Current Research (1999) Newfoundland Department of Mines and Energy
Geological Survey, Report 99-1, pages 215-253

MAFIC ROCKS OF THE PANTS LAKE INTRUSION AND RELATED Ni–Cu–Co MINERALIZATION IN NORTH–CENTRAL LABRADOR

A. Kerr
Mineral Deposits Section

ABSTRACT

The Mesoproterozoic Pants Lake intrusion (PLI) was emplaced passively into sulphide-bearing paragneisses and orthogneisses of the Churchill Province, immediately west of the Nain–Churchill boundary. In the four years since the Voisey's Bay discovery, the PLI has become a major focus for Ni–Cu exploration, and is now known to host widespread disseminated, and rarer massive, magmatic sulphide mineralization. The PLI represents the closest analogue to the Voisey's Bay troctolitic host rocks recognized in northern Labrador.

The three main units of the PLI are a fine-grained, variably layered olivine gabbro containing cumulus olivine, a massive, coarse-grained leucogabbro containing late interstitial olivine, and a black olivine gabbro that is texturally akin to the massive leucogabbro and locally difficult to discriminate from it. The coarse-grained unit appears to postdate the layered unit, but the relationship of the black olivine gabbro to other units is ambiguous. The PLI component intrusions are broadly sheet-like in geometry, and range in thickness from < 50 m to over 600 m. Their present geometry is complex, and may reflect the superposition of tilting and/or gentle folding on primary intrusive variations in thickness and anatomy. The mineralized basal contacts of intrusions lie within feasible exploration depths over large areas, and are far from fully explored.

Magmatic sulphide mineralization is ubiquitous near the basal contacts of the PLI component intrusions, and is commonly associated with distinctive, contaminated, sulphide-bearing mafic rocks that include textural equivalents of the "basal breccias" and "leopard troctolites" described from the Voisey's Bay deposit. Metal contents at 100 percent sulphide are, on average, lower than at Voisey's Bay, but Co is significantly higher at a given Ni content. There are indications of higher metal contents, up to 11.8% Ni and 9.7% Cu, in sulphide zones that may represent fractionated sulphide liquids. The PLI mineralized sequences appear to be intrusion-wide "stratigraphic" features, rather than being confined to feeder conduit systems, and their distribution and relationships to the intrusions may differ from the Voisey's Bay area. In both areas, the mineralized sequences record the emplacement of discrete sulphide- and fragment-bearing magma pulses into active, dynamic, mafic magma chambers, but the precise details of their evolution may differ. However, the PLI clearly demonstrates that the distinctive rock types and processes seen (and inferred) at Voisey's Bay are present elsewhere in Labrador.

INTRODUCTION

Mineral exploration in northern Labrador increased dramatically in 1995, following the Voisey's Bay discovery of late 1994, but overall activity has declined since 1996. However, the "South Voisey's Bay Project" of Donner Minerals and their joint venture partners progressively expanded from 1995 to 1998, reflecting positive indicators of economic-grade mineralization, and recognition that the geology has many intriguing similarities to the area around Voisey's Bay itself (e.g., Kerr and Smith, 1997; Fitzpatrick *et al.*, 1998).

The Geological Survey of Newfoundland and Labrador has been examining the regional geology, mineralization and mafic host rocks since 1996. This article brings together observations and ideas developed over this period, and integrates them with results from the exploration program. Interpretations presented here are current (but still early) views, and will be refined and/or modified as additional information is gathered from continued exploration and related research theses. However, in view of the wide interest in this project an overview of this type is timely.

The study area is located in north–central Labrador, about 130 km south of Nain and 90 km west of Hopedale, and forms part of a highland area north of the Adlatok (or Ugjoktok) River. Regionally, the area (Figure 1) is dominated by Paleoproterozoic gneisses of the Churchill Province, and is situated between two major Mesoproterozoic igneous

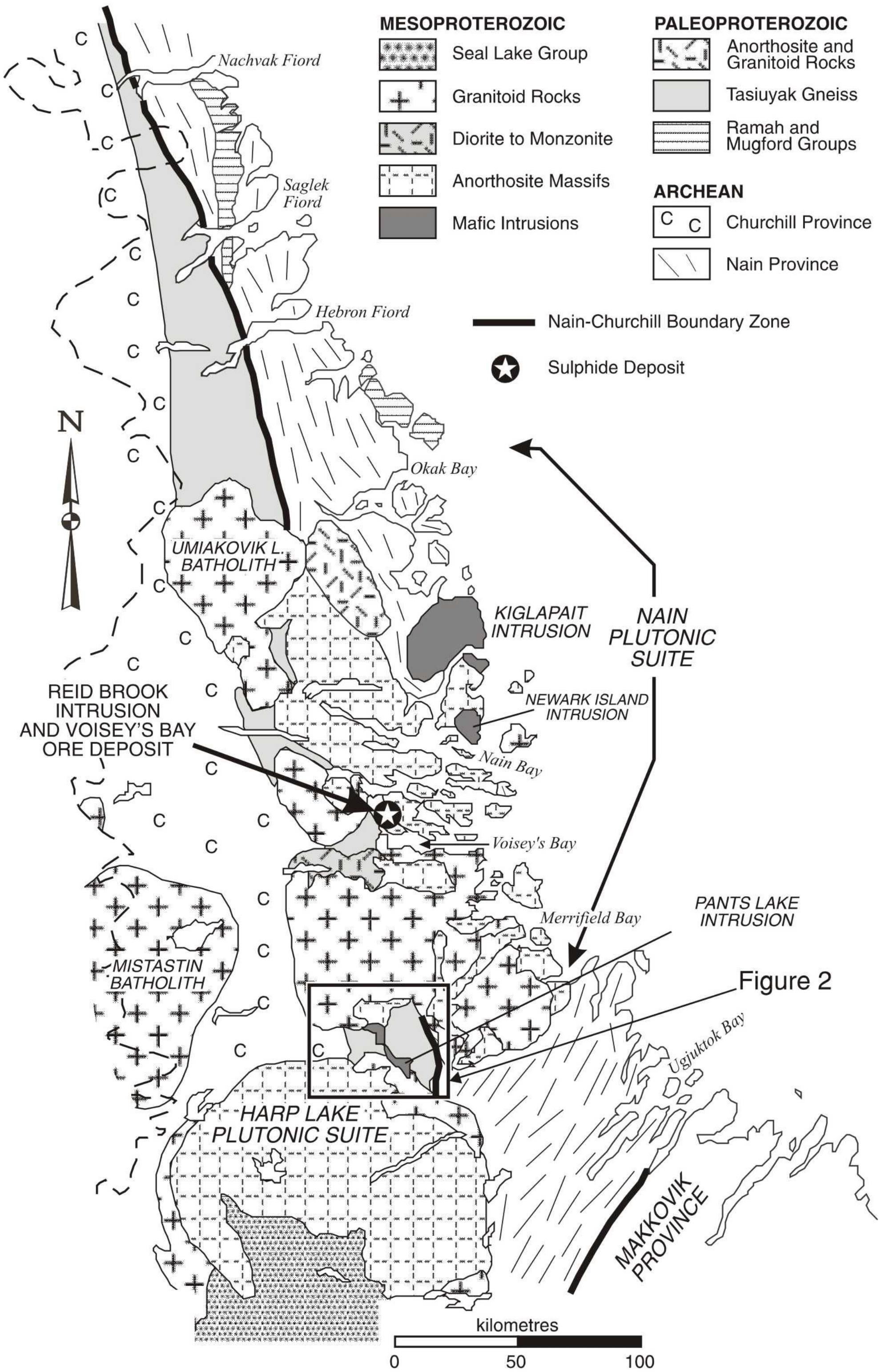


Figure 1. *General geology of northern Labrador, showing the Nain and Churchill provinces, and the Mesoproterozoic Nain and Harp Lake plutonic suites. The area of active exploration at the South Voisey's Bay project, and the Pants Lake intrusion, are indicated.*

complexes, i.e., the Nain Plutonic Suite (1350 to 1290 Ma) and the Harp Lake Plutonic Suite (~ 1450 Ma). The Nain Province–Churchill Province boundary zone lies in the eastern part of the area, but its characteristics in this region are poorly known (Ryan, 1996). The gneisses of the Churchill Province are intruded, over a wide area, by post-tectonic mafic plutonic rocks that collectively form the Pants Lake intrusion (PLI), assigned to the Nain Plutonic Suite. The PLI hosts widespread Ni–Cu sulphide mineralization, and is the main focus of this article.

Sulphide mineralization was first noted by Thomas and Morrison (1991), who also initially delineated the mafic rocks of the PLI. There was essentially no exploration prior to late 1995, when Donner Resources acquired an interest in a large tract of land centred on anomalous Ni values in lake sediment, which are spatially associated with the PLI mafic rocks. Public-domain information released from the exploration program has been summarized in previous reports (Kerr and Smith, 1997, 1998; Kerr, 1998a), and is not repeated here. The 1998 program was the most extensive to date, and included about 15 000 m of diamond drilling. Although no economic deposits have been discovered, Donner Minerals have stated their intention to mount a 1999 exploration program.

REGIONAL GEOLOGY

The geology of the area is depicted in Figure 2. The present outline and subdivision of the PLI is mainly derived from mapping by Donner Minerals and Teck Corporation (Wares, 1997; Fitzpatrick *et al.*, 1998), whereas country rock units are taken from Hill (1982), Thomas and Morrison (1991) and company mapping. The current project is aimed mostly at understanding mineralization, and no systematic mapping was conducted. However, key contacts and sections were examined, and areas outside the joint venture were mapped at a reconnaissance level.

GEOLOGICAL FRAMEWORK

The area includes four main "packages" of rocks. In the east, quartzofeldspathic orthogneisses and associated supracrustal rocks are part of the Hopedale Block of the Archean Nain Province. These are in presumed tectonic contact with gneisses and granitoid rocks of the Churchill Province, which are dominated in this area by Paleoproterozoic supracrustal rocks. These are dominated by pelitic to psammitic paragneiss and leucocratic granitic orthogneiss, commonly intermixed on an outcrop scale. Undeformed Mesoproterozoic anorthosites, diorites and granites occur in the north and south, and intrude both Nain and Churchill province gneisses. Those in the south are assigned to the Harp Lake Plutonic Suite, and those in the north to the Nain Plutonic Suite (although none are dated). The youngest component of the latter is the Pants Lake intrusion consisting of an elongated belt of mafic plutons running northwest–southeast through the centre of the area (Figure 2).

NAIN PROVINCE BASEMENT ROCKS

These are described by Thomas and Morrison (1991), and were reexamined adjacent to the Nain–Churchill boundary. The rocks are dominated by banded, grey, tonalitic to granodioritic orthogneiss; the banding partly reflects transposed primary compositional variation and partly, the results of migmatization. Concordant bands of dark grey to black amphibolite represent either supracrustal remnants or transposed mafic dykes. No intense deformation or mylonitization were observed in Archean gneisses adjacent to the Nain–Churchill boundary, but it is present in paragneiss west of the boundary (*see below*). The Archean gneisses contain small shear zones adjacent to, and subparallel with, the boundary.

CHURCHILL PROVINCE BASEMENT ROCKS

Pelitic and Psammitic Paragneiss

This is the dominant unit within the Churchill Province in the study area, as noted by Thomas and Morrison (1991). Subsequent company mapping has confirmed this pattern, but the gneisses are highly variable on an outcrop scale, and mappable compositional variants are difficult to define. Paragneiss outcrops invariably contain up to 50 percent leucocratic granitoid gneiss and pegmatite, and granitoid gneiss outcrops invariably contain numerous screens and zones of paragneiss. Thus, delineation of "paragneiss" and "orthogneiss" units is inherently subjective. The pattern illustrated in Figure 2 is derived mainly from company mapping (Fitzpatrick *et al.*, 1998), and modified from Thomas and Morrison (1991) in areas outside the exploration project.

