taheke Lake lobe is in fact the lateral equivalent of the mineralized sequence elsewhere in the body (Figure 22). Such an interpretation implies that there is a close genetic relationship between the black olivine gabbro and the mineralized sequence.

The Worm intrusion forms an east-dipping, sheet-like body that is stratigraphically similar to the Happy Face lobe, *i.e.*, it is dominated by massive leucogabbro. It dips rather steeply (about 35°) compared to the North or South intrusions (Figure 14). The Worm intrusion is interpreted as a southern extension of the North intrusion, although a direct connection is difficult to demonstrate in the field. The connection between the east-dipping Worm intrusion and the generally flat-lying Mineral Hill intrusions is similarly unclear.

Interpretation of the South Intrusion

The South intrusion shows many features that would be expected in a relatively static, tranquil, sill-like magma chamber. The very consistent stratigraphy of the body indicates that mafic cumulates developed almost everywhere in the body, presumably through gravitational separation of olivine from plagioclase. Mineral compositional trends also imply that the body crystallized ‘in place’, with only minor replenishments by fresh mafic magma. The discontinuity in the upper part of the South intrusion suggests that it may have developed in two stages; the gneissic screens and local sulphides seen at this level are interpreted as the original basal contact of an early sheet-like intrusion that was then transgressed by the main (lower) part of the South intrusion. The chilled diabase-like rocks that are common in the upper section are believed to be intrusive sheets or veins derived from the slightly younger lower section. However, unequivocal evidence of these age relationships is lacking, and the gabbros in the upper section are geochemically indistinguishable from those below.

Interpretation of the North Intrusion

The complexity of the North intrusion is attributed to a combination of original intrusive geometry, multiple magma emplacements, and superimposed mild deformation, but it is not easy to decide which of these is mainly responsible for the present geometry. The intrusion is a slab-like body that was formed from at least three major magmatic pulses. The lowermost unit comprises the black olivine gabbro and the associated rocks of the mineralized sequence. The black olivine gabbro was widely developed only in the area of the Taheke Lake lobe, but minor examples of this rock type do occur elsewhere in the body, at an equivalent stratigraphic level. The unusual sulphide-bearing rocks of the mineralized sequence were probably also part of this pulse, and were formed from early (?) sulphide- and fragment-charged batches of magma. The fine-grained, layered olivine gabbro forms the middle unit, which has its thickest development in the NDT lobe, but is present in all areas, except for parts of the northeast Taheke Lake lobe. The massive leucogabbro forms the uppermost unit in most parts of the body. However, it appears to be absent in the northeastern part of the Taheke Lake lobe where the black olivine gabbro is thickest. The age relationships between the three main component units of the North intrusion are not well established. There is evidence that the massive leucogabbro was the last to be emplaced, because it appears to form veins or sheets that cut the fine-grained olivine gabbro. In contrast, contacts between fine-grained, layered olivine gabbro and black olivine gabbro, where observed in drillcore, are diffuse, and marked by ‘composite’ rocks composed of fine-grained inclusions in coarser gabbroic matrix. The relationship between these two units is ambiguous, and it seems likely that their parental magmas coexisted in a liquid or partly liquid state.

The present fold-like geometry of the North intrusion is here attributed to later mild deformation, although the alternative explanation of an entirely primary origin remains possible. Any such deformation must presumably also have affected the South intrusion, although there is no clear evidence for it in that area. Mild deformation and warping of post-1322 Ma age may be widespread in this part of Labrador, but would essentially be impossible to detect in the absence of relatively young marker units that have subhorizontal attitudes. The PLI form the only such markers in a very large area of Labrador. The absolute timing of this possible deformation is unknown. It could be a distal manifestation of the *ca.* 1100 Ma Grenville Orogeny or, at the other extreme, it could be related to the Late Cretaceous opening of the Labrador Sea – there are essentially no constraints upon its timing, other than it being younger than 1322 Ma.

The geometry of the North intrusion is important from a mineral exploration perspective, because it places large areas of the prospective basal contact region within feasible drilling range. It also means that prospective mafic rocks are also present in the subsurface beyond the exposed portion of the North intrusion, most notably in the northern and northeastern parts of the Taheke Lake lobe. This area is of considerable interest, because it contains the thickest development of black olivine gabbro, and also the thickest parts of the mineralized sequence. It remains relatively untested compared to the area of the Northern Abitibi zone (Figure 15). To the northwest of the Taheke Lake lobe, the situation is less clear, because the North intrusion is not present in a hole drilled northwest of Taheke Lake (Figure 20). The reasons for this absence are not clear; it is possible that there is a reversal in dip direction that brings the basal contact above the erosion surface or, alternatively, a significant steepening of dip. The gravity anomaly in the Taheke Lake area (Figure 23) may also be an indication of a deeper intrusive 'root' in this area.

To date, no feeder dyke system to the North intrusion has been located during exploration. The Worm intrusion (*see* below) is the most obvious candidate from a geometric perspective, dipping some 30° to the east, but its stratigraphy is essentially identical to that of the North intrusion, specifically the Happy Face lobe. It seems more likely that it is a dipping (folded?) extension of the latter. A thin mafic intersection noted northwest of Taheke Lake in hole SVB-98-111 (Fitzpatrick *et al.*, 1999; Kerr, 1999) is probably not related to the North intrusion, because it is compositionally distinct. The location of a feeder system is clearly an important question, because significant sulphide mineralization in the Voisey's Bay area is intimately linked to a feeder conduit system and its entry point into a larger magma chamber (Li and Naldrett, 1999; Lightfoot and Naldrett, 1999).

Affinities of Smaller Intrusive Bodies

As discussed above, the Worm intrusion is best interpreted as a more steeply dipping extension of the adjacent Happy Face lobe. The Mineral Hill intrusions also resemble the North intrusion, and geochemical data also suggest such a link. Also, parts of the mineralized sequence in the Mineral Hill intrusions have affinities with typical mineralized rocks from the North intrusion. The Cartaway and Doughnut intrusions are not well known, and have never been drilled. However, both contain an upper massive leucogabbro unit, and it seems likely that they represent distal extensions of the North intrusion, as suggested for the nearby Mineral Hill intrusions. They also share their flat-lying attitudes.

MAGMATIC SULPHIDE MINERALIZATION

Summary

Magmatic sulphide mineralization was first noted in the area by Thomas and Morrison (1991), but the wide extent of such mineralization was only recognized following exploration work in 1995 and 1996. The best-known and most extensive sulphide mineralization is present near the base of the North intrusion. Nearly all magmatic sulphide mineralization in the PLI is associated with basal contact regions, but there are differences in the character of mineralization from place to place.

Mineralization in the South intrusion is known mostly from deep drilling in 1997 and 2002. Aside from a thin and sporadic sulphide zone in the upper part of the intrusion, nearly all mineralization is contained within the basal, mafic cumulate sequence that occurs everywhere in the Sarah Hill lobe (Figures 9 and 12). The sulphides form interstitial patches in melagabbro and peridotite, and also in gabbroic rocks near the very base of the intrusion. They are associated with digested and reacted fragments of paragneiss. The absolute grades are low, due to the generally low sulphide content, but sulphide metal contents are locally high, up to 4% Ni and 1.5% Cu, particularly in the upper part of the mafic cumulate sequence. These high Ni/Cu ratios are atypical of PLI mineralization. The only significant sulphide accumulations were in holes drilled by Falconbridge in 2002, in which semi-massive sulphides were encountered. These also gave generally low Ni assays (<1%), which is typical of the lowest part of the mineralized sequence.

The mineralized sequence of the North intrusion is more complex than that of the South intrusion. It is present in almost every location where the basal contact of the intrusion has been tested by drilling. Although there are some variations from lobe to lobe, its stratigraphy is remarkably consistent throughout the intrusion. It is divided into two parts, *i.e.*, an upper heterogenous subsequence and a lower homogeneous subsequence, both of which contain sulphide mineralization. In most cases, mineralized rocks do not sit directly upon the footwall gneisses; rather, there is an underlying weakly mineralized to barren fine-grained olivine gabbro, which is locally chilled against the gneisses (Figure 26).

The heterogeneous subsequence is dominated by the rock type known as composite gabbro, which is complex and variable in appearance. This rock type is characterized by ellipsoidal inclusions of fine-grained, olivine-rich troctolite and gabbro, contained in a coarse-grained, sulphide-bearing gabbroic matrix. The mafic inclusions are accompanied by variably reacted and digested gneiss fragments, which typically increase in abundance downward. Mafic inclusions are texturally similar to fine-grained olivine gabbro (*i.e.*, they have cumulus olivine), whereas the gabbroic matrix is texturally similar to massive leucogabbro or black olivine gabbro (*i.e.*, it has late, oikocrystic olivine). In terms of general appearance, the matrix material most closely resembles black olivine gabbro.

The homogeneous subsequence contains a variety of sulphide-bearing gabbros, in which sulphide occurs as interstitial material and larger, droplet-like masses. Digested gneiss fragments are also widespread in these rocks, although not as abundant as in the composite gabbro. The most distinctive variant is leopard gabbro, which contains large poikilitic clinopyroxenes in a sulphide-rich troctolite matrix; the name is derived from its yellow- and black-spotted appearance. Most of the gabbros in the homogeneous subsequence are texturally akin to fine-grained, layered olivine gabbro (*i.e.*, they have cumulus olivine), but poikilitic olivine diabase, possibly the fine-grained equivalent of black olivine gabbro, also occurs locally. As described above, the homogeneous subsequence generally fades downward into barren gabbro at the very base of the intrusion.

Composite gabbro and leopard gabbro are akin in many respects to 'basal breccia' and 'leopard troctolite', as described from the Voisey's Bay deposit (Naldrett *et al.*, 1996; Li and Naldrett, 1999). Massive sulphides are rare, but are most commonly observed at or just below the basal contact, where they invade the lowermost barren gabbro and underlying gneisses. They vary considerably in texture, and include 'clean' material exhibiting loop-textures similar to those described at Voisey's Bay and 'dirty', heterogeneous, inclusion-rich material. The best Ni and Cu grades are generally found in massive sulphides of the former type.

Nickel and Cu grades from North intrusion mineralization vary widely. These variations are due, in part, to variations in sulphide abundance, but, in part, reflect variations in sulphide metal contents. The highest grades (11.75% Ni, 9.7% Cu) came from an unusual sulphide vein in the footwall gneisses; excluding this occurrence, the best intersections (Holes SVB-97-67 and 98-131) contained from 2 to 5% Ni. Sulphide metal contents from the North intrusion are variable, but appear to change systematically through the mineralized sequence. The lower part of the homogeneous subsequence is commonly metal-poor (<1% Ni in sulphides), but the composite gabbros of the upper heterogeneous subsequence locally contain sulphides with up to 6% Ni and 8.5% Cu. However, generally, sulphides in the upper part of the heterogeneous subsequence contain around 2% Ni and 2% Cu, as indicated by geochemical plots (Figure 28). The contrasts in sulphide metal contents between the two subsequences appear to be consistent throughout the North intrusion (Figure 29). North intrusion mineralization has remarkably consistent Ni/Cu ratios (typically around 1.0) in all areas. Nickel/cobalt ratios are also very consistent at 7 to 9 (Figure 30). These Ni/Cu and Ni/Co ratios are low compared to typical Voisey's Bay mineralization (Ni/Cu ~ 2; Ni/Co > 20).

Sulphide mineralization in the Worm and Mineral Hill intrusions appears to be generally similar to that seen in the North intrusion, and there is a particularly strong similarity between the mineralized sequence in the Worm intrusion and that of the adjacent Happy Face lobe. Mineralization at Mineral Hill consists dominantly of homogeneous, sulphide-bearing olivine gabbro that resembles the lower homogeneous subsequence, and has low sulphide metal contents (<1% Ni). Composite gabbros are relatively rare in this area, although thin intersections of similar material were noted in a few drillholes.

Interpretation of South Intrusion Mineralization

The South intrusion mineralized sequence appears to be a gravitational accumulation at the base of a crystallizing magma chamber, where sulphide droplets and gneissic fragments were concentrated by the same process as the associated cumulus olivine crystals. The variations in metal tenor within the sequence may represent changes in the bulk ratio of silicate magma to sulphide magma ('R factor'; Naldrett, 1989) as the magma chamber evolved. The later (stratigraphically highest) sulphides may have encountered, and equilibrated with, a greater volume of magma, and therefore extracted greater amounts of metals. They may also have acquired extra Ni by reacting with olivines in the associated cumulate rocks. The basal contact of the South intrusion is a large and mostly unexplored area (Figures 11 and 12). Although represented as a plane in the geometric analysis, this surface probably has a distinct topography, which might contain depressions that could trap sulphide liquid. The potential tonnage of low-grade mineralization in this region is large and, although absolute grades are uneconomic, it indicates that significant amounts of metal were available for concentration. The relatively high (*ca.* 4% Ni, 2% Cu) sulphide metal contents in parts of the South intrusion resemble values typical of the Voisey's Bay deposit, and indicate that significant exploration potential remains in this area. As discussed in the section on Geochemistry, the South intrusion has a closer geochemical affinity with the Voisey's Bay intrusion than does the North intrusion. The southern part of the South intrusion (Adlatok River lobe) remains unexplored and undrilled, and the some of the best sulphide metal contents reported come from hole SVB-97-89, which is the southernmost hole in the area.

The geochronological data (Smith *et al.*, 2001; *see* appendix A.1) indicate that South intrusion mineralization formed in a separate intrusive event at *ca.* 1338 Ma, whereas the North intrusion mineralization was not formed until *ca.* 1322 Ma.

Interpretation of North Intrusion Mineralization

The mineralized sequence of the North intrusion contains complex rock types that are not seen elsewhere in the North intrusion. In most cases, the mineralized sequence is not gradational with the overlying unmineralized rocks, but rather has a sharp boundary against them. It also has a consistent bipartite stratigraphy, consisting of a heterogeneous, breccia-like upper section, and a more homogeneous lower section that contains disseminated sulphides (Figure 27). The mineralized sequence is present in all parts of the North intrusion, and its development must therefore have been part of a single broad event. Collectively, these features indicate that the mineralized sequence formed from one or more discrete pulses of magma that carried immiscible sulphide liquids and digested gneiss fragments. These were probably relatively early influxes of magma, as the mineralized sequence is situated at the base of the North intrusion. However, the normal laws of stratigraphic superposition do not apply in magmatic environments, and there was probably some resident magma in the chamber at the time of their arrival.

In the upper heterogeneous subsequence, the distinctive rock type here termed composite gabbro provides fundamental clues to the 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 *et al.*, 1996; Li and Naldrett, 1999). It is here interpreted to have formed when a sulphide- and fragment-charged magma batch was emplaced into (or passed through) partially consolidated mafic magma that was already resident in the chamber. The result is a 'mixed' rock containing texturally distinct enclaves and matrix, both of mafic composition, and variable amounts of gneissic debris. The rounded troctolitic inclusions resemble mafic enclaves interpreted to have formed in environments where one magma 'froze' upon contact with the other (*e.g.*, Vernon, 1984; Weibe, 1987). Textural variations among 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, composite gabbros range from rare examples containing angular mafic fragments (representing disruption of mostly solid resident material) to blotchy, 'curdled' rocks in which matrix-inclusion relationships are indistinct (representing 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 sulphide-bearing magma spread out within the magma chamber.

The mafic enclaves most closely resemble the fine-grained, layered olivine gabbro unit, but rarer 'exotic' varieties (*e.g.*, fine-grained norites) may be samples of other mafic magmas that lay in the intrusion pathway (Kerr, 1999). The sulphide-bearing matrix most closely resembles the black olivine gabbro unit. In the Taheke Lake lobe, black olivine gabbro appears to pass directly down into sulphide-bearing composite gabbro, locally interlayered with mineralized poikilitic olivine diabase, which is essentially 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 olivine gabbro parent magma and fine-grained olivine gabbro magma (Kerr, 1999). In summary, 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 (Figure 22).

Gneissic fragments in composite gabbro may include some locally derived material, but their extensive digestion and reaction implies that most came from deeper levels, and that they had long residence times in the mafic magma. These inclusions are dominated by Ca-rich plagioclase, corundum, and spinel, and resemble those described from the analogous rocks at Voisey's Bay (Li and Naldrett, 1999, 2000). The complete range of reactions, with which Li and Naldrett (2000) have explained the progressive transformation of Tasiuyak gneiss, has yet to be documented at Pants Lake. However, the similarity of the end products implies that the protolith materials were similar in both areas, as indicated by the regional geology.