Paragneisses are white- to pale-grey- or rusty-weathering, and well banded. Banding is defined primarily by the alternation of granitic layers and biotite-rich bands, and likely records repeated migmatization, and deformation. Well-banded gneiss commonly passes along strike into nebulitic material indicating, some late, static migmatization. The darker, restitic material consists of quartz, plagioclase, K-feldspar, biotite, muscovite, garnet and sillimanite, indicating amphibolite-facies conditions. Cordierite is locally prominent, and likely present as a cryptic phase in most outcrops. Leucocratic zones commonly contain large garnets up to 2 cm in diameter, and have a "spotty" appearance. Graphite is locally abundant in the restite, and many outcrops are rusty-weathering, suggesting that disseminated

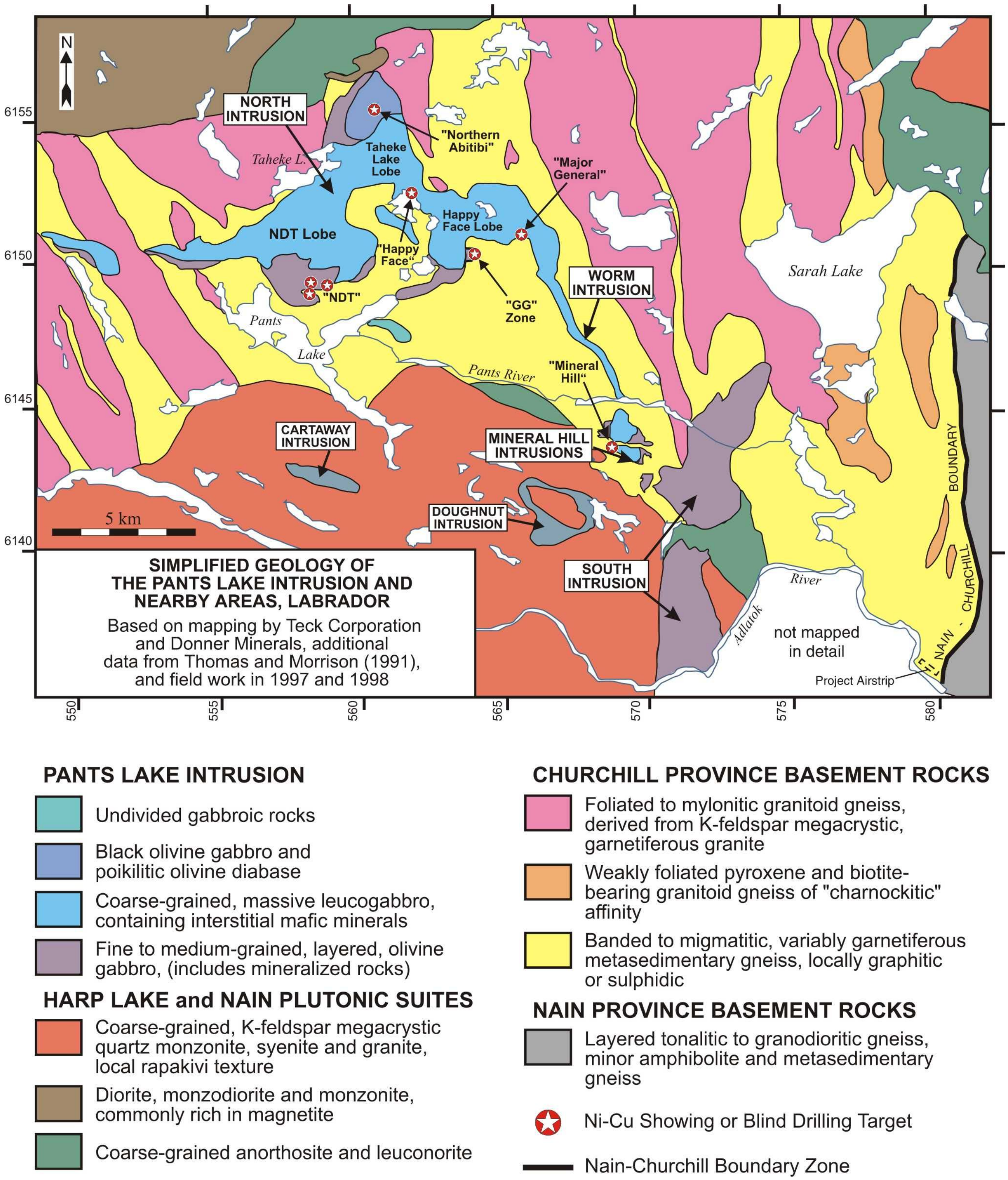


Figure 2. *Simplified geological map of the Pants Lake intrusion and surrounding area. Geology largely derived from mapping by Donner Minerals and Teck Corporation, with information from Thomas and Morrison (1991), Hill (1982) and field work by the author. Note that some unit distributions, notably in the northern part of the North intrusion are presently based largely on drillhole information. Numbers on the margins of the figure are UTM coordinates in zone 20.*

sulphide is also present. The latter has been entirely oxidized in many outcrops, but is noted also in diamond-drill core.

The structural pattern in the paragneisses is locally complex, with well-developed rootless and interference-type folds, indicative of polyphase deformation (Thomas and Morrison, 1991). Mylonitic zones having a northwest–southeast trend (parallel to regional trends) occur in some outcrops, and deflect an earlier mineral fabric (with a sinistral sense of motion) producing spectacular crenulated outcrops. The regional structural pattern may mirror these outcrop-scale relationships, as foliations in the paragneiss unit fall into two groups, with broadly northwest–southeast and east–west attitudes (Fitzpatrick *et al.,* 1998).

Granitoid Gneisses

Hill (1982) and Thomas and Morrison (1991) recognized two types of granitoid gneiss within the area, and company mapping (Fitzpatrick *et al.*, 1998) confirms this subdivision. "Charnockitic" granitoid gneisses occur adjacent to the Nain–Churchill boundary, north and south of Sarah Lake, and consist of medium- to coarse-grained, granoblastic gneiss composed of quartz, plagioclase, orthopyroxene and hornblende, and lesser biotite and opaques. These rocks resemble "charnockite" or "enderbite" gneiss reported from equivalent regions of the Churchill Province to the north (e.g., Ryan, 1996). The more widespread type consists of garnetiferous granitoid gneiss and pegmatite, which is present in almost every paragneiss outcrop. In many cases, the granitic material is texturally variable, and likely represents local anatectic segregations. In addition to this pervasive outcrop-scale material, there are several regional granitoid gneiss units (Figure 2), also of probable anatectic origin. These are dominated by white, coarse-grained, variably K-feldspar porphyritic, garnetiferous granitoid gneiss, locally showing well-preserved igneous textures. More commonly, these show a cataclastic texture, and the contacts between some "orthogneiss" and "paragneiss" areas contain mylonitic zones.

MESOPROTEROZOIC PLUTONIC ROCKS

Anorthosite

Anorthosite rocks assigned to the Nain and Harp Lake plutonic suites occur in three main areas (Figure 2), two of which are adjacent to, or within, the outcrop area of the PLI. These anorthosite rocks present a problem, as many are superficially similar to coarse-grained, massive leucogabbro of the PLI, and the two are easily confused. Much of the north intrusion of the PLI was grouped with Nain Plutonic Suite anorthosite rocks by Hill (1982). In all areas, the anorthosites are typical coarse- grained plagioclase cumulates containing interstitial to subophitic orthopyroxene, commonly brown- weathering. A yellow–brown interstitial phase noted in some outcrops, particularly in the south, may be an iron-rich olivine. Although the anorthosites in the north and south belong to different plutonic suites, and are likely of different ages, they are generally similar in appearance. Coarse-grained, plagioclase-rich plutonic rocks have been intersected in several deep drillholes collared adjacent to, or within, the PLI, and were originally thought to be part of its massive leucogabbro unit (*see below*). However, these are now considered to be part of anorthositic plutons that predate the PLI (D. Fitzpatrick and P. Moore, personal communication, 1998), as they are intruded by dioritic rocks, diabase dykes and granitic veins, all of which are rare in PLI gabbros.

Ferrodiorite and Monzodiorite

These occur only in the northwest of the area (Hill, 1982), and were confirmed by company mapping (Figure 2); they are assigned to the Nain Plutonic Suite. Where fresh, these are typically medium-grained, grey–green rocks, but they are commonly deeply weathered and rusty. The plagioclase-rich variants are similar in general appearance to many of the anorthosites. Dykes of medium-grained diorite intrude neighbouring anorthosites, and rafts of anorthosite are present in the diorites, indicating that the diorites are younger, which is a common pattern. Hill (1982) suggested that many of the intermediate plutons had a broad sheet-like geometry, and this pattern is also known from the Nain area (Ryan, 1990).

Quartz Monzonite, Syenite and Granite

The largest area of Mesoproterozoic granitoid rocks is located between the Pants River and the Adlatok River (Figure 2), and forms part of the Arc Lake Granite, assigned to the Harp Lake Plutonic Suite (Emslie, 1980; Thomas and Morrison, 1991). This is dominated by massive syenite and granite, commonly K-feldspar porphyritic, containing variably developed mantled-feldspar ("rapakivi") textures. Primary mafic minerals include orthopyroxene and clinopyroxene, and rarer fayalitic olivine; the latter is associated with rusty-weathering. Anorthositic rafts are present in some outcrops, and gneissic inclusions are also present, particularly near the northern contact. Mesoproterozoic granite also occurs northeast of Sarah Lake (Hill, 1982).

Pants Lake Intrusion (PLI)

The PLI was defined as a separate entity by Fitzpatrick *et al.* (1998), who used the term "Pants Lake Intrusive Suite". In accordance with provisions of the stratigraphic code, the term Pants Lake intrusion is employed here. U–Pb geochronological studies (G.R. Dunning, confidential report to Donner Minerals, 1998) indicates that it should be included with the Nain Plutonic Suite, rather than the Harp Lake Plutonic Suite. No details of the geochronology are presented here, but the PLI yields an age that falls within the age range of troctolitic intrusions at Voisey's Bay, as reported by Amelin *et al.* (1997, 1998). The PLI is dominated by olivine gabbro of various types, described in detail in a following section.

Mafic Dykes

Mafic dykes are most commonly observed in plutonic rocks of the Nain and Harp Lake plutonic suites. These must also cut gneissic basement rocks, but are less commonly seen in these units. Most are fresh, aphanitic to fine-grained diabase, and locally show alteration and shearing along their contacts. At least some have the east–northeast trend typical of the Harp Dykes (Emslie, 1980), but there is likely more than one generation present. Mafic dykes are only rarely observed to cut the PLI. A "flat-lying Harp dyke" described by Emslie (1980) south of Pants Lake is actually a gently dipping sheet of PLI gabbro.

PANTS LAKE INTRUSION

The PLI consists of several discrete mafic intrusions distributed through the centre of the area (Figure 2). The scattered geography, common rock types, and complex three-dimensional geometry of the PLI require that its description be broken into two parts. The characteristics of the principal rock types, excluding mineralized rocks, are presented first. This is followed by a discussion of the relationships and geometry of the component intrusions, as presently understood, and the possible links between them.

GEOGRAPHIC AND PETROLOGICAL SUBDIVISIONS

Component intrusions of the PLI (Figure 2) contain similar rock types, and many are "stratigraphically" similar, but there are also important variations in their character and anatomy. From south to north, the main subdivisions are here termed the South intrusion, the Mineral Hill intrusions, the Worm intrusion and the North intrusion. For descriptive purposes, the North intrusion is subdivided into the NDT lobe, Happy Face lobe and Taheke Lake lobe (Figure 2). There are also two smaller intrusions entirely contained within the granites of the Harp Lake Plutonic Suite; these are termed the Doughnut intrusion and the Cartaway intrusion. The latter lies outside the Donner Minerals joint venture project.

The PLI includes several rock units, but these are not necessarily all present in each geographic subdivision. The two most abundant units are fine-grained, layered, olivine gabbro and coarse- grained, massive, leucogabbro. The former is most abundant in the South intrusion, but also occurs in the lowermost parts of the North intrusion. The latter is the dominant unit in surface outcrops of the North intrusion. Melagabbro and peridotite forms a minor (but important) unit in the South intrusion, so far encountered only in drillholes. Black olivine gabbro (commonly abbreviated to simply "black gabbro") occurs in some parts of the North intrusion. This fine- to coarse-grained unit was previously described as troctolitic (Fitzpatrick *et al.*, 1998), but is generally of gabbroic composition. This rock type is difficult to distinguish from texturally similar massive leucogabbro, and the pattern in Figure 2 largely reflects drillhole information. Two other rock types are locally associated with the external contacts of the PLI. Diabase is locally seen at lower and upper contacts, where it records chilling effects. Intrusive breccia occurs in several areas at contacts, and consists of angular to locally resorbed gneissic fragments in a fine-grained mafic matrix. In addition to these, several distinctive and unusual rock types occur in a thin zone of mineralized rocks at or just above basal contacts, particularly in the North intrusion. These are collectively termed the mineralized sequences, as suggested by A.J. Naldrett (personal communication, 1998) and are discussed separately, in conjunction with mineralization.

PRINCIPAL ROCK TYPES

Layered Fine-Grained Olivine Gabbro

This unit is present in all the component intrusions, but may not have been derived from the same magma batch in different areas. The most extensive and informative exposures are in the North intrusion, notably the NDT lobe. It is more poorly exposed in the South intrusion. In most other areas, this unit is spatially associated (or part of) mineralized sequences, and characteristics are obscured by gossan development.

North of Pants Lake, the unit displays the orange–red-weathering typical of olivine-rich rocks. On fresh surfaces, it is a grey–green to dark grey, fine- to medium-grained (1 to 4 mm), granular rock, consisting of olivine, plagioclase, subophitic clinopyroxene, and minor magnetite and biotite. Layering is locally well developed on vertical cliff faces (Plate 1a), but is more difficult to see on flat outcrop surfaces, as it is subhorizontal to gently dipping. Layering is invariably subtle, and appears in drill core as only slight variations in colour and grain size. In some areas, the unit develops a characteristic "speckly" texture due to the presence of small (2 to 4 mm) plagioclase phenocrysts. The unit is monotonous, and subtle compositional and textural variations are commonly visible only in drill core (Plate 1d). The fine-grained, layered, olivine gabbro of the South intrusion is identical in appearance. Fine-grained olivine gabbro seen

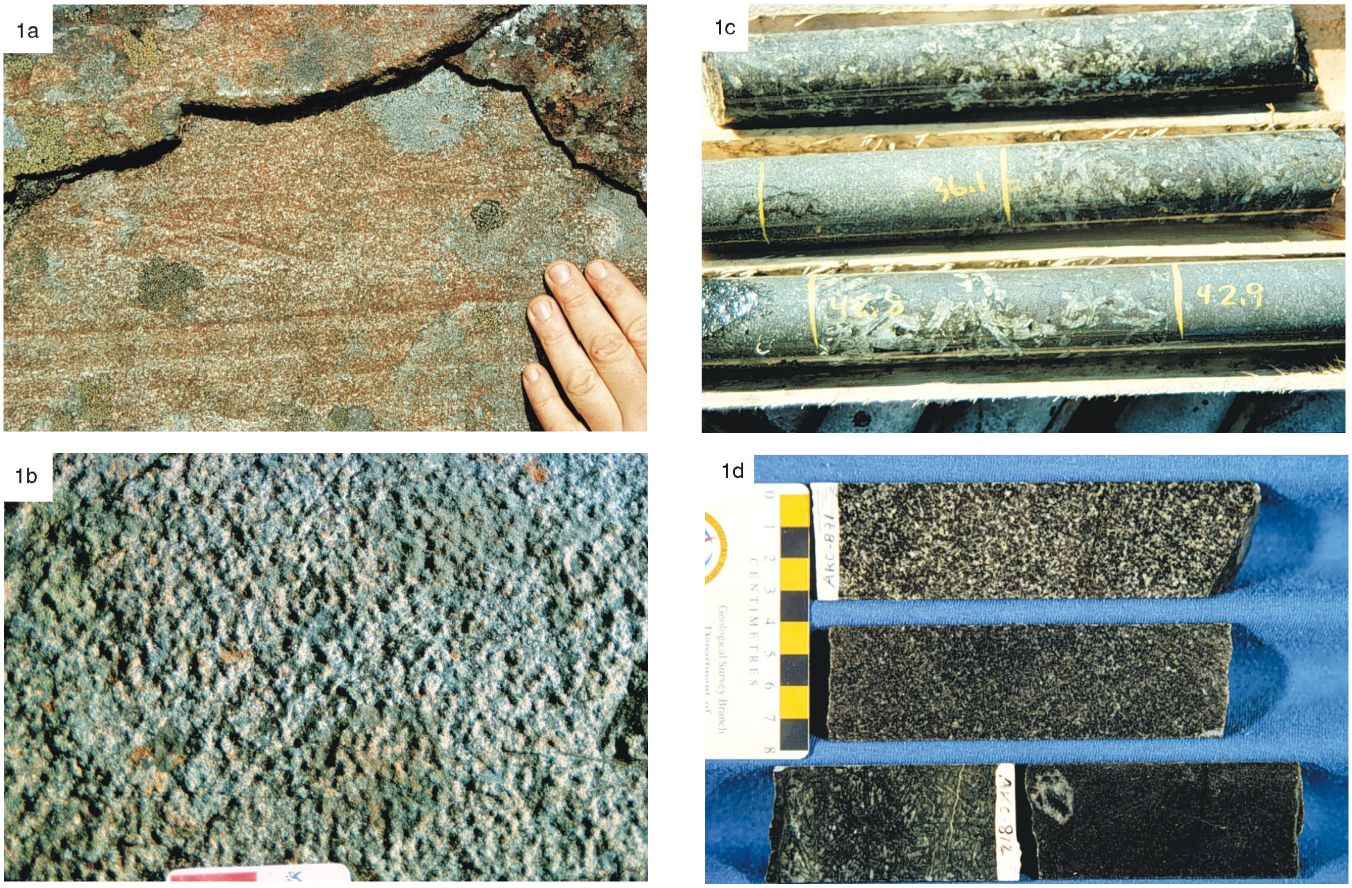


Plate 1. *Fine-grained, layered olivine gabbro unit of the Pants Lake intrusion. (A) Primary layering, defined by variations in mafic mineral content, with local "crossbedding" in centre of photo, NDT lobe, North intrusion. (B) Knobbly weathering texture indicating the presence of clinopyroxene oikocrysts in olivine-rich matrix, Mineral Hill intrusion. (C) Drill-core intersection showing veins of coarse-grained leucogabbro unit cutting fine-grained gabbro, hole 98-112. (D) Examples of textural variations in drill-core samples of the fine-grained unit. Note gneissic fragment in core sample at lower right.*

in the Mineral Hill, Cartaway and Worm intrusions, and locally near the base of the North intrusion, shows a characteristic "knobbly-weathering" texture (Plate 1b). This is caused by large (8 to 15 mm) poikilitic clinopyroxenes, set in a more recessive olivine-bearing groundmass. This texture is similar in many respects to the distinctive "leopard-texture" developed in parts of the mineralized sequence.

In thin section, fine-grained, layered olivine gabbro unit consists of olivine (30 to 60 percent), plagioclase (40 to 60 percent; typically An_{50}–An_{55}) and clinopyroxene (5 to 30 percent), along with minor amounts of red biotite, magnetite, and serpentine (after olivine). Orthopyroxene is present only rarely, as thin rims on scattered olivine grains. A few examples are true troctolites, but most are classified as olivine gabbro. The unit displays a common texture, in which olivine is granular, plagioclase is lath-like, and clinopyroxene is interstitial (Plate 2a), subophitic or (more rarely) poikilitic (Plate 2b). Small olivine grains are typically included in plagioclase laths. The texture indicates that olivine crystallized first, followed by plagioclase, and that clinopyroxene crystallized late. Magnetite and biotite are also late-crystallizing phases. The crystallization sequence indicates that many of these rocks are plagioclase–olivine cumulates, but the range in modal compositions is limited, except locally in the South intrusion.

Melagabbro and Peridotite

These rock types occur in four drillholes in the South intrusion, where they form part of a mafic cumulate sequence near its basal contact. They were originally recognized by H. MacDonald and A.J. Naldrett. In drill core, they are dark green, variably serpentinized, medium- to coarse-grained rocks consisting mainly of olivine, clinopyroxene and interstitial plagioclase. Most examples contain at least 10 to 20 percent plagioclase, and are probably most accurately described as melagabbro. The contacts between this rock type and associated layered olivine gabbro are abrupt but gradational, suggesting that they are closely related. They are also locally interlayered with fine-grained olivine gabbro. Two samples examined in thin section showed significant serpentinitic alteration.

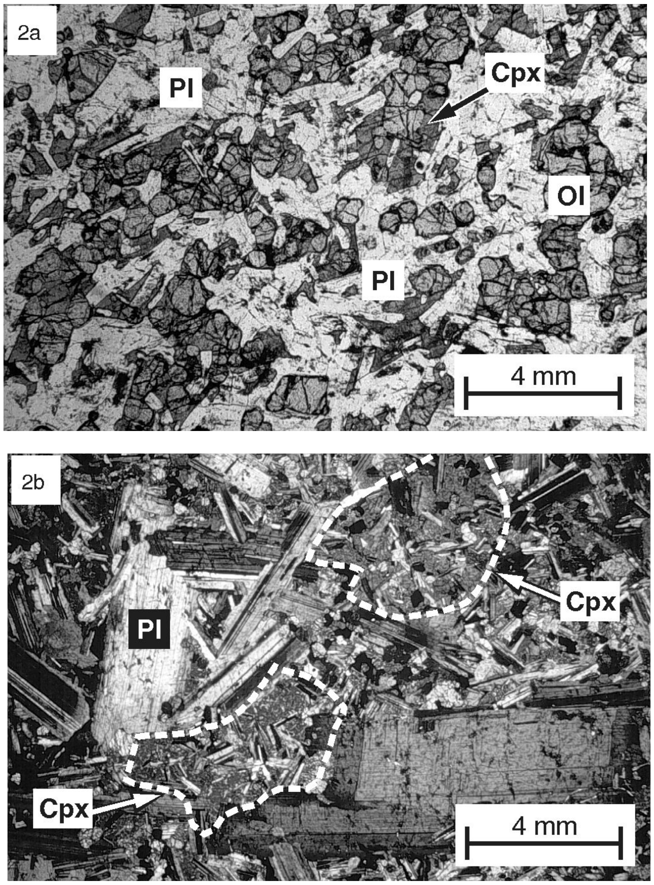


Plate 2. *Petrography of fine-grained, layered olivine gabbro. (A) Typical texture, consisting of plagioclase laths, granular, cumulus olivine and late, clinopyroxene, PPL. (B) Porphyritic variant, also showing development of clinopyroxene oikocrysts, XP. Boundaries of individual clinopyroxene oikocrysts are shown by white lines. Ol – olivine, Pl – plagioclase, Cpx – clinopyroxene, PPL – plane-polarized light, XP – crossed polarizers.*

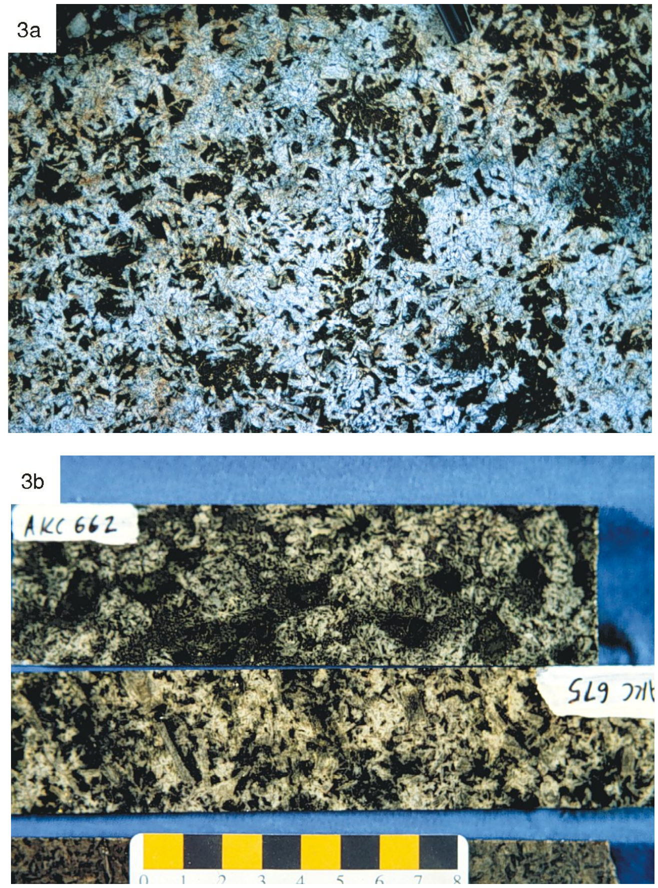


Plate 3. *Coarse-grained massive leucogabbro of the Pants Lake intrusion. (A) Typical field appearance, Worm intrusion, note interstitial habit of all mafic minerals. (B) Typical drill-core samples. The upper core sample is altered adjacent to the upper contact, and the lower sample is a more typical fresh, seriate-textured variety.*

Parts of the melagabbro and peridotite unit host significant disseminated magmatic sulphides, and they form part of the South intrusion mineralized sequence. The unit also contains scattered and variably digested gneissic fragments. The mineralization is discussed in a later section.

Massive Coarse-Grained Leucogabbro

Outside the South intrusion, massive, coarse-grained, leucogabbro is the dominant rock type on surface. 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 3a,b). Plagioclase crystals are commonly in the 1 to 2 cm range, and form stubby prisms, but the unit locally becomes extremely coarse grained, particularly in the Worm intrusion (Plate 3a). Mafic minerals show an interstitial to subophitic habit, have contrasting green- and brown-weathering colours, and show variable alteration to amphibole and/or chlorite. The most leucocratic variants resemble Nain or Harp Lake plutonic suite anorthosites. Many outcrops were initially mapped as gabbronorite, as the contrasting mafic minerals were assumed to be pyroxenes on the basis of their habit; however, most examples are actually olivine gabbro.

In thin section, the best-preserved examples consist of plagioclase (60 to 80 percent), olivine (5 to 20 percent) and clinopyroxene (10 to 20 percent), with lesser amounts of biotite and magnetite (Plate 4a). Modal analysis is difficult, as the mafic minerals commonly form large, single, optically continuous crystals, and individual thin sections are troctolitic, or olivine-free. Drill-core examination suggests that olivine is generally less abundant than clinopyroxene, and most rocks are olivine gabbro. The larger plagioclase crystals show prominent zoning. Plagioclase compositions are more variable than in the fine-grained gabbro, but have a similar maximum of around An_{55}. Olivine, locally, is unusual pale grey, probably caused by fine iron-oxide dust, and

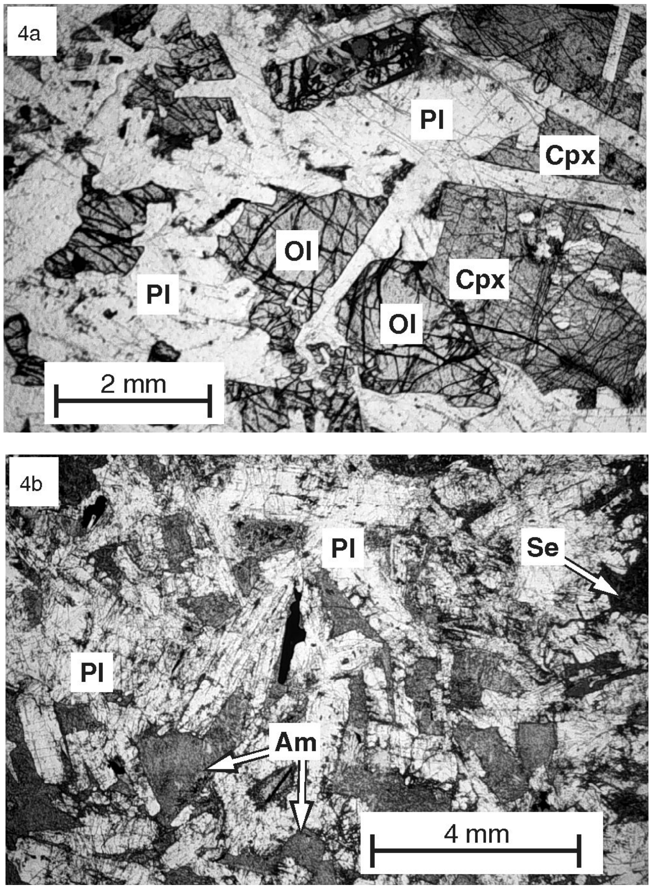


Plate 4. *Petrography of coarse-grained, massive leucogabbro. (A) Typical texture in a fresh sample, showing interstitial to oikocrystic habit of olivine and clinopyroxene, PPL. (B) Altered variant showing extensive retrogression of mafic minerals (to actinolite, chlorite and serpentine) but retention of original textural relationships, PPL. Pl – plagioclase, Ol - olivine, Am – amphibole, after clinopyroxene, Se – serpentinized olivine, Cpx - clinopyroxene, (photos in PPL – plane-polarized light).*

clinopyroxenes are commonly purplish and weakly pleochroic, suggesting 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, indicating that they crystallized late, in contrast to early olivine of the layered olivine gabbro unit (Plate 4a).