The lower homogeneous subsequence of the mineralized sequence is dominated by fine-grained olivine gabbros that most closely resemble the fine-grained, layered olivine gabbro unit, but contain disseminated sulphides. In contrast to the upper heterogeneous subsequence, which is interpreted to be a dynamic mixing environment, the lower subsequence represents a quieter environment in which sulphides were able to settle gravitationally. Its most distinctive component is 'leopard gabbro', which consists of clinopyroxene oikocrysts sitting within a mineralized, troctolitic matrix. This has many affinities to 'leopard troctolite', as described from Voisey's Bay, which has been interpreted to form by growth of clinopyroxene crystals in sulphide-bearing magma (Naldrett *et al.*, 1996; Li and Naldrett, 1999). However, the texture could just as easily form *via* the introduction of sulphides into a partially crystalline magma in which clinopyroxene oikocrysts already existed, *i.e.*, through liquid-state mixing processes. Indeed, the unusual correlation between Ni and Fe^{2+} in olivines from the Voisey's Bay leopard troctolite (Li and Naldrett, 1999) implies that mixing between sulphide-rich and sulphide-free magmas was also involved there.

The lower part of the mineralized sequence developed, in part, as sulphide droplets and gneissic fragments derived from an influx of sulphide-rich magma (now represented by the composite gabbros) 'rained down' into underlying, partly crystallized, mafic magma. However, this underlying magma may have already contained its own sulphide liquid, because very fine-grained interstitial mineralization typically accompanies the larger, droplet-like accumulations. The lowermost section of the mineralized sequence is commonly barren, and is interpreted to have cooled and solidified prior to the arrival of sulphide- and fragment-charged magma batches above it. As noted above, sulphides in the upper section of the mineralized sequence typically have higher Ni and Cu contents (typically 1.5 to 3% Ni) compared to those in the lower section (typically 0.5 to 1% Ni). These differences also imply that the lower section of the mineralized sequence already contained low-tenor sulphide liquid, and that variable amounts of higher tenor sulphide liquid were subsequently added by 'sulphide rain' when a second batch of sulphide-charged magma arrived above it. The time lapse between emplacements of these two pulses is interpreted to be brief, but, of course, there are no absolute constraints.

Comparisons with the Voisey's Bay Area

The composite gabbro and leopard gabbro of the Pants Lake North intrusion have close affinities to the feeder breccia and leopard troctolite at Voisey's Bay, and are an obvious point of similarity (Kerr and Smith, 1997; Kerr, 1999). However, there are important differences in the anatomy and internal relationships of the mineralized sequences of the North intrusion and those of the Voisey's Bay intrusion.

Most sulphide mineralization at Voisey's Bay is hosted by (or associated with) discrete feeder conduit systems, such as the dyke-like body that hosts the Ovoid, Discovery Hill and Reid Brook zones (Naldrett *et al.*, 1996, Li and Naldrett, 1999; Evans-Lamswood *et al.*, 2000). Although disseminated sulphide mineralization is commonly found near the base of the Eastern Deeps troctolite body, the richest mineralization occurs adjacent to the entry line of the feeder conduit sheet (Naldrett *et al.*, 1996; Evans-Lamswood *et al.*, 2000). The mineralized sequence of the North intrusion has some resemblance to this dispersed basal sulphide accumulation, which is hosted by basal breccia and variable-textured troctolite (Li and Naldrett, 1999; A.J. Naldrett, personal communication, 1998). Although there are no reports of a persistent stratigraphy at Voisey's Bay, disseminated mineralization at the base of the Eastern Deeps chamber is interpreted to be the distal manifestation of an influx of sulphide- and fragment-charged magma (Li and Naldrett, 1999), similar to that invoked here for the North intrusion.

As noted above, exploration drilling has yet to identify any feeder conduit systems associated with the either the North or South intrusions. The location of a feeder conduit system beneath the North intrusion remains a mystery, but it is a riddle that an exploration geologist would love to solve, as comparisons with Voisey's Bay imply that it should be a prime site for massive sulphide accumulation. However, feeder conduits are small drilling targets (the dyke 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 metres below the basal contact. Thus, this is a clear case where absence of evidence does not (yet) equate to evidence of absence.

The spatial relationship between composite gabbro (–feeder breccia at Voisey's Bay) and leopard gabbro (–leopard troctolite at Voisey's Bay) also appears to be different in the two areas. At Voisey's Bay, the feeder breccia forms the lower part of the feeder sheet, and the leopard troctolite the upper part (Naldrett *et al.*, 1996; Li and Naldrett, 1999). The North intrusion mineralized sequence has precisely the opposite stratigraphy (Figure 27). More detailed work at Voisey's Bay now suggests that there are complex vertical and lateral facies variations in the feeder system, likely related to changes in fluid-dynamic environment (Evans-Lamswood *et al.*, 2000). The leopard troctolite is interpreted to reflect a more tranquil magmatic environment, consistent with the views expressed here for its counterpart in the North intrusion. It is naïve to expect that the distribution of 'facies' within two dynamic, evolving, magma systems should be identical.

Finally, the South intrusion mineralized sequence appears to be a gravitational accumulation, which 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 sulphide mineralization, and have been interpreted as disrupted cumulates transported by later magmas (Li *et al.*, 2000). They probably formed in much the same way as the mineralized melagabbro and peridotite of the Pants Lake South intrusion.

Geochemistry of Magmatic Sulphide Mineralization

Sulphide mineralization in the PLI has lower Ni/Cu (~1) and Ni/Co (~7) compared to mineralization at Voisey's Bay, where Ni/Cu averages ~2 and Ni/Co ranges from 15 to 30 (Figure 30; Kerr, 1999; Lightfoot *et al.*, 2001). Differences in Ni/Cu ratios are likely a function of differing silicate magma compositions, but Ni/Co ratios may also be affected by sulphide segregation processes, due to differences in $D_{sulf/mag}$ values for Ni and Co (Naldrett, 1989). Thus, the lower Ni/Co in the PLI may in part be a function of significantly lower silicate magma: sulphide liquid ratios (R factors), as Co is less sensitive to mass-balance effects, due to its smaller $D_{sulf/mag}$ value. In this context, it may be significant that the lowest Ni/Co ratios at Voisey's Bay are in the Reid Brook deposit, which also has lower sulphide Ni contents suggestive of lower R-factors (Lightfoot *et al.*, 2001). Nickel/copper ratios are affected by R factor variations, but are less sensitive to such effects because the contrasts in $D_{sulf/mag}$ are less marked for these elements. The consistency of metal ratios and the restricted variation of sulphide metal contents in the PLI imply that development of sulphide liquids took place on an intrusion-wide scale, probably at greater depth. Sulphide mineralization in the PLI cannot be a local effect at the present erosion level, or more variations in metal ratios and metal contents would be observed. It is suggested that the differences in Ni/Cu ratios between Pants Lake and Voisey's Bay reflect magmatic compositional differences.

The most important geochemical difference between Pants Lake and Voisey's Bay from an economic perspective lies in sulphide metal contents. Empirical data from the PLI show that most sulphides contain 2% Ni and 2% Cu, or less (Figures 26 and 28) compared to 3.5 to 5% Ni and about 2% Cu at Voisey's Bay (Naldrett *et al.*, 1996; Lightfoot *et al.*, 2001). These modest values for the PLI are consistent with the assays from most massive sulphide intersections in the PLI, and with the low Ni/Co ratios. They are also consistent with estimates based on Ni depletion in the unmineralized mafic rocks of the PLI (*see* later discussion). All these features imply low R factors (<350) during sulphide segregation, compared to values of 600 to 2000 at Voisey's Bay. Such inferences currently suggest that the per-tonne value of PLI sulphide 'ore' (if such is ultimately defined) would only be about half that of typical Voisey's Bay material. There are, however, a few exceptions; some (but not all) sulphides from the South intrusion have high Ni and high Ni/Cu, and some parts of the Taheke Lake lobe contain metal-rich sulphides.

In their model for the Voisey's Bay deposit, Li and Naldrett (1999) proposed that a relatively low-tenor sulphide liquid formed initially following sulphide exsolution, but was subsequently upgraded by continued interaction with fresh magma that had not previously exsolved sulphides. This hypothesis essentially represents a multistage, 'stepwise' increase in the R factor, and is supported by the relative abundance of troctolites that show little or no Ni depletion in the Voisey's Bay intrusion (Li and Naldrett, 1999). These less-depleted rocks are interpreted to represent this continued magmatic flux. The hypothetical initial sulphide liquid at Voisey's Bay would have had Ni contents akin to those of sulphides from the PLI, and olivines in rocks that show Ni depletion at Voisey's Bay have similar Ni contents to those in the PLI (Li and Naldrett, 1999; A.J. Naldrett, in Fitzpatrick *et al.*, 1999). As virtually all unmineralized rocks from the PLI are Ni depleted, there is very limited evidence for any magmas with higher (>150 ppm) Ni contents. This observation led both Kerr and Ryan (2000) and Li *et al.* (2001) to suggest that sulphide liquids in the PLI were not upgraded to the same extent, or not upgraded at all. This possibility leads directly to the inference that multistage processes, involving dynamic magmatic systems, may be essential to generate high-grade sulphide liquids in mafic systems, where relatively low (<200 ppm) magmatic Ni contents and mass-balance effects limit the tenor of any liquid developed by single-stage 'batch' processes. Simple, single-stage segregation may be effective in the context of Ni-rich ultramafic magmas (*e.g.*, komatiite-hosted Ni deposits) but is likely inadequate in more evolved mafic systems.

Nevertheless, there is at least some evidence for multistage processes in the North intrusion Mineralized sequence, in the contrasting sulphide metal contents of the lower (early?) and upper (late?) subsequences. If this pattern indeed represents two discrete magmatic pulses, as suggested above, it suggests at least some multistage upgrading. There are also significant variations in sulphide Ni content and Ni/Cu ratios in the South intrusion that suggest interaction with different magma batches. Thus, contrary to the conclusions of Li *et al.* (2001), upgrading processes may have operated to some extent in the PLI. A more pertinent question is how far such processes may have progressed – and, in particular, if there was a third or fourth influx of magma, with which a much richer sulphide liquid might be associated. Empirical data (Figure 28) imply that the Taheke Lake lobe of the North intrusion is a likely hiding place for higher grade sulphides, and to-date, the poorly explored South intrusion is also another prime candidate for future evaluation. This comment applies particularly to the untested Adlatok River lobe.

GEOCHEMISTRY

Summary

In general, unmineralized rocks from the PLI have very similar major- and trace-element patterns, and the major petrological units overlap extensively in composition. However, there are some subtle, yet systematic, geochemical contrasts that point to different origins for the North and South intrusions.

Units that occur in both the 1338 Ma South intrusion and 1322 Ma North intrusion, *i.e.*, fine-grained, layered olivine gabbro, melagabbro-peridotite, and diabase, are compositionally different in the two areas. South intrusion samples have distinct major-element compositions characterized by higher TiO_2, P_2O_5, Na_2O and K_2O at a given MgO content (Figures 32 to 35). There are also some trace-element contrasts, notably higher Ba, Sr, Zr, Y, and Nb in the South intrusion, and steeper REE patterns reflecting LREE enrichment (Figures 39 to 44). A plot of [Sr + Ba] vs. [Ce / Y] provides an effective discrimination method for the South and North intrusions (Figures 41 and 42). Collectively, these contrasts indicate that the South intrusion parental magmas were geochemically distinct. The South intrusion appears to have closer compositional affinities than the North intrusion to the Voisey's Bay intrusion.

Rock types that occur only in the 1322 Ma North intrusion are geochemically similar to the fine-grained, layered olivine gabbro from that area, indicating that all three units in the North intrusion are related. Samples from the Worm intrusion and Mineral Hill intrusions are geochemically similar to the North intrusion, indicating that they are also linked to it. The fine-grained olivine gabbro, massive leucogabbro and black olivine gabbro units within the North intrusion overlap extensively in composition, and geochemistry alone cannot discriminate them. The fine-grained olivine gabbro has a slightly more primitive composition than the other units, and the most primitive examples within this unit come from the Taheke Lake lobe, in the north. The most evolved examples of fine-grained olivine gabbro come from the Mineral Hill intrusions, in the south. Massive leucogabbro and black olivine gabbro units have closely similar compositions, although the latter is slightly more primitive on an 'average' basis. The mafic rocks of the North intrusion more closely resemble the Mushuau intrusion of the Voisey's Bay area than they do the Voisey's Bay intrusion itself.

All unmineralized mafic rocks from the PLI have low Ni and Cu contents (<100 ppm of each), although variations in the amount of olivine make Ni data rather 'noisy'. Nickel and Co are strongly correlated in unmineralized rocks, suggesting that both are controlled by olivine. Copper/zirconium ratios are universally low (<<1), and the decoupling of these two elements (which normally behave incompatibly in mafic magmas) suggests that Cu has been preferentially removed by the segregation of sulphide liquids.

The data of MacDonald (1999) and Naldrett (1999; in Fitzpatrick *et al.*, 1999) show that there are also differences in mineral geochemistry trends between the South and North intrusions. The fine-grained olivine gabbro of the South intrusion is mostly characterized by a 'normal' olivine fractionation trend (*i.e.*, Fo contents diminish with height), whereas the fine-grained olivine gabbro unit of the North intrusion shows a reversed olivine fractionation trend (*i.e.*, Fo contents increase with height). The massive leucogabbro unit of the North intrusion shows a poorly defined normal olivine fractionation trend, whereas the black olivine gabbro unit appears to have a reversed olivine fractionation trend.

Geochemical studies of mineralized rocks are complicated by the presence of sulphides, which affect both major- and trace-element compositions. Attempts to examine major- and trace-element variation trends were generally unsuccessful, and there are very few differences in composition between mineralized and unmineralized rocks. Differences in the behaviour of Ni, Cu and Co in the mineralized rocks can be attributed to the influence of sulphides, and there are no consistent differences for other trace elements, including the REE. Composite gabbros from the North intrusion mineralized sequence are geochemically similar to unmineralized gabbros, despite the obvious presence of reacted gneiss fragments in the former. Similarly, mineralized, homogeneous gabbros from the lower part of the mineralized sequence closely resemble their unmineralized counterparts, except for Fe, Ni, Cu and Co contents. The most striking indications of this similarity come from the REE patterns, which are unaffected by sulphides.

Sulphur isotope studies (Li *et al.*, 2001; Smith *et al.*, 2001) suggest that there is a good correspondence between the sulphur isotope compositions of sulphides in the PLI and those of sulphides in the paragneisses of the Churchill Province. The Sm–Nd isotopic data indicate that the South and North intrusions have consistent εNd isotpic compositions at 1330 Ma, with εNd between -1 and -2; these results are closely similar to those reported from the Voisey's Bay Intrusion (Amelin *et al.*, 2000). The only exception to this is a sample of fragment-rich composite gabbro, which has much lower εNd of -3.5. Country-rock gneisses have low εNd of -7.5 to -11.

General Geochemical Affinities of the Pants Lake Intrusion

The typical SiO_2 contents of 41 to 50%, and MgO contents of <12% show that the PLI are not 'primitive' in the strict sense of the word (*i.e.*, they are not ultramafic or picritic), but they are certainly amongst the least evolved intrusions within the NPS and resemble other examples of anorogenic mafic intrusions listed by Scoates and Mitchell (2000).The similarity in the overall geochemical traits of PLI gabbros is not surprising in view of their common mineralogy.

Within the North intrusion, there is a general evolutionary progression from 'primitive' melagabbro and peridotite, through the fine-grained olivine gabbro and black olivine gabbro, to massive leucogabbro. Such patterns do not necessarily indicate differences in parent magma compositions, as they could be controlled simply by mineral proportions. However, the textural differences between these units that suggest different crystallization sequences (*see* section on 'Geology and Petrology of the Pants Lake intrusions'), coupled with the contrasts in olivine fractionation trends (MacDonald, 1999) suggest that individual North intrusion units crystallized from separate, but closely related, batches of magma. The REE profiles of all North intrusion units are identical, aside from differences related to abundance of cumulus plagioclase (Figures 43 and 44), and this fact provides the strongest evidence for a genetic link among them, and also to the Worm and Mineral Hill intrusions.

Comparisons with the Voisey's Bay Area

Mafic rocks of the PLI are petrologically similar to those of the Voisey's Bay area. Average compositions and variation diagrams indicate a general correspondence between the PLI and both the Voisey's Bay and Mushuau intrusions for some major elements (Figures 32 and 33), but rigorous comparisons are difficult as only average compositions are currently available from Voisey's Bay (Li *et al.*, 2000). Rare-earth-element profiles from South intrusion units closely match those of the Voisey's Bay intrusion, whereas those from the North intrusion more closely resemble the Mushuau intrusion (Figure 43). Extended trace-element profiles (normalized to primitive mantle) lead to essentially the same conclusions (Figure 45).