Altered massive leucogabbro is noted in drillholes that preserve an upper "cap" of gneissic country rocks. Clinopyroxene and olivine are extensively altered to secondary amphibole, serpentine and iron oxide (Plate 4b), but the retrogression diminishes downhole from the upper contact. The upper regions of the massive leucogabbro unit also contain rounded, very fine-grained inclusions of unknown origin; in thin section, these consist or extremely fine-grained amphibole-rich material surrounded by coarser hornblende.

Black Olivine Gabbro

This unit is presently known only from the northern part of the North intrusion, where closely spaced drilling has been conducted. Its characteristics are best known from drill core, where it is a medium- to coarse-grained dark grey to black rock that superficially appears very mafic. Its appearance is deceptive, as it contains over 60 percent dark-weathering plagioclase, with the remainder consisting mostly of olivine and purple–bronze clinopyroxene. Plagioclase is commonly prismatic and well-twinned, in contrast to the more equant habit typical of the massive leucogabbro (Plate 5a). Large, optically continuous olivine and clinopyroxene crystals displaying spectacular poikilitic textures, are

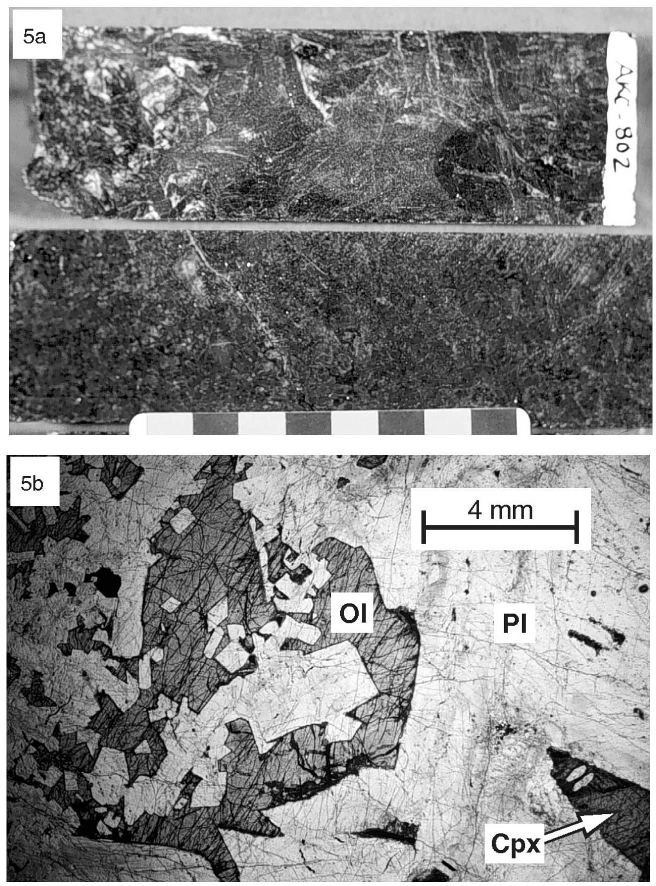


Plate 5. *Characteristics of black olivine gabbro unit of the Pants Lake intrusion. (A) Typical drill-core samples of coarse-grained and medium-grained varieties. Despite their dark colour, these samples are plagioclase-rich. (B) Large poikilitic olivine crystal in thin section; note similarity to coarse-grained leucogabbro texture of Plate 4. Ol – olivine, Pl – plagioclase, Cpx – clinopyroxene. Photo in PPL (plane-polarized light).*

common in many examples. There are marked grain-size variations within this unit, and finer grained examples are black diabase-like rocks that contain large poikilitic olivines and pyroxenes. Although some of the finer grained types are superficially similar to the layered olivine gabbro, their texture is distinctly different in thin section.

In drill core, black gabbro may show a blotchy appearance, probably indicating variable secondary effects, and the lighter coloured regions resemble the massive grey leucogabbro. It is also texturally similar to the massive leucogabbro, and contains the same late, interstitial, olivine and clinopyroxene (Plates 4a, 5b). In surface outcrops, the distinction between the two units is very difficult. Present information suggests that the black olivine gabbro occurs on surface in much of the area northeast of Taheke Lake, but its precise outline is approximate. In thin section, the coarse-grained black gabbro is closely similar to typical massive leucogabbro. The dark colour exhibited by plagioclase appears to be related to numerous tiny iron-oxide inclusions. The finer grained variants are spectacular rocks in which both olivine and clinopyroxene form poikilitic crystals; their texture resembles that of a coarse diabase.

Given the similarities between the coarse-grained, massive, leucogabbro and the black olivine gabbro, their status as discrete units has been keenly discussed. The author was initially reluctant to separate them, but subsequently agreed with Fitzpatrick *et al*. (1998) after examining several key 1998 drillholes. These intersected both units, indicating that they are indeed distinct, and demonstrate that they have different relationships to the fine-grained, layered olivine gabbro. The black olivine gabbro sits beneath the fine-grained unit, whereas the massive leucogabbro sits above it. However, this relationship is not clearly reflected in the outcrop pattern of the three units, as defined by mapping to date (Figure 2).

Diabase

Diabase occurs near the basal contacts of PLI intrusions in several drillholes, and is a chilled version of overlying fine-grained gabbro, 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 texturally akin to the layered olivine gabbro. In hole SVB-97-56 (near the Happy Face showing, Figure 2) a similar diabase unit is developed at the upper contact of the massive leucogabbro unit, and grades downward into it.

Diabase also cuts the host gneisses in drill core, normally close to the contacts of the PLI. Some examples probably represent a chilled facies, which may not be preserved at the contact itself. However, diabase-like units observed in gneisses below the intrusions have a greenish, altered appearance, and contain extensive hornblende, most of which appears primary. These are interpreted as older minor intrusions that predate the emplacement of the PLI. Diabase is only rarely observed within the PLI away from contact regions, which is consistent with the rarity of diabase dykes in the field. However, there are several intervals of diabase and very fine-grained gabbro in deep holes completed in the South intrusion. These appear to have sharp contacts, implying that they postdate the dominant layered olivine gabbro in this area. In thin section, all of these rocks are typical diabases, consisting of finely intergrown plagioclase, clinopyroxene and olivine. They commonly have a turbid appearance due to dispersed iron oxide and alteration. It is commonly difficult to estimate the amount of olivine in these fine-grained rocks, but it is usually present.

Intrusive Breccias

Locally spectacular intrusive breccias (not shown in Figure 2) are developed around the North intrusion, and also in some gabbro outliers near the South intrusion. Typical examples contain angular to rounded blocks of orthogneiss and lesser metasedimentary gneiss. The matrix to the blocks may contain minor sulphide, and in one of the southern examples appears vesicular, and possibly subvolcanic, as noted by Thomas and Morrison (1991). Inclusions of graphite are also recorded at this, and other localities. In the North intrusion, intrusive breccias appear to be developed locally at the contacts of both layered olivine gabbro and massive leucogabbro, representing lower and upper contacts respectively (Fitzpatrick *et al.*, 1998). Although there is local assimilation and contamination in these breccia units, the gneiss fragments do not show the reaction textures observed in drill core from the mineralized sequence and most breccias are sulphide-poor. The xenolith population appears to be mostly of local origin, and had only a short "residence time" in the magma. These breccias are regarded as distinct from complex, sulphide-bearing, breccia-like rocks associated with the mineralized sequences.

GEOMETRY, STRATIGRAPHY AND RELATIONSHIPS

Diamond drilling since 1995 has shown that the PLI component intrusions have complex geometries, much of which would be difficult to infer from surface patterns alone. This section discusses their geometry, stratigraphy and geological relationships, using summary maps and cross-sections (Figures 3, 4 and 5). Cross-sections all incorporate a mild (200 percent) vertical exaggeration in order to adequately represent the geology, and true unit thicknesses and dip angles are slightly distorted.

South Intrusion

Only the northern portion of this intrusion (south of the Pants River valley; Figures 2 and 3) is discussed here. This is dominated by fine- to medium-grained, variably layered olivine gabbro. The coarse-grained massive leucogabbro unit occurs only as short intervals with sharp contacts in drill core, which have the appearance of intrusive veins or sheets. Five deep vertical drill holes (SVB-97- 79, 86, 89, 94 and 98-100) penetrate the intrusion, and four reached its basal contact (Figure 3b,c). In holes 79 and 86, peridotite and melagabbro are interlayered with fine-grained olivine gabbro, and represent a basal mafic cumulate sequence, located 500 to 600 m below the surface. Identical cumulate rocks occur close to surface in hole 100, and a thin intersection of sulphide-bearing gabbro at the very top of hole 89 probably represents this horizon. The four basal contacts lie on a plane striking at about 010°, and dipping west at about 15°. The gabbro has a continuous true thickness of about 600 m in the area of hole 79, but hole 94 (abandoned at 501 m) contains a central intersection of gneisses, separating two gabbroic units, the upper of which hosts basal mineralization. At the equivalent stratigraphic level in hole 79, minor sulphide mineralization is associated with thin screens of older plutonic rocks. The upper gabbroic sections in holes 79 and 86 contain a higher density of diabase dykes compared to the lower sections. These contrasts suggest that the South intrusion may itself be composite, and record two or more magmatic influxes. The basal contact in hole 79 preserves a fine- to medium-grained, barren gabbro that grades downward into a chilled zone. This provides a possible sample of the initial magma that entered the chamber, which solidified prior to the formation of the overlying mafic cumulates.

The western subsurface limit of the South intrusion is not defined. It should be present in the lower part of the deep drillhole SVB-97-91 (Figure 3b), but this intersected older Harp Lake Plutonic Suite 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 lie below the base of hole 91 at 1099 m. The nature and attitude of the southern contact is unknown at present.

Mineral Hill Intrusions

Figure 3 illustrates geometric relationships between the South intrusion and thinner sheet-like intrusions that host sulphide mineralization, including the Mineral Hill showing. Hole 98-110 intersected three discrete mafic intrusions (Figure 3c). The lower two probably correlate with the two upper mafic intersections in hole 94, and the uppermost unit probably correlates with mineralized gabbro in holes 96-35 and 36 near Mineral Hill (Figure 3d). Each mafic interval in hole 98-110 contains an upper section of coarse-grained massive leucogabbro, and has a thin mineralized sequence near its base. The upper part of hole 91 also contains a mafic unit containing basal mineralization, but there is no sign of the middle mafic unit from hole 94 (Figure 3a).

Shallow 1996 drilling illustrates intrusive geometry in the area of the Mineral Hill showing (Figure 3d). The pattern can be interpreted as a single sheet-like body, which has been gently folded (or displaced by a fault) or as two separate sheet-like intrusions. Given the evidence from hole 110, the latter interpretation is preferred here (Figure 3d). Although there are some uncertainties in correlation, the Mineral Hill intrusions clearly represent stacked subhorizontal to gently west-dipping sheets sitting structurally above the South intrusion. The middle mafic section in hole 94 (Figure 3b,c) may represent part of the conduit system that originally linked them to the South intrusion, but there is no evidence within this of the coarse-grained massive leucogabbro seen in the higher intrusions.

The Worm Intrusion

The Worm intrusion is probably the least understood component of the PLI. The intrusion forms a positive-weathering ridge trending at about 140°, and the outcrop pattern suggests that it is unlikely to be a subhorizontal sheet. The nature of the southern contact, where it approaches the Mineral Hill and South intrusions, is obscured by drift in the Pants River valley. In the north, it appears to merge directly into the North intrusion southeast of the Happy Face showing (Figure 2). The dominant rock type in the Worm intrusion is coarse-grained, massive leucogabbro which locally is very-coarse grained (e.g., Plate 3a). There are local exposures, particularly on the west side, of fine-grained olivine gabbro with poikilitic clinopyroxene. Sulphides occur locally at the north end, where a crude layering in a small showing (probably defined by disk-like mafic inclusions, as discussed later) is apparently truncated along strike by the massive leucogabbro.

About 1 km north of the Pants River, holes 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 3e). This is a near-surface attitude only, and it may steepen at depth. The sheet consists largely of coarse-grained leucogabbro, overlying a mineralized sequence. Other drillholes farther to the north do not constrain the attitude of the intrusion. Locally, the Worm intrusion is very thin; in hole 96-15 (located north of Figure 3a), the entire sequence from coarse leucogabbro to footwall gneiss is contained in less than 50 m.