Lightfoot and Naldrett (1999) and Li *et al.* (2000) suggest that the Mushuau and Voisey's Bay intrusions had differing contamination histories, and that the latter assimilated more Tasiuyak gneiss country-rock material, leading to geochemical contrasts. The PLI data could be interpreted in a similar manner, but evidence suggests that country-rock assimilation was a very important factor in the North intrusion. Therefore, the geochemical differences between South and North intrusions could instead be related to magmatic source regions. If mineral potential is directly linked to magma composition (which is not necessarily so), geochemical affinities with the Voisey's Bay intrusion highlight the South intrusion as a future exploration target. As noted previously, some sulphides associated with this body 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.

Significance of Olivine Fractionation Trends

The normal olivine fractionation trend in the South intrusion (MacDonald, 1999; Figure 48) is suggestive of an approach to closed-system fractionation, where a batch of magma crystallizes in place, and the residual liquid is enriched in iron. This interpretation fits very well with the presence of mafic cumulates toward the base of the South intrusion. The mafic cumulates also suggest a tranquil environment. Minor reversals of the fractionation trend indicate periodic small influxes of new magma, with more primitive compositions.

In contrast, the fine-grained olivine gabbro and black olivine gabbro units of the North intrusion both have reverse olivine fractionation trends (MacDonald, 1999; Figure 48). Such trends are more consistent with approaches to open-system behaviour, where there are more frequent influxes of 'primitive' fresh magma. Minor intervals showing normal fractionation trends indicate short interludes of static crystallization. A more protracted normal fractionation trend in the upper part of the fine-grained olivine gabbro unit (hole SVB-97-77) suggests that the magma supply eventually diminished. The relatively dynamic environment indicated by such trends implies that large amounts of magma may have moved through the North intrusion en route either to the surface, or to a now-eroded, overlying, magma chamber. The limited data from the massive leucogabbro of the North intrusion (hole SVB-97-77) suggest that this unit has a broadly normal fractionation trend (MacDonald, 1999). This trend suggests that the unit resulted from the closed-system crystallization of a batch of magma.

There is a distinct reversal in olivine compositional trends at the top of the North intrusion mineralized sequence in hole SVB-97-77, suggesting that the sulphide-bearing rocks represent a batch of magma discrete from the overlying fine-grained unit. However, such is not the case in hole SVB-97-75, where the mineralized sequence seems to pass directly upward into black olivine gabbro, consistent with the other evidence suggesting a link between them.

Geochemistry of the Mineralized Sequence

Geochemical data show that mineralized melagabbro and peridotite in the South intrusion are related to unmineralized gabbros higher in the intrusion. This conclusion is consistent with the idea that they formed as mafic cumulates. Similarly, the average compositions of the upper and lower sections of the North intrusion mineralized sequence resemble those of its unmineralized units, aside from differences in Fe_2O_3 (total) and chalcophile elements, which are largely due to sulphides. The REE patterns of mineralized sequence rocks are also essentially identical to those of unmineralized units (Figure 47). The geochemical data thus support all other indications that both mineralized sequences from the North and South intrusions have close genetic relationships to the larger intrusive bodies with which they each are associated.

In the North intrusion mineralized sequence, composite gabbros are geochemically indistinguishable from more homogeneous gabbroic rocks. This similarity is predictable for gneiss-fragment-poor varieties, because they are essentially troctolitic inclusions in a gabbroic matrix (Kerr, 1999). However, sulphide-rich composite gabbros, in which gneiss fragments are more abundant, show little geochemical evidence of the gneissic material. In this context, it is important to remember that the geochemical contributions of the residual plagioclase-spinel assemblages are dominated by CaO, Al_2O_3, MgO and Fe_2O_3 (total), which are already abundant in mafic magmas, and vary independently as a function of both igneous processes and the amount of sulphides. Thus, it is not surprising that a clear geochemical signature from digested gneiss fragments is elusive, especially as the data are not corrected for sulphides. The lack of a clear contamination signature in composite gabbros provides further evidence that digestion and reaction of the gneiss xenoliths was not a purely local process, but rather occurred at greater depths. Contaminants released by the transformation of the gneisses (*e.g.*, SiO_2, K_2O, Na_2O, and various incompatible trace elements) must have been dispersed into a much larger volume of magma and likely contribute to the overall, regional geochemical traits of the North intrusion. Similar conclusions can be made in the case of gneissic inclusions in the mafic cumulate sequence of the South intrusion. Overall, these relict inclusions must have contaminated a much larger volume of mafic magma than that which now surrounds them. Similar conclusions were reached by Li *et al.* (2000) for Voisey's Bay, but these authors were able to identify a subtle geochemical signature from fragments in some fragment-rich rocks. The Nd isotopic data support the idea of large-scale contamination of the PLI magmas and, at least on a local scale, these data do record the physical presence of gneiss fragments in samples.

Scale and Significance of Metal Depletion Signatures

Virtually all unmineralized rocks in the PLI contain less than 100 ppm Ni and less than 100 ppm Cu. Diabases, which provide minimum values for the Ni contents of the magmas themselves, generally contain <50 ppm Ni. The copper/zirconium ratios are also universally low (<<1), and many rocks are strongly Cu-depleted. This decoupling of two elements that are normally covariant in mafic magmas is an indication of sulphide segregation (Lightfoot *et al.*, 1994; Li and Naldrett, 1999), as are the low Ni contents of olivines in the PLI. Collectively, these results indicate that virtually all magmas forming the PLI interacted with sulphide liquids at some point in their histories.

The scale of this depletion signature implies the processing of very large amounts of magma, and the extraction of very large amounts of metal. First-order calculations place some general constraints on these amounts, but require knowledge of the initial Ni contents of the magmas prior to their depletion by sulphide liquids. In this context, Morse *et al.* (1991) estimated the bulk Ni content of the Kiglapait intrusion (also part of the NPS; Figure 7) at about 125 ± 25 ppm. 'Normal' (*i.e.*, unmineralized) troctolite from the Voisey's Bay intrusion has an average Ni content of approximately 250 ppm. The latter is influenced by cumulus olivine, but provides a useful upper limit. An initial value of 150 ppm Ni is assumed here, with 250 ppm Ni as an upper limit. The very consistent Ni/Cu ratio observed in PLI mineralized samples (Figure 28) implies that the amount of Cu extracted from the magmas was similar to the amount of Ni, but initial Cu contents are harder to constrain.

If the magmas that formed the PLI initially had 150 ppm Ni, but contained only about 50 ppm Ni after sulphide segregation, they would have lost about 67% of their Ni to sulphide liquids, and one km^3 of such mafic magma would have lost 0.3 million tonnes of Ni metal, assuming a density of 3. The surface area of the PLI is currently about 50 km^2, and individual intrusions are several hundred metres thick. PLI rocks are also present widely in the subsurface, and have likely been partly eroded. Thus, a first-order estimate of at least 50 km^3 of metal-depleted magma seems reasonable. These calculations imply 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 PLI is assumed to cover the same 50 km^3, at an average thickness of 10 m, with an average grade of 0.25% Ni (all of which are probably overestimates), some 3.75 million tonnes of Ni metal can be accounted for. These calculations indicate the presence of a large subeconomic resource of Ni associated with the PLI but, more importantly, suggest that even larger amounts of Ni remain unaccounted for. By way of comparison, the Voisey's Bay deposits contain a total resource of about 2.2 million tonnes of Ni metal (Inco Ltd., 2000). Such simplistic calculations certainly provide a rationale for further exploration but, unfortunately, the recognition of missing metal does not provide clues as to its location or physical form (*i.e.*, massive or disseminated mineralization).

The low Ni contents and ubiquitous depletion of PLI mafic rocks also have implications for the potential grade of undiscovered sulphide deposits. Sulphide liquid/silicate magma partition coefficients for Ni ($D_{sul/mag}$) are probably 300 to 600 in basaltic systems (*e.g.*, Naldrett, 1989; Barnes and Maier, 1999). Thus, sulphide liquids in equilibrium with an entire batch of silicate magma containing only 50 ppm Ni would have Ni contents of 15 000 to 30 000 ppm, *i.e.*, 1.5 to 3.0% Ni. This agrees well with the empirical data, which cluster around 2% Ni, within an overall range extending from 0.5 to greater than 10% (Kerr, 1999; Kerr and Ryan, 2000; Figures 26 and 28). Strong depletion of silicate magmas is also consistent with a low mass ratio of silicate magma to sulphide liquid (R factor), which commonly results in relatively low-grade sulphides. For an initial magmatic Ni content of 150 ppm (as outlined above), the R factor required to produce a sulphide liquid containing 2% Ni is between 180 ($D_{sul/mag}$ =500) and 250 ($D_{sul/mag}$=300). The generation of sulphide liquid containing 4% Ni (more typical of the Voisey's Bay deposit) would require higher R-factors from 600 ($D_{sul/mag}$=500) to almost 2000 ($D_{sul/mag}$=300), assuming the same initial magmatic Ni contents.