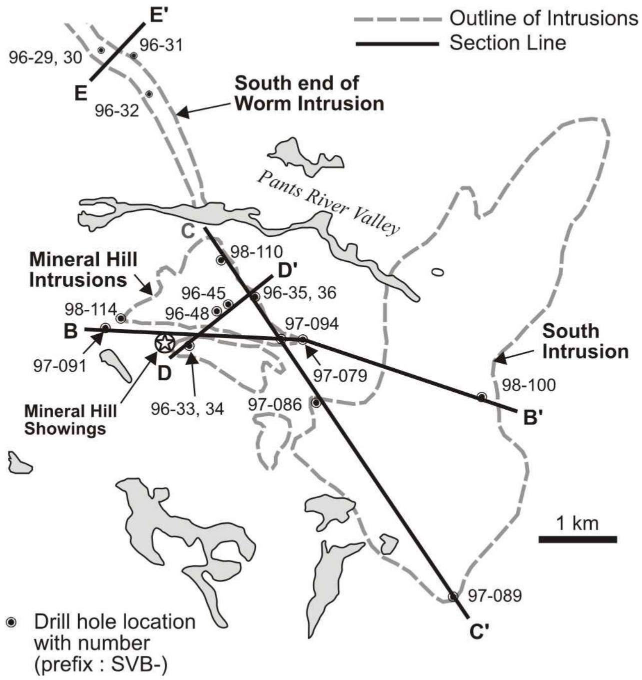
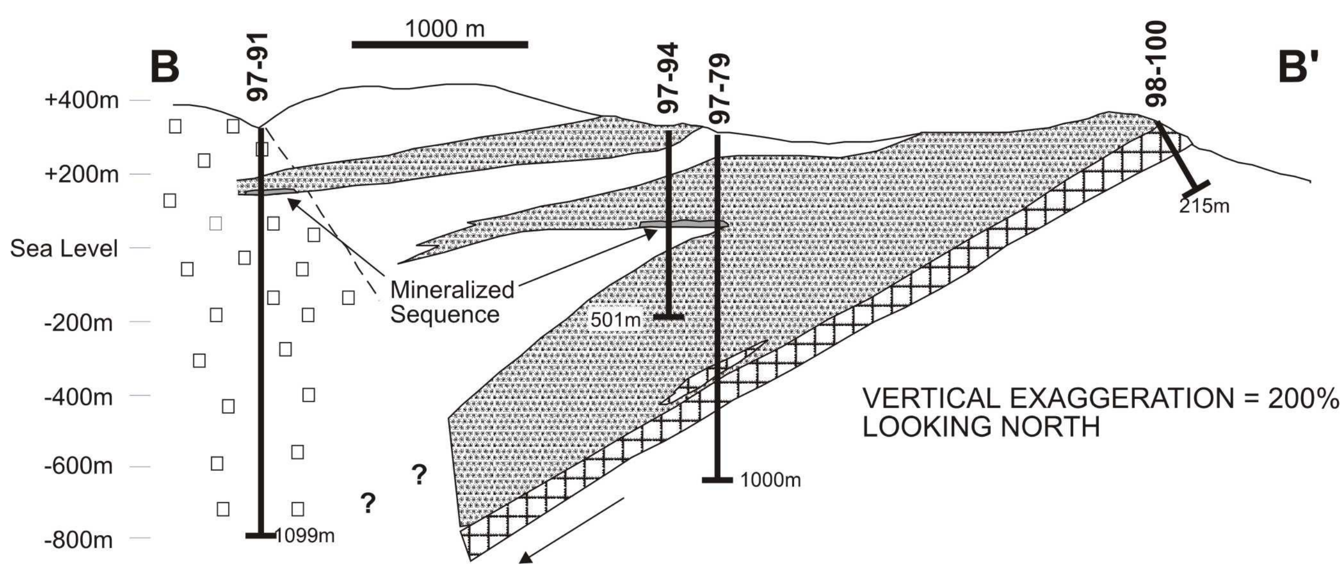


Figure 3. *Geometric views of the South intrusion, Mineral Hill intrusions and Worm intrusion. (A) Map showing outline, drillhole locations and section planes. (B) Approximately east–west cross-section of South intrusion (B-B'). (C) Approximately northwest–southeast cross-section of South intrusion (C-C'). (D) Approximately east-northeast–west-southwest cross-section of Mineral Hill area (D-D'). Distribution of mineralized sequence is partly schematic. (E) Northeast–southwest cross-section of the Worm intrusion (E-E') Cross-sections include 200 percent vertical exaggeration for clarity.*



Cartaway and Doughnut Intrusions

These two small bodies have not been drilled, but the outcrop patterns and geological contact relationships suggest that both are sheet-like. The Cartaway intrusion was originally noted by Emslie (1980) as a "flat-lying" Harp Dyke. It contains an upper massive leucogabbro and a lower fine- grained gabbro, locally with poikilitic clinopyroxene. The total thickness is approximately 50 to 70 m, and it dips very gently northward. The terminations of the unit (Figure 2) are limits of mapping only, and extensions of it may be present elsewhere south of Pants Lake. The Doughnut intrusion has not been examined by the author.

North Intrusion

The North intrusion is the most complex component body of the PLI. Its surface and subsurface area is large, and the only closely spaced drilling is at the northern tip (Figure 4). Elsewhere, it is poorly known at depth, and only a tiny fraction of its basal contact has actually been tested. For purposes of description, the intrusion is logically subdivided into three "lobes", which are here termed the NDT lobe, Happy Face lobe and Taheke Lake lobe.

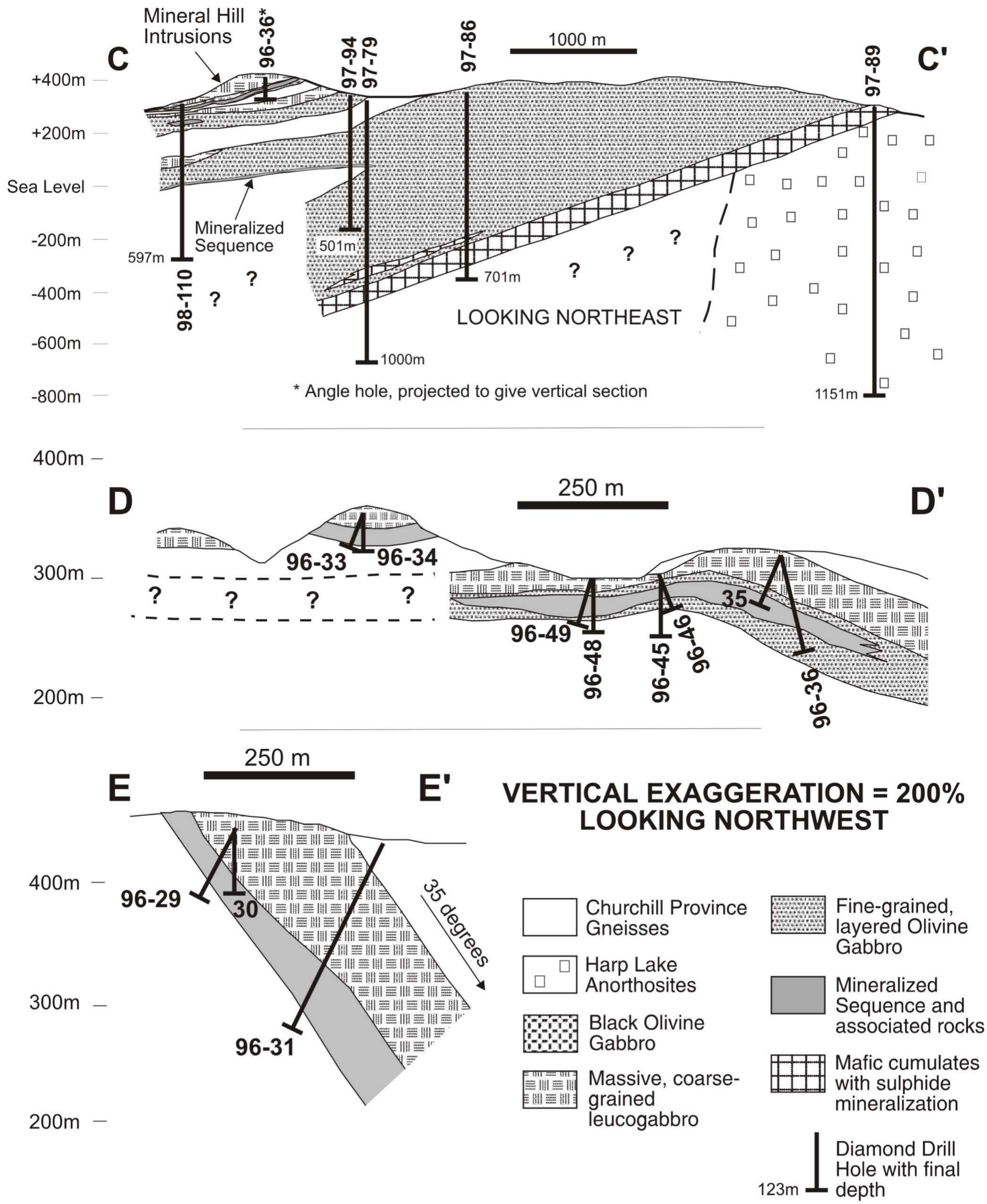


Figure 3. *Continued.*

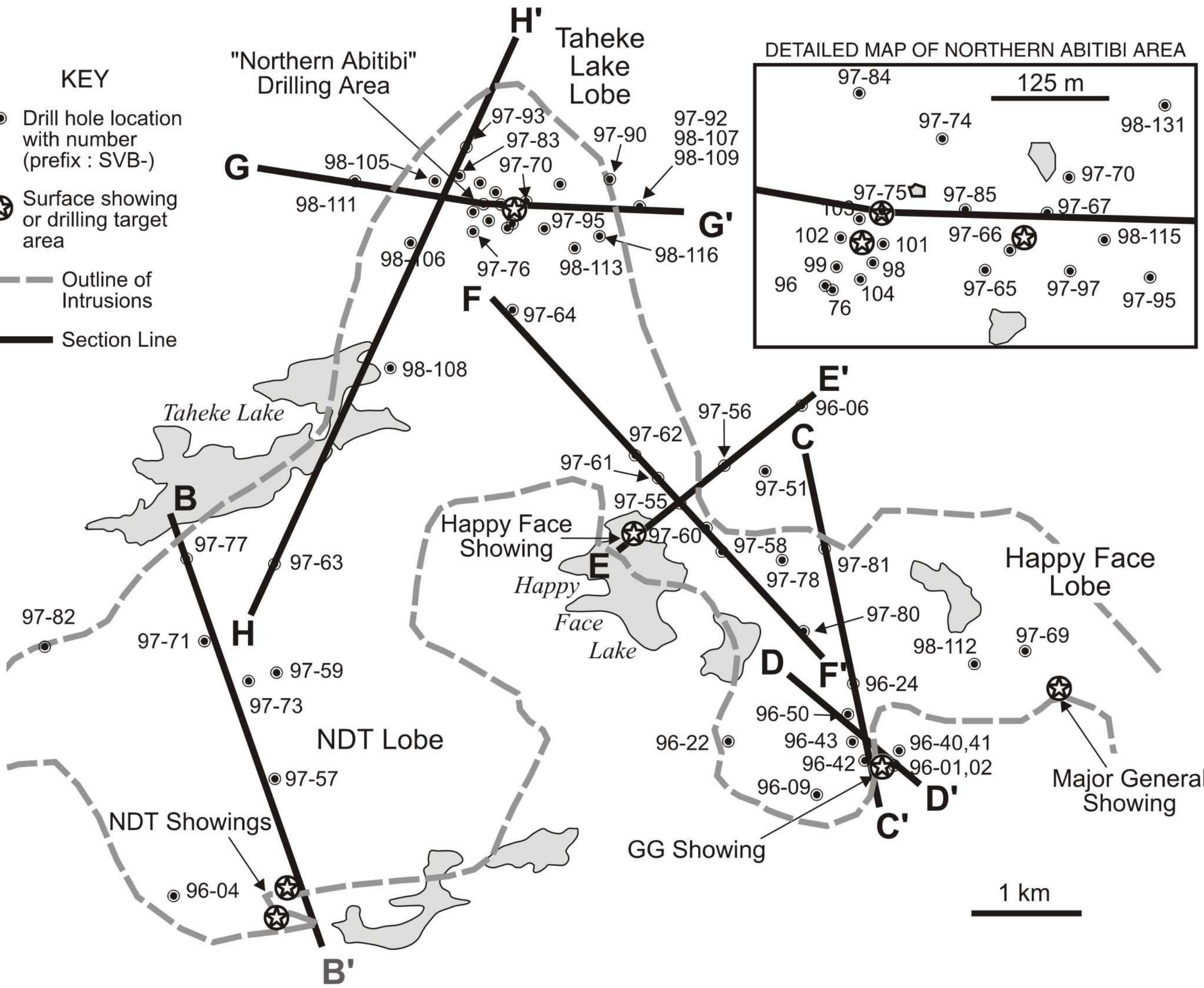


Figure 4a. *Geometric views of the North intrusion. (A) Map showing outline, drillhole locations, and section planes. (B) NDT lobe, north–south cross-section (B-B'). (C) Happy Face lobe, north–south cross-section (C-C'). (D) Happy Face lobe, cross-section near GG showing (D-D'). (E) Happy Face lobe, northeast–southwest cross-section (E-E'). (F) Happy Face lobe, northwest–southeast cross-section (F-F'). (G) Taheke Lake lobe, east–west cross-section including Northern Abitibi drilling area (G-G'). (H) Taheke Lake lobe, southwest–northeast cross-section (H-H'). Cross-sections include 200 percent vertical exaggeration for clarity.*

NDT Lobe

This occupies the area between Pants Lake and Taheke Lake (Figures 2 and 4a), and includes the "NDT" surface showings. A north–south cross-section from the surface showings to Taheke Lake (Figure 4b) indicates a north-dipping intrusion at least 400 m thick, with about 100 m of massive leucogabbro underlain by up to 300 m of fine- to medium-grained, layered, olivine gabbro. A basal mineralized sequence, locally up to 30 to 40 m thick, projects to the surface showings (Figure 4b). The basal contacts of drillholes define an approximate plane, striking at 060°, and dipping at about 12° to the northwest. It is not clear what happens north of Taheke Lake, because there is no sign of a thick intrusion in hole 98-111. In the west, the intrusion becomes narrower, and its basal contact must descend from about 500 m elevation at surface, to only 31 m above sea level in hole 97-82, which implies a steeper northward dip of 25 to 30°.