AN INTEGRATED MODEL FOR THE PANTS LAKE INTRUSIONS

A generalized model for the development of the PLI and their associated magmatic sulphide mineralization is presented below. As is always the case, further research is required to test some aspects of this, but it provides a working model.

The tectonic boundary between the Nain and Churchill provinces is not envisaged to have played any direct role in the localization of the PLI, although it may have had an indirect role on the scale of the entire NPS. However, the geographic location of the PLI, *i.e.*, within sulphide-bearing metasedimentary gneisses of the Churchill Province rather than Nain Province orthogneisses, is considered to be a critical metallogenic factor, as suggested for Voisey's Bay (Naldrett *et al.*, 1996; Kerr and Ryan, 2000). In the Pants Lake area, there were two discrete episodes of mafic magmatism and sulphide mineralization, represented by the South and North intrusions, respectively.

The South intrusion was emplaced at about 1338 ± 2 Ma. It is considered to have developed in two stages, with the upper part (above about 250 m depth; Figure 12) crystallizing first. Abundant diabase sheets and dykes that cut these rocks are believed to be derived from the underlying (slightly younger) magma chamber. The parental magmas experienced significant country-rock contamination, leading to their steep REE patterns, although this feature may, in part, be source-related. Reacted gneiss fragments contained within the South intrusion mineralized sequence attest to interaction with metasedimentary gneisses. This was an important factor in the development of sulphide liquids within the magmas, but it is not clear if the latter was accomplished by simple bulk addition of sulphur, selective addition through hydrothermal transfer, or contamination-related changes in magma composition (*cf.* Li and Naldrett, 2000; Ryan, 2000). Sulphur isotope data (Smith *et al.*, 2001; Smith, 2006; Li *et al.*, 2001) indicate a component of country-rock sulphur, but do not closely constrain its relative importance. Whatever the exact mechanism, it appears that initial development of sulphide liquids took place at deeper levels, prior to the arrival of magmas near the present level of exposure. The South intrusion magma chamber then crystallized under an approach to closed-system conditions, without large influxes of new mafic magma. The sulphides, and reacted gneissic fragments brought up from depth, settled with cumulus olivine to form the mineralized melagabbro and peridotite near the base of the chamber. Sulphide metal contents at the base of the intrusion and in the thin (earlier?) mineralized zone around 250 m depth are low (~1% Ni), but increase to values of around 4% Ni in the upper part of the mineralized sequence. This pattern is believed to record the increasing residence time of sulphides within the chamber, and increased settling distances within the magma column, both of which would allow greater opportunity for extraction of metals.

The North intrusion represents a separate event at around 1322 ± 2 Ma that involved several discrete batches of mafic magma. The first to be emplaced is suspected to be the parent to (at least part of) the fine-grained olivine gabbro unit, although this is difficult to establish. The chamber appears to have been a relatively dynamic environment, which was tapped, and replenished with progressively less-fractionated magma, as indicated by the reversed olivine fractionation trends. Over time, a chilled rind developed at the base of the magma chamber, which would later be preserved as the barren unit that sits at the base of the mineralized sequence. The conspicuous Ni depletion in the fine-grained gabbro suggests that it had previously interacted with sulphide liquids, presumably occurred at greater depth. However, little or no sulphide was apparently carried upward at this stage. The feeder conduit system for the North intrusion is suspected to lie somewhere under the northern part of the body, as the most magnesian fine-grained olivine gabbros are found in the Taheke Lake lobe. The Mineral Hill intrusions contain the most evolved examples of this unit. If these sill-like bodies are a distal southern extension of the North intrusion, which seems likely, this pattern is consistent with increasing fractionation of the magma as it moved laterally through several kilometres.

Sulphide- and fragment-charged magmas arrived soon after this initial magma influx, and are believed to be temporally and genetically associated with the parent magma to the black olivine gabbro. The latter has a restricted distribution in the northern part of the North intrusion, which again suggests that the conduit entry point lies somewhere in this region. There were at least two discrete pulses of sulphide-charged magma. The first carried a low-tenor sulphide liquid and relatively few gneissic fragments. This may reflect developing stratification in a lower magma chamber, where denser sulphides and restite had settled gravitationally. On arrival, this first pulse had only limited interaction with the resident magma, and it began to crystallize under relatively tranquil conditions. This magmatic influx penetrated as far south as the Mineral Hill area, where low-tenor sulphides dominate the mineralized sequence, but it did not penetrate extensively into the NDT lobe of the North intrusion. The reasons for such behaviour are not clear, but one could speculate that the chamber floor had some distinct topographic variations. It was quickly followed by a second (and more voluminous?) influx, which carried abundant gneissic debris and higher tenor sulphide liquids. This magma interacted much more extensively with the resident, partly crystallized mafic magma, which froze upon their mutual contact, developing the distinctive and complex rock types termed composite gabbro. This second pulse penetrated into the NDT lobe, where composite gabbro is widespread (but thin), but it apparently did not reach the Mineral Hill area in significant amounts. The thickest developments of the mineralized sequence are in the Taheke Lake lobe. This observation again suggests that the conduit system lies beneath this area. Sulphide liquids and reacted fragments 'rained down' into the underlying, previously unmineralized magma, and/or into the earlier sulphide-bearing unit, but the contrasts in sulphide metal contents between the two influxes were generally preserved. The sulphide-bearing magmatic pulses are considered to have been forced upward by the parent to the black olivine gabbro unit. The sulphide-rich pulses were then followed by more homogeneous and generally sulphide-free magma. The development of composite gabbro-like rocks along the upper boundary of the black olivine gabbro in the Taheke Lake lobe implies that the parental magma to the black olivine gabbro also spread out beneath the parent to the fine-grained unit. However, the more restricted development of the black olivine gabbro suggests that this magma did not penetrate as widely as the earlier sulphide-bearing influxes.

Although the above sequence of events is preferred, the age relationships between the fine-grained gabbro unit, black olivine gabbro unit and the mineralized sequence remain ambiguous. An alternative interpretation is that formation of the mineralized sequence and black olivine gabbro are early, and predate the arrival of the parent to the fine-grained olivine gabbro unit.

Regardless of the exact sequence of events, features of the North intrusion imply the existence of a subjacent 'staging' magma chamber within which sulphide liquids initially formed prior to their arrival close to the present surface. The development of sulphide liquids is considered to have resulted from assimilation of and interaction with the country-rock gneisses but, as in the case of the South intrusion (and at Voisey's Bay), the exact mechanisms remain unclear. However, the reacted gneiss fragments, which are closely associated spatially with the sulphides, clearly indicate the importance of such processes, and suggest that they are generally linked to mineralization.

The final stage in the development of the North intrusion was the emplacement of the parent magma to the massive leucogabbro unit. This unit is unmineralized, but its low Ni contents and Cu/Zr ratios imply that the magma had a previous encounter with sulphide liquids. The massive leucogabbro forms veins that apparently crosscut the fine-grained olivine gabbro unit, and the lower (earlier) units may thus have been partly solidified at the time of its emplacement. The massive leucogabbro is suggested to represent a plagioclase cumulate initially developed within the lower magma chamber, after the expulsion of the sulphide-rich material. This was subsequently emplaced as a mixture of phenocrysts and interstitial liquid, above the earlier North intrusion units.

Finally, gentle folding and tilting of post-1322 Ma age influenced the present geometric pattern of the North intrusion, and presumably would have affected other parts of the PLI also, although its effects are less obvious. This event could be related to the development of the Grenville Province, or even to the Mesozoic opening of the Labrador Sea, or it could be related to Mesoproterozoic extension and uplift associated with the emplacement of the NPS as a whole (Ryan, 1998). If the latter scenario applies, these effects may simply have been part of an overall tectonic regime that created the 'spaces' for the development of the PLI and other Mesoproterozoic intrusions.