All of the drillholes in this area show similar rock types and relationships. The relationship between fine-grained olivine gabbro and massive leucogabbro is commonly ambiguous, but short intervals of coarse-grained gabbro within the former may be intrusive veins or sheets. The layered olivine gabbro locally develops a "speckly" porphyritic appearance and, near its base, is almost as coarse-grained

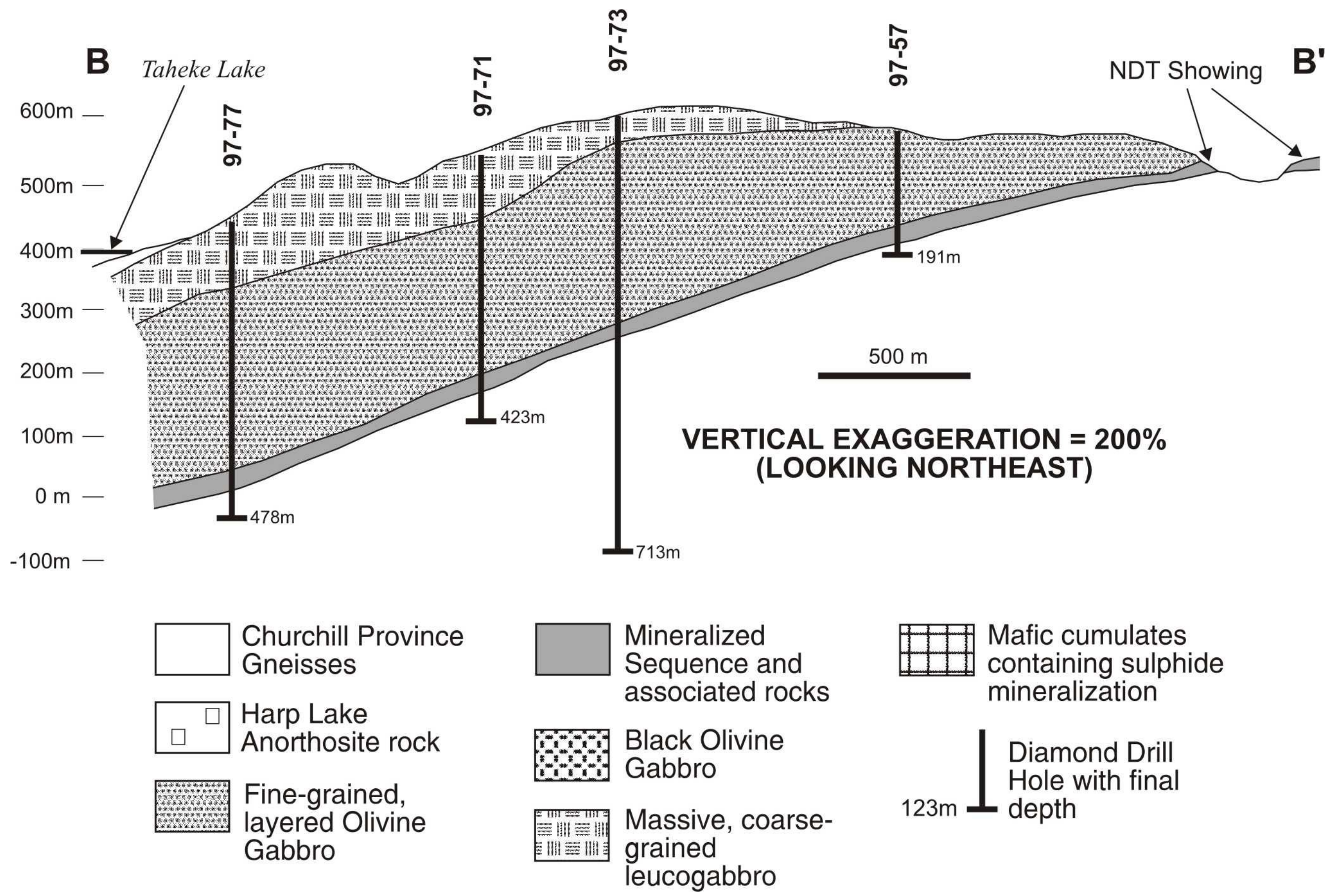


Figure 4b. *Geometric views of the North intrusion. (A) Map showing outline, drillhole locations, and section planes. (B) NDT lobe, north–south cross-section (B-B'). (C) Happy Face lobe, north–south cross-section (C-C'). (D) Happy Face lobe, cross-section near GG showing (D-D'). (E) Happy Face lobe, northeast–southwest cross-section (E-E'). (F) Happy Face lobe, northwest–southeast cross-section (F-F'). (G) Taheke Lake lobe, east–west cross-section including Northern Abitibi drilling area (G-G'). (H) Taheke Lake lobe, southwest–northeast cross-section (H-H'). Cross-sections include 200 percent vertical exaggeration for clarity.*

as the upper unit, but retains granular, cumulus olivine. Some of these rocks are troctolitic, and may represent zones of olivine accumulation. A similar rock occurs just above the mineralized sequence in hole 96-04 (Figure 4a) implying that this is a persistent feature. 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 lobe. A fine-grained, dark rock having a coarse diabasic texture, and poikilitic olivine, was noted near the base of hole 97-63, and may correlate with the black olivine gabbro seen in the Taheke Lake lobe.

Happy Face Lobe

The Happy Face lobe is separated from the NDT lobe by a region of gneisses, locally overlain by small gabbro outliers (Figure 2; Figure 4a). It includes the surface showings known as Happy Face, Major General and GG. In this area, the North intrusion ranges from a thin subhorizontal sheet, to a northeast-dipping sheet from 100 to 200 m in thickness (Figure 4). At the GG showing, there is a typical sequence of coarse-grained massive leucogabbro sitting above a mineralized sequence (Figure 4d). One of these holes (96-02) indicates a second gabbro unit at slightly deeper levels. This is the only evidence at present in the North intrusion for "stacked" sheet-like intrusions akin to those documented at Mineral Hill. A north-northwest–south-southeast section (Figure 4c) suggests that the gabbro dips gently (about 5°) to the north, achieving a thickness of about 200 m, most of which is massive leucogabbro (Figure 4e). However, a southwest–northeast cross-section from the Happy Face showing to hole 96-06 shows a northeast dip of about 12°, and also possibly gentle folding or undulation (although minor faulting could also explain the pattern). A final view is provided by a northwest–southeast cross-section from hole 64 to hole 80, which indicates a depression in

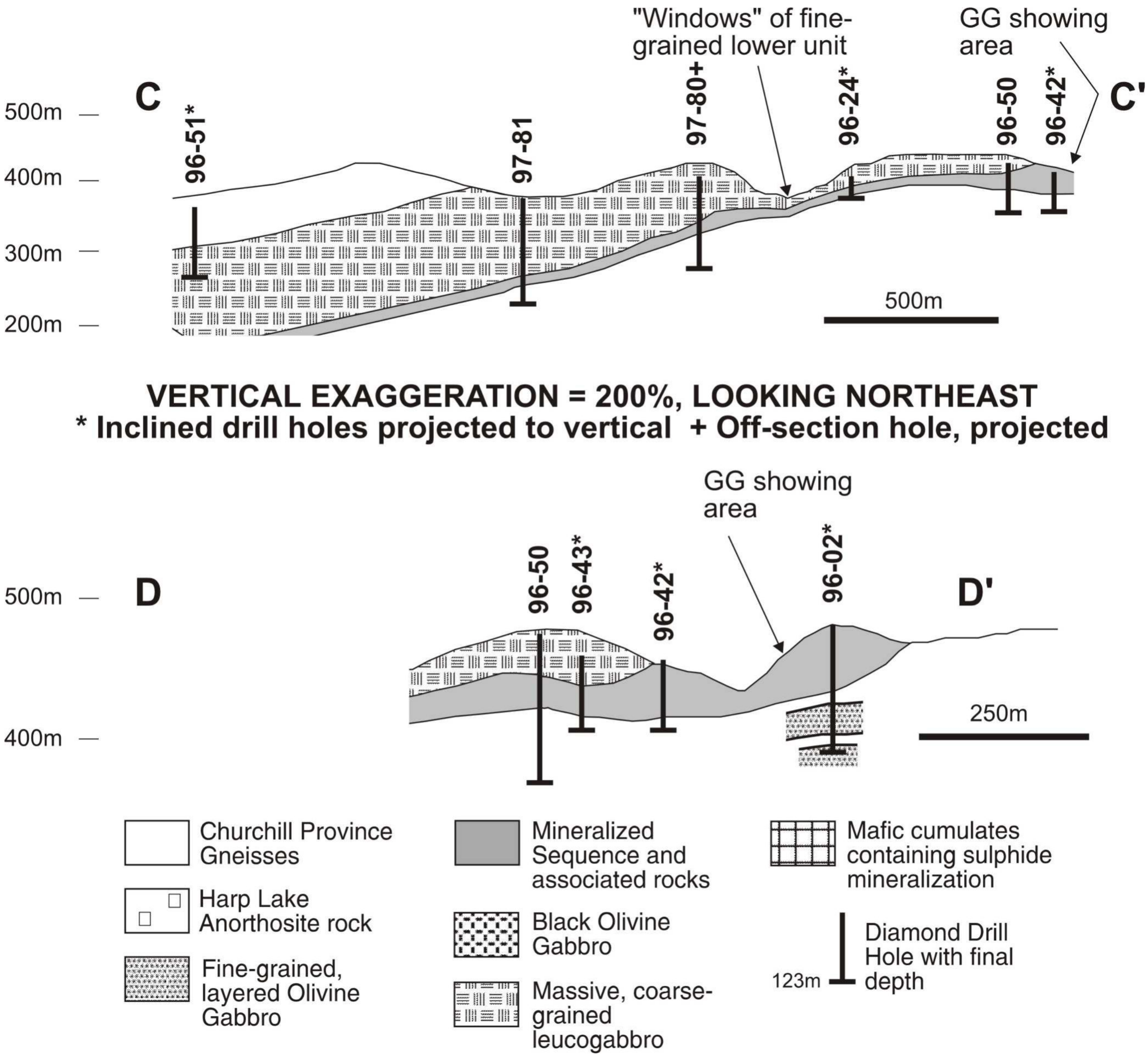


Figure 4c-d. *Geometric views of the North intrusion. (A) Map showing outline, drillhole locations, and section planes. (B) NDT lobe, north–south cross-section (B-B'). (C) Happy Face lobe, north–south cross-section (C-C'). (D) Happy Face lobe, cross-section near GG showing (D-D'). (E) Happy Face lobe, northeast–southwest cross-section (E-E'). (F) Happy Face lobe, northwest–southeast cross-section (F-F'). (G) Taheke Lake lobe, east–west cross-section including Northern Abitibi drilling area (G-G'). (H) Taheke Lake lobe, southwest–northeast cross-section (H-H'). Cross-sections include 200 percent vertical exaggeration for clarity.*

the basal contact, centred near hole 97-78 (Figure 4f). Thin sequences of a dark-coloured rock containing poikilitic olivine (in holes 58 and 80) sit between the massive leucogabbro and the mineralized sequence, and may correlate with the "black gabbro" of the Taheke Lake lobe. The latter was also observed in hole 98-112, northwest of the Major General showings (Figure 4a), and may lurk unrecognized in other holes. The total thickness of gabbro is probably only 50 m or so south and southeast of hole 64.

In the Happy Face lobe, the mineralized sequence is commonly developed just below the base of the massive leucogabbro unit, and there is generally no thick layered olivine gabbro sequence. The stratigraphy, and the overall