CONCLUDING REMARKS

The PLI contain the first major discovery of widespread magmatic sulphide mineralization in mafic rocks of the NPS since the Voisey's Bay discovery. The information from PLI adds significantly to the perceived economic potential of this area. There are striking similarities in the ages, geological settings, petrology, geochemistry and sulphide mineralization of the mafic intrusions at Pants Lake and Voisey's Bay, and it is clear that similar ore-forming processes were in operation. Although known mineralization in the PLI is mostly disseminated and low-grade, the probable total amount of contained Ni metal resembles that at Voisey's Bay, *i.e.*, at least 1 to 2 million tonnes of metal. Extensive Ni-depletion in mafic rocks of the PLI suggests that much larger amounts of Ni and Cu (>15 million tonnes of each metal) remain unaccounted for in this area. This observation provided a powerful incentive for continued exploration, despite possible limitations on grades.

Notwithstanding the differences from Voisey's Bay discussed here, several key features of the PLI lend strong support to aspects of genetic models proposed by others (*e.g.*, Li and Naldrett, 1999) for mineralization at Voisey's Bay. These include a critical role for sulphide-bearing country rocks in the development of sulphide liquids, and the necessity for multistage processes that allow the interaction of a sulphide liquid with several batches of silicate magma, such that sulphides can become enriched in metals. Multistage processes of this type may be a general requirement in evolved (gabbroic) systems, where lower magmatic Ni contents limit the efficiency of single-stage processes. This factor may also be the most important difference between the Voisey's Bay and Pants Lake areas from an economic perspective, as present evidence suggests that multistage enrichment was less effective in the latter. The PLI are not currently a focus for mineral exploration but this may change. This document provides a comprehensive statement of our current knowledge about the PLI, but it will hopefully not represent the final chapter in research and exploration of the area.

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APPENDIX 1: U-Pb ZIRCON AND BADDELEYITE GEOCHRONOLOGICAL DATA

The U–Pb geochronological data from the Pants Lake intrusions were not obtained through the Geological Survey research project in this area, but were completed under contract to Donner Minerals Ltd., the principal exploration company active in the project area. The results of these studies were subsequently only reported in abstracts (Smith *et al.*, 1999; 2001). These results have been quoted elsewhere (*e.g.*, Kerr, 2003), but were not reported in full until their inclusion in a thesis by Smith (2006). As the latter source is not easily obtained, the numerical data and concordia diagrams are included as an appendix to this report, to facilitate access to the information. The descriptions of zircon fractions and interpretation of results below are adapted from those included by Smith (2006), which are directly taken from communications provided by G.R. Dunning and J.N. Connelly, who completed the analyses.

PANTS LAKE NORTH INTRUSION

The sample dated from the North intrusion was collected from hole SVB-97-67 (for location, *see* Figure 11, at a depth of approximately 150 m. According to the author's observations and the company drill logs (Fitzpatrick *et al.*, 1998), the rock type at this location is the basal section of the black olivine gabbro, considered to be intimately linked to the sulphide mineralization. The work was conducted at Memorial University of Newfoundland, under the supervision of G.R. Dunning. Specific information on analytical procedures was not provided in material included by Smith (2006), but it is assumed to correspond to methods outlined in reports on geochronological work completed at Memorial University during the same general time period by thermal ionization mass spectrometry.

The sample provided two datable minerals; angular fragments of clear zircon and equant prisms of baddeleyite (zirconium oxide; ZrO_2). The latter is a common accessory phase in gabbroic rocks. Two baddeleyite fractions and a single zircon fraction were analyzed (Table A1). The baddeleyite fractions gave $^{207}Pb/^{206}Pb$ ages of 1321 Ma; the zircon fraction gave a $^{207}Pb/^{206}Pb$ age of 1325 Ma. The fractions are almost, but not quite, concordant. Regression of all three analyses using a lower intercept of 50 ± 50 Ma indicates an age of 1322.2 ± 2 Ma, which was interpreted as the time of crystallization.

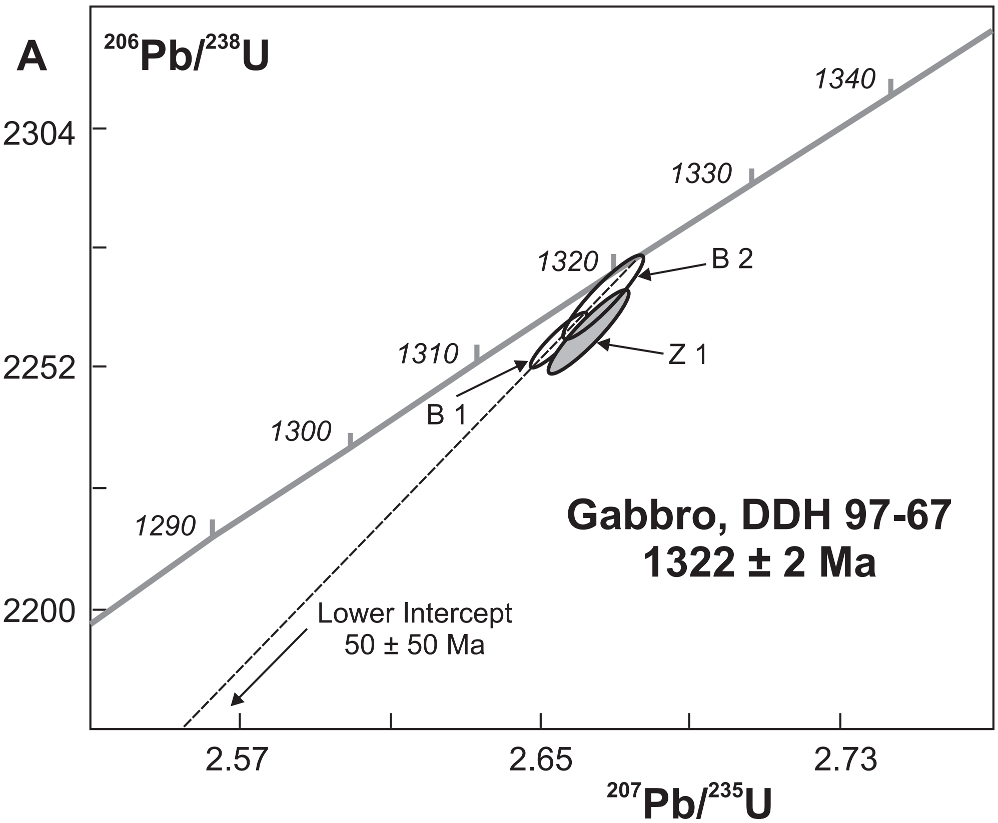
PANTS LAKE SOUTH INTRUSION

The sample dated from the South intrusion was collected from hole SVB-97-79, but the material included by Smith (2006) does not provide information on the exact depth of sampling. However, it is the author's understanding that it represents the lower section of the gabbro, located above the zone of sulphide mineralization associated with mafic cumulates. The work was conducted at the University of Texas in Austin, Texas, USA, under the supervision of J.N. Connelly. Information on analytical procedures provided in material included by Smith (2006) indicates standard separation procedures, followed by heavy liquid separation and magnetic separation. Isotopic analysis was by thermal ionization mass spectrometry.

The sample provided no zircon, but it did contain baddeleyite. Three fractions of this mineral were analyzed (Table A1). The analyses were between 1.4 and 1.7% discordant, and had $^{207}Pb/^{206}Pb$ ages of 1336 to 1337 Ma; they plot in almost exactly the same location (Figure A1). The analyses were treated in a similar way to those from the North Intrusion, *i.e.*, they were regressed using a lower intercept of 100 ± 100 Ma. On this basis, the age of crystallization was interpreted as 1338 ± 2 Ma. Note that this differs slightly from the 1337 ± 2 Ma age reported by Smith *et al.* (2001).

DISCUSSION

The U–Pb ages obtained for these two samples clearly indicate a *ca.* 16 Ma age difference between the North and South intrusions, despite the general similarities in the rock types. Such a difference is also consistent with subtle differences in their trace element geochemistry. In both cases, regression of the data assumes that the lower intercept (*i.e.*, the time of Pb loss) is close to 0 Ma. This approach is supported by the lack of post-emplacement deformation and metamorphism in the area of the intrusions.