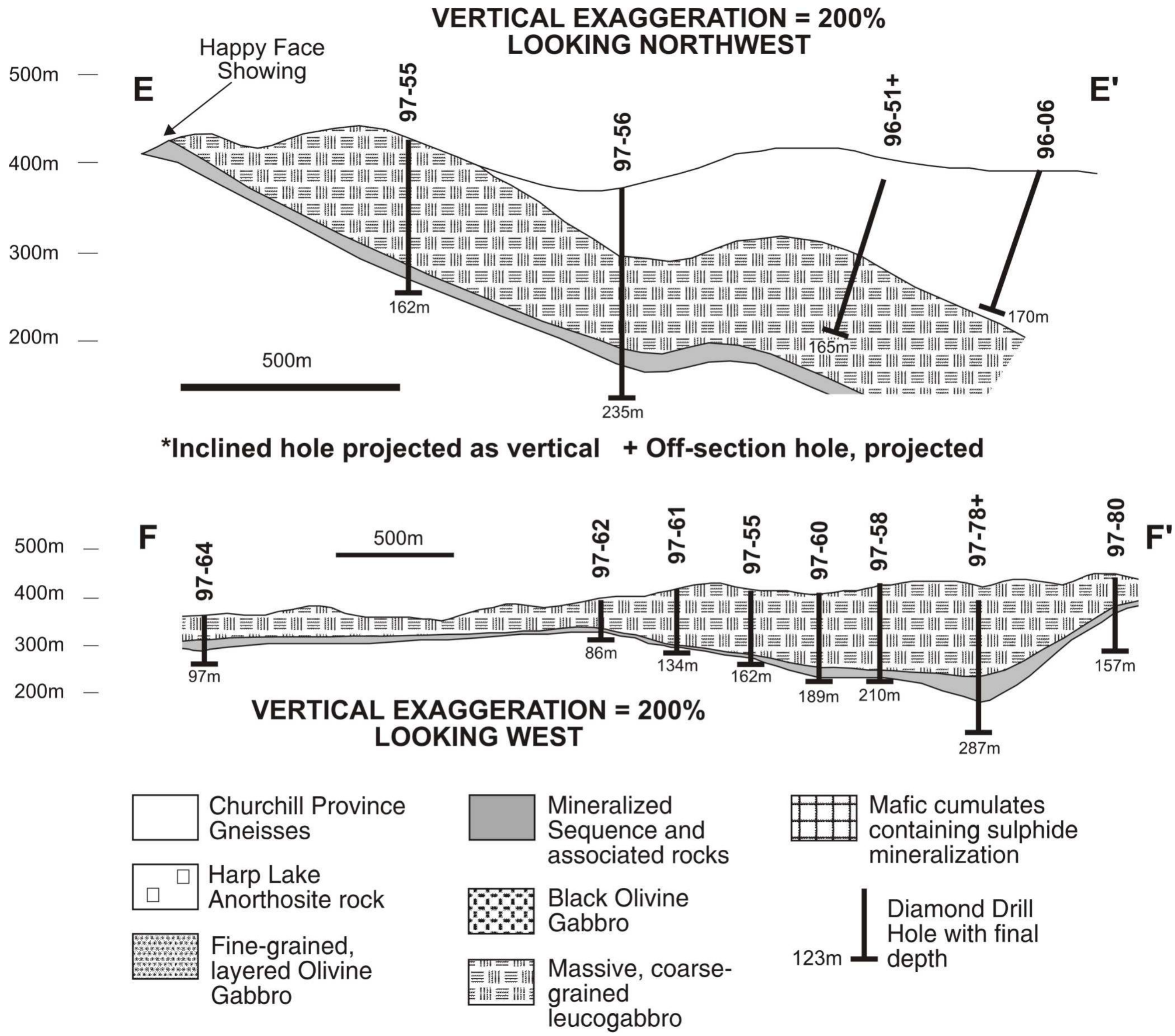


Figure 4e-f. *Geometric views of the North intrusion. (A) Map showing outline, drillhole locations, and section planes. (B) NDT lobe, north–south cross-section (B-B'). (C) Happy Face lobe, north–south cross-section (C-C'). (D) Happy Face lobe, cross-section near GG showing (D-D'). (E) Happy Face lobe, northeast–southwest cross-section (E-E'). (F) Happy Face lobe, northwest–southeast cross-section (F-F'). (G) Taheke Lake lobe, east–west cross-section including Northern Abitibi drilling area (G-G'). (H) Taheke Lake lobe, southwest–northeast cross-section (H-H'). Cross-sections include 200 percent vertical exaggeration for clarity.*

thicknesses of units, resemble those observed in the Worm intrusion.

Taheke Lake Lobe

The Taheke Lake lobe forms the northern portion of the North intrusion. Aside from a small (<1 km^2) area, its geometry is defined only by widely spaced drilling (Figure 4a). An east–west section through the lobe indicates a sheet-like mafic intrusion with a thickness of around 200 m, which dips below the gneisses to the east, at about 15° (Figure 4g). However, hole 98-111, drilled less than 0.5 km west of the supposed upper contact, contains no sign of a mafic intrusion of equivalent thickness. A 30 m intersection of gabbro, containing some sulphides, represents the only PLI-like rocks observed in this hole, and has yet to be examined by the author. There are several possible interpretations for what happens between holes 105 and 111, as shown in

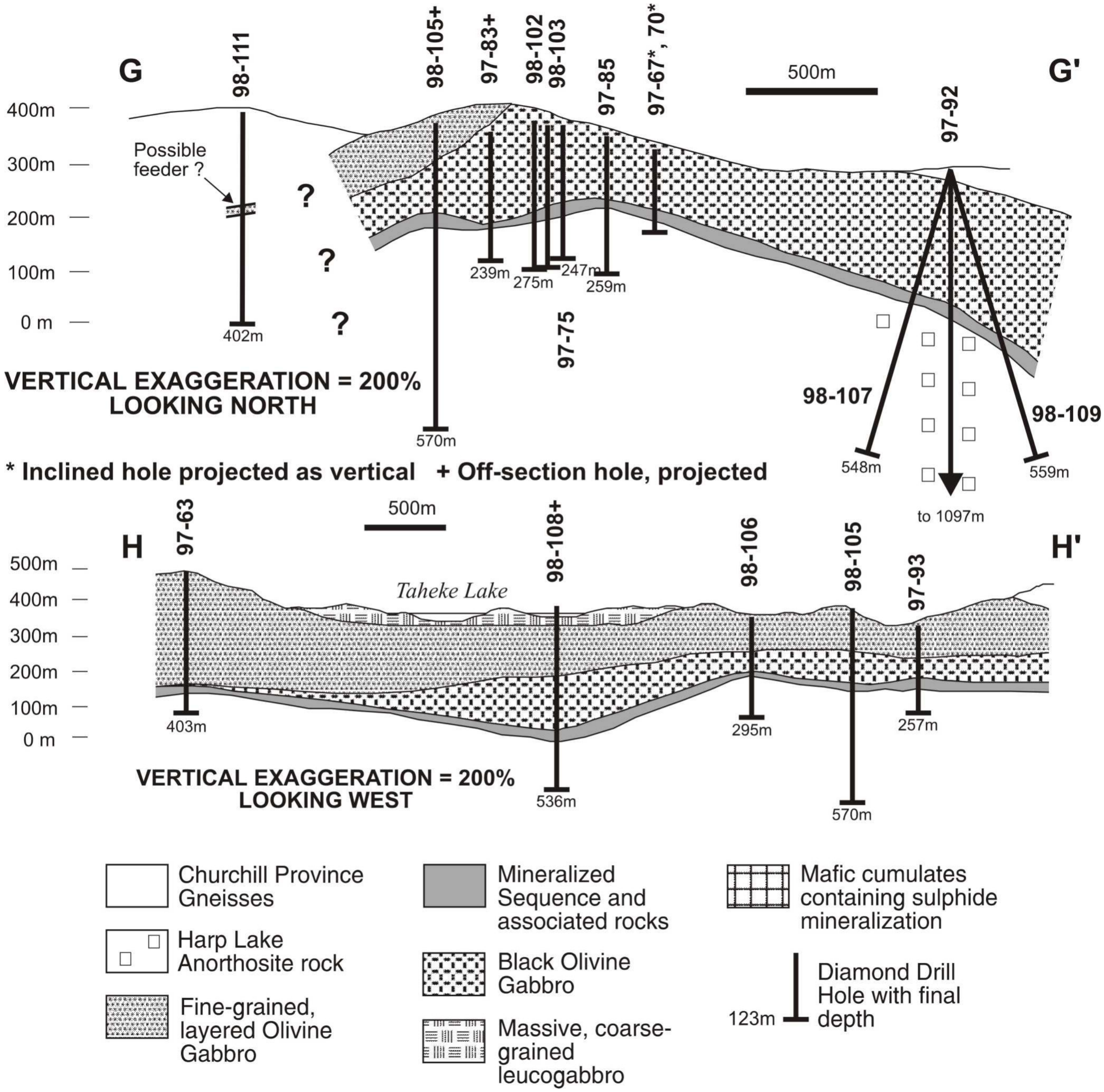


Figure 4g-h. *Geometric views of the North intrusion. (A) Map showing outline, drillhole locations, and section planes. (B) NDT lobe, north–south cross-section (B-B'). (C) Happy Face lobe, north–south cross-section (C-C'). (D) Happy Face lobe, cross-section near GG showing (D-D'). (E) Happy Face lobe, northeast–southwest cross-section (E-E'). (F) Happy Face lobe, northwest–southeast cross-section (F-F'). (G) Taheke Lake lobe, east–west cross-section including Northern Abitibi drilling area (G-G'). (H) Taheke Lake lobe, southwest–northeast cross-section (H-H'). Cross-sections include 200 percent vertical exaggeration for clarity.*

Figure 4g. First, the hole 111 intersection could represent a thinned extension (a feeder ?) to the intrusion (P. Moore and K. Sparkes, personal communication, 1998) and second, the intrusion could pass below hole 111, which requires a rapid increase in dip to more than 50°. Alternative explanations include structural disruptions, or a switch in dip direction that brings the base of the intrusion to surface between holes 105 and 111.

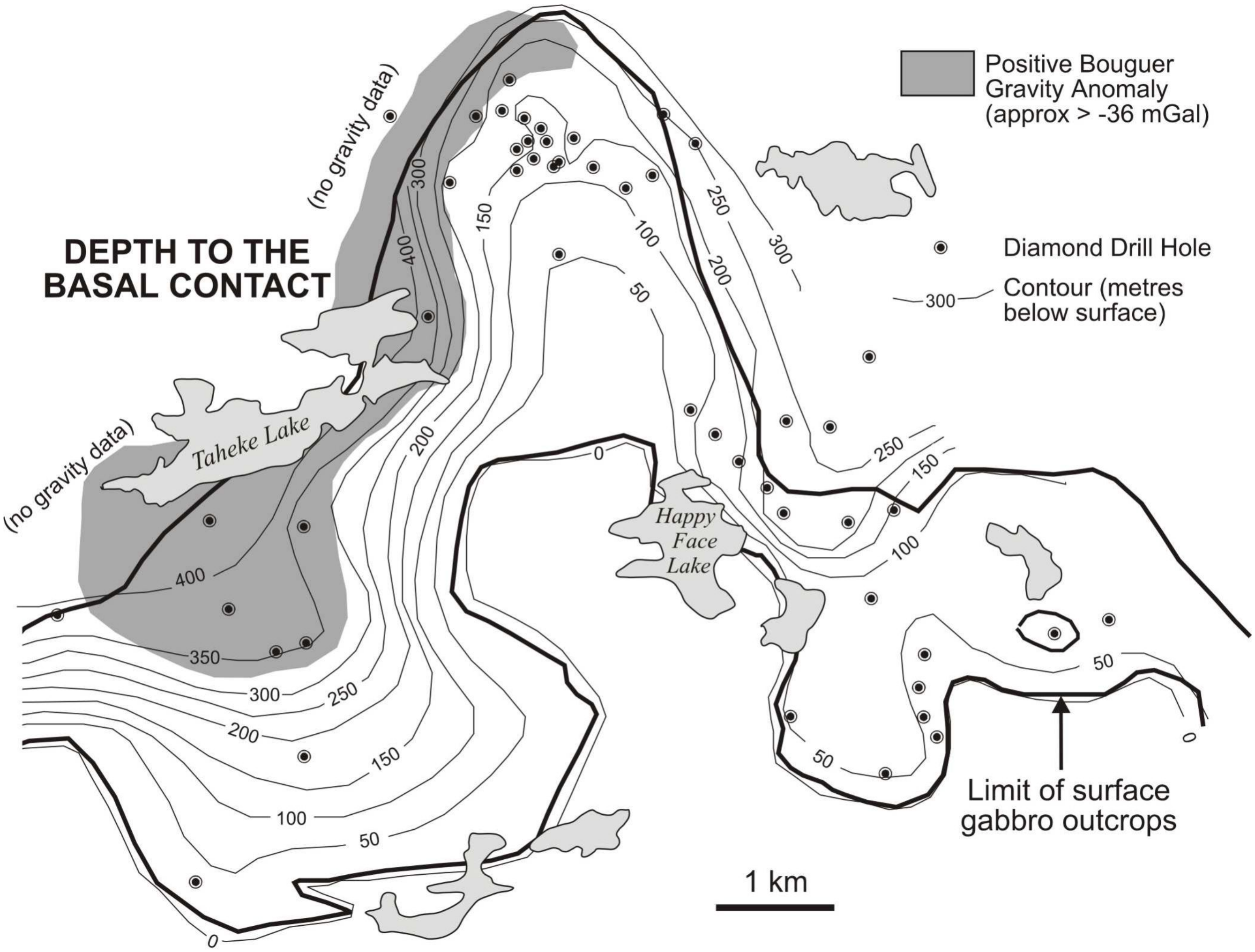


Figure 5. *A summary of the three-dimensional geometry of the North intrusion.* ***(A)*** *Isopachs showing the depth to the basal contact; within the outline of the body, these correspond to vertical thickness of the gabbro. Approximate extent of positive gravity anomaly is also indicated. (B) True structural contours (relative to sea level) on the basal contact of the intrusion, corresponding to a "topographic map" of the basal surface.*

The massive leucogabbro unit is mainly absent in the Taheke Lake lobe, where there is a thick sequence of the black olivine gabbro, which is present at surface. 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 97-70). Deep holes such as 97-92, and 98-105, 107 and 109 indicate that the North intrusion does not include "stacked", sheet-like bodies. A long intersection of coarse-grained plagioclase-rich rocks in hole 92 was originally considered as a possible feeder system (to the massive leucogabbro ?) but it is intruded by ferrodioritic rocks, implying that it is an older anorthosite.

A different perspective is provided by a southwest–northeast section along the northwest edge of the lobe, through Taheke Lake (Figure 4h). The slightly undulatory geometry of the intrusion is seen, as is the presence of a depression beneath Taheke Lake. A thin cap of the massive leucogabbro is present locally, and the intrusion probably continues beneath high hills of gneisses and Nain Plutonic Suite rocks north of hole 93. However, it is not clear what happens northwest of Taheke Lake, as there is no thick intrusion in hole 111 (*see above discussion*). The black olivine gabbro forms a discrete lower unit in this region, which is thickest in hole 108. This unit may extend all the way to hole 97-63, where thin intervals of fine-grained gabbro containing 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.