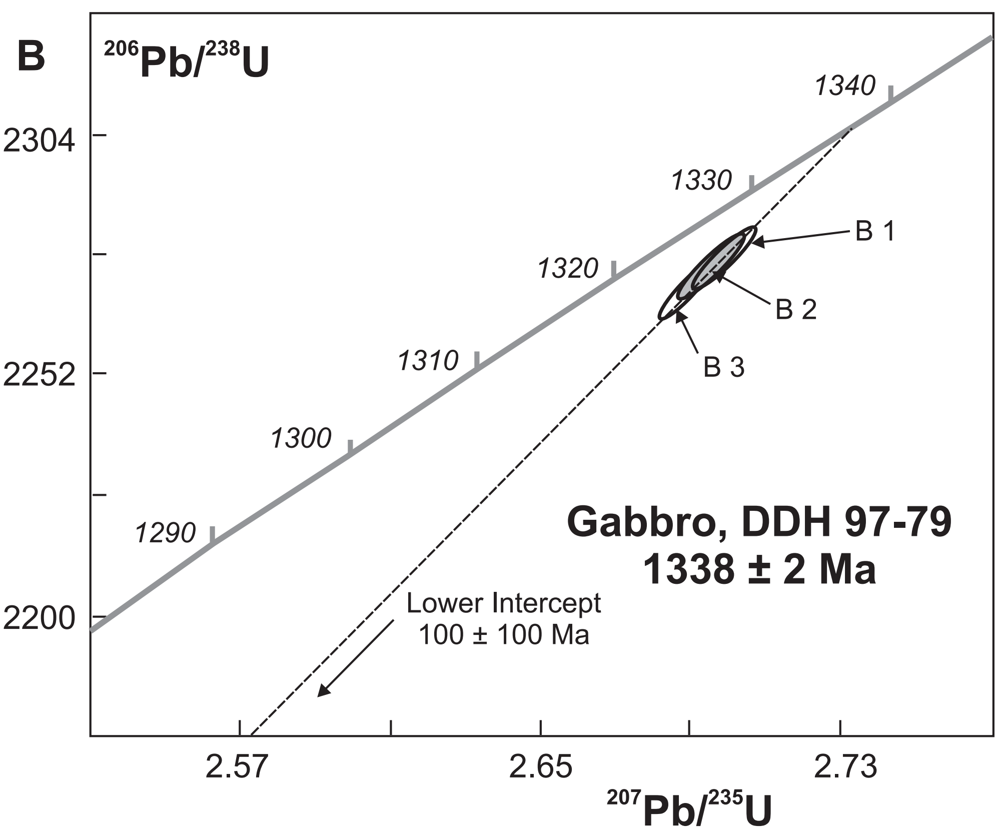


Figure A1. *U-Pb concordia diagrams for samples from the Pants Lake Intrusions. See text for discussion of data sources.*

Table A.1. U–Pb TIMS analytical data for samples from the Pants Lake intrusions

Fraction[1]	Description[2]	Wt. ug	U ppm	Pb^3 ppm	$^{206}Pb/^{204}Pb$ [4]	Pb^5 pg	Isotopic Ratios[6] $^{208}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	±2SE Abs	$^{206}Pb/^{238}U$	±2SE Abs	$^{207}Pb/^{206}Pb$	±2SE Abs	Ages (Ma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
NORTH INTRUSION - DRILLHOLE SVB-97-67 (~150 M)																
Z 1	Zircon, abraded fragments	7	232	71.4	2252	10	0.4962	2.6621	0.0094	0.22599	0.00084	0.08544	0.00016	1313.0	1318.0	1325.0
B 1	Baddeleyite, abraded prisms	16	221	49	5419	9	0.0557	2.6547	0.0074	0.22584	0.00062	0.08525	0.00008	1313.0	1316.0	1321.0
B 2	Baddeleyite, abraded prisms	12	183	40.8	3444	9	0.0547	2.6646	0.0076	0.22667	0.00066	0.08526	0.00010	1317.0	1319.0	1321.0
SOUTH INTRUSION - DRILLHOLE SVB-97-79 (precise depth not specified)																
B 1	Baddeleyite, small euhedral	5	138	29.7	3820	3	0.0110	2.6985	0.0058	0.22767	0.00048	0.08597	0.00010	1322.0	1328.0	1337.0
B 2	Baddeleyite, v. small euhedral	3	153	32.7	2498	3	0.0078	2.6956	0.0072	0.22750	0.00054	0.08594	0.00010	1321.0	1327.0	1337.0
B 3	Baddeleyite, v. small euhedral	3	139	29.9	3276	3	0.0208	2.6888	0.0064	0.22699	0.00050	0.08591	0.00010	1319.0	1325.0	1336.0

Notes

1 All zircon fractions are abraded following the method of Krogh (1982)

2 Fraction descriptions: simplified after original sources; the same labels are used on concordia diagrams.

3 Radiogenic Pb

4 Measured ratio, corrected for spike and fractionation

5 Total common Pb in analysis corrected for fractionation and spike

6 corrected for blank Pb and U and common Pb, errors quoted are 2 sigma absolute; corrections for common Pb were made using Stacey-Kramers compositions

The original sources for these data were unpublished reports submitted to Donner Minerals by G.R. Dunning and J.N. Connelly; the data in the table were transcribed from material included in the thesis by Smith (2006).

APPENDIX 2: SULPHUR ISOTOPE DATA

Table A.2 lists sulphur isotope data that was reported in the thesis study by Smith (2006); the analyses were completed at Memorial University of Newfoundland; analytical procedures are discussed by Smith (2006); these data are illustrated as histograms in Figure 48

Table A.2. Sulphur isotope analyses from the Pants Lake intrusions and related rocks types

Sample Number	Drillhole	Description	Mineral	$\delta^{34}S$ (per mil)
NORTH INTRUSION				
NAI-1	SVB-97-75	Massive sulphide	cp	-3.21
NAI-2	SVB-97-75	Massive sulphide	po	-2.79
75-C1	SVB-97-75	Massive sulphide	cp	-2.81
75-C1 (dupl.)	SVB-97-75	Massive sulphide	cp	-2.38
75-C2	SVB-97-75	Massive sulphide	po	-3.12
116-174	SVB-98-116	Blotchy sulphide	po	-3.26
96-B	SVB-97-96	Sulphide fragment (?)	po	-2.51
96-A	SVB-97-96	Massive sulphide	po	-2.95
98-131	SVB-98-131	Massive sulphide	po	-3.12
113-169	SVB-97-113	Massive sulphide	po	-2.41
113-169 (dupl.)	SVB-97-113	Massive sulphide	po	-2.41
20-71	SVB-96-20	Semimassive sulphide	po	-2.07
15-86B	SVB-96-15	Blotchy sulphide	po	-2.37
57-36	SVB-97-57	Blotchy sulphide	po	-2.6
20-69	SVB-96-20	Blotchy sulphide	po	-2.16
58-54	SVB-97-58	Massive sulphide	po	-2.48
04-24	SVB-96-06	Blotchy sulphide	po	-1.93
73-40	SVB-97-73	Blotchy sulphide	po	-2.24
MINERAL HILL AREA				
36-112	SVB-96-36	Disseminated sulphide	po	-5.25
36-113	SVB-96-36	Disseminated sulphide	po	-1.99
34-100	SVB-96-34	Sulphide ‘band’	po	2.51
SOUTH INTRUSION				
79-141	SVB-97	Heavy dissemianted sulphide	po	-3.54
79-141 (dupl.)	SVB-97	Heavy disseminated sulphide	po	-3.92
79-147	SVB-97	Blotchy sulphide	po	-2.56
79-146	SVB-97	Disseminated sulphide	po	-2.12
CHURCHILL PROVINCE GNEISSES				
98-136	SVB-98	Disseminated sulphide	po	-1.33
98-136 (dupl.)	SVB-98	Disseminated sulphide	po	-1.32
97-96	SVB-97	Disseminated sulphide	po	-4.78
58-55	SVB-97	Disseminated sulphide	po	-2.85
47-106	SVB-96	Disseminated sulphide	po	-4.91
COARSE-GRAINED ANORTHOSITE (HARP LAKE INTRUSIVE SUITE ?)				
92-12	SVB-97	Disseminated sulphide	po	-0.99
92-12	SVB-97	Disseminated sulphide	po	-2.51
92-8	SVB-97	Disseminated sulphide	po	-6.43
92-8	SVB-97	Disseminated sulphide	po	-5.95
92-11	SVB-97	Disseminated sulphide	po	-4.29

Notes
cp - chalcopyrite; po - pyrrhotite
Data transcribed from the thesis by Smith (2006); for further details on locations, etc., consult this source.
All sulphur isotope values are expressed in per mil values relative to troilite from the Canyon Diablo meteorite (CDT) standard