Three drillholes in this area (97-93, 98-106 and 108) provide critical geological information. In holes 93 and 106 an upper fine-grained olivine gabbro is underlain by black

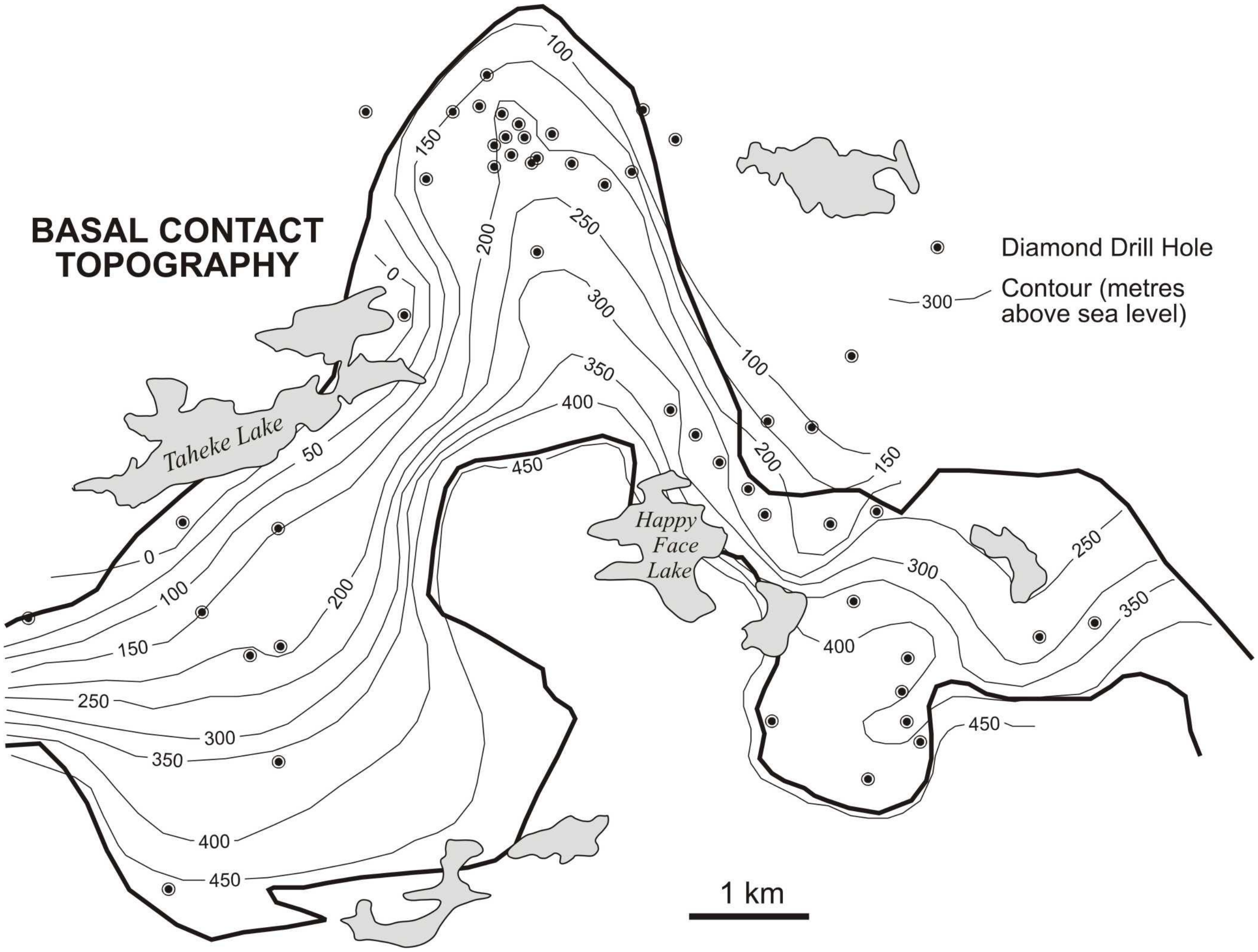


Figure 5. *A summary of the three-dimensional geometry of the North intrusion. (A) Isopachs showing the depth to the basal contact; within the outline of the body, these correspond to vertical thickness of the gabbro. Approximate extent of positive gravity anomaly is also indicated.* ***(B)*** *True structural contours (relative to sea level) on the basal contact of the intrusion, corresponding to a "topographic map" of the basal surface..*

olivine gabbro containing interstitial to poikilitic olivine, which becomes finer toward the base, and varies to a diabase-like rock. Contact relationships are fairly abrupt in hole 93, and imply that the black gabbro is younger (Fitzpatrick *et al.*, 1998), but the boundary is defined by a thick and heterogeneous composite unit in 106. In both cases, minor sulphides are present at the contact, within the lower black olivine gabbro unit. Hole 108 is similar, but also contains an upper massive leucogabbro section. The fine-grained, layered olivine gabbro in the central part of the hole is cut by leucogabbro veins containing (relatively) chilled margins. Similar relationships are also seen in hole 112 in the Happy Face lobe. Collectively, they imply that the black gabbro is indeed a discrete unit, which sits beneath or within the fine-grained unit, and has a close temporal relationship it. The coarse-grained, massive, leucogabbro sits above the fine-grained unit, and apparently intruded it as veins and sheets.

Overall Geometry

Contour maps of the depth to the basal surface of the intrusion and the topography of this surface provide a good illustration of the overall geometry of the North intrusion. Thickness contours (isopachs) correlate well with regional gravity surveys, which show an elongate "high" along the southeast side of Taheke Lake, extending into the centre of the NDT lobe (Figure 5a). Topographic contours on the basal contact show that it is more complex, and resembles an eroded hillside, with a central ridge running from the Happy Face area through the centre of the Taheke Lake lobe (Figure 5b). The area of intense drilling actually sits on the top of this "ridge", which apparently plunges northward. Another part of this topographic high protrudes toward Taheke Lake, and separates the NDT lobe from the remainder of the intrusion; near the northeast end of Taheke Lake, the dip of the basal surface must steepen to 25° or so. As discussed previously, there are many uncertainties in the area north and west of Taheke Lake, so no attempt has been made to portray the alternative interpretations implied by Figure 4g.

This pattern resembles a north-plunging fold that has a fold axis trending at about 150°, roughly parallel to the regional strike of the Churchill Province gneisses. However, there are clearly regional variations in the thickness of the intrusion, and its internal stratigraphy, which indicate that at least some of this geometry reflects original intrusive geometry, with possible superposition of regional tilting and uplift. For example, the "valley" that defines the NDT lobe may 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 origin of the fold-like pattern is more problematic, but it may reflect an originally sinuous feeder system, rather than an imposed geometry. The above discussion is speculative, and there are probably several configurations that can explain the known geometry of the North intrusion. Calibration of regional gravity data with the drillhole information, followed by modelling of various configurations, may provide a method to evaluate various options. The problematic area between holes 105 and 111 obviously has a bearing on this problem.

MINERALIZATION

Magmatic sulphide mineralization is associated with the basal intrusive contacts of the South intrusion, Mineral Hill intrusions and the North intrusion of the PLI. The mineralized sequences of the North and Mineral Hill intrusions are similar, but they are distinct from their counterpart in the South intrusion. This section reviews mineralization and several genetically associated silicate rock types. Mineralized rocks from several early (1996) drillholes were previously described in a thesis project by Hodder (1997).

SOUTH INTRUSION MINERALIZED SEQUENCE

The South intrusion mineralized sequence is presently mostly known from drillholes 97-79, 86 and 98-100 (Figure 3), which encountered mineralization in mafic and ultramafic cumulate rocks near the base of the intrusion. If the thin zone of mineralization at the top of hole 89 is included, the total potential area of this basal mineralization is large, and it may continue north of the Pants River valley (Figure 3).

Hole 97-79 intersected two discrete mafic–ultramafic intervals. The uppermost (about 28 m thick), contains less than 3 percent sulphides, which are clearly interstitial with respect to all silicates (Plate 6a). A lower interval, up to 50 m thick, contains more abundant (but still <10 percent) sulphide, with a similar interstitial habit. The heaviest sulphide concentrations (up to 50 percent) are at the base, associated with a more leucocratic gabbroic rock (Plate 6b). The sulphides are dominated by pyrrhotite, lesser chalcopyrite and rare visible pentlandite. The host rocks contain partially digested, blue–grey to white gneissic fragments, some of which show dark reaction rims (Plate 6a). The mineralized rocks apparently fade into a medium-grained, barren gabbro, which is chilled against the footwall gneisses. Hole 86 intersected a similar sequence, including almost 90 m of variably mineralized rocks, showing a distinct downhole increase in the amounts of sulphides and gneissic fragments. The mineralized rocks contain 0.1 to 0.55% Ni, and 0.1 to 0.32% Cu (Donner Minerals, Press Release, July 1998, November 17, 1998; Fitzpatrick *et al.*, 1998; Geological Survey data). Recalculation to 100 percent sulphide (*see* appendix) indicates that the sulphides contain from 0.7 to 4.0 % Ni, and 0.4 to 1.5% Cu (Figure 6). Values are highest in the upper section, typically 2.0 to 4.0% Ni and 0.7 to 1.4% Cu at 100 percent sulphide, but the amount of sulphides is low. The heavier basal mineralization is relatively

Plate 6. *Mineralized rocks from the South intrusion. (A) Melagabbro to peridotite containing minor interstitial sulphides and gneissic fragments, seen as white patches. (B) Gabbroic unit containing magmatic sulphide mineralization and showing well-developed interstitial sulphide textures.*

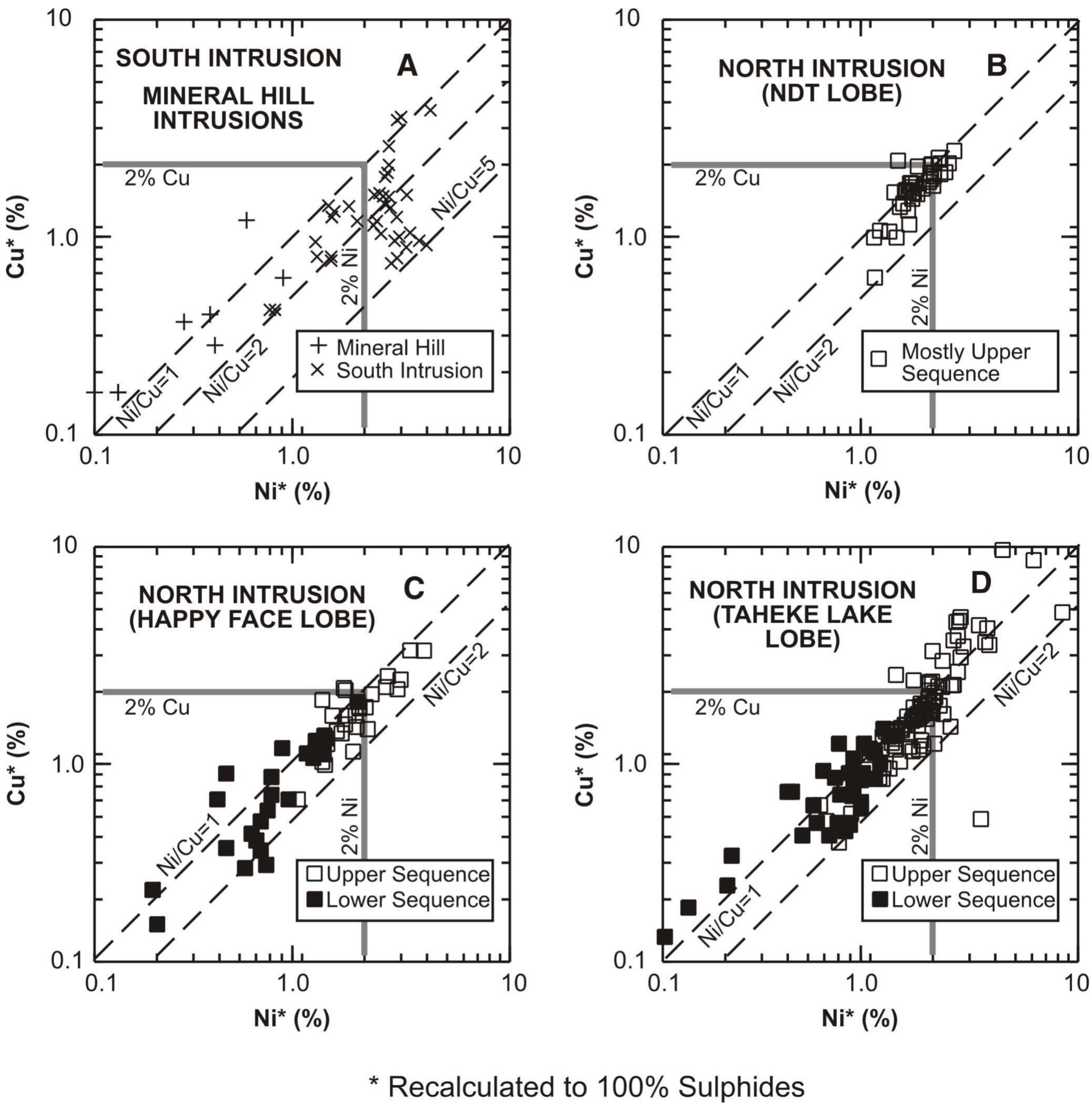


Figure 6. *Copper and nickel contents of sulphide mineralization in the Pants Lake intrusion. (A) South intrusion and Mineral Hill intrusions. (B) North intrusion, NDT lobe. (C) North intrusion, Happy Face lobe. (D) North intrusion, Taheke Lake lobe. All data are recalculated to 100 percent sulphides, and are mostly derived from samples with >2 wt% S. Calculation and correction methods are outlined in the Appendix.*

metal-poor, containing around 0.7% Ni and 0.4% Cu at 100 percent sulphide. Nickel–copper ratios range from slightly over 1.0 in lower grade areas to 2 or more in the upper interval. The South intrusion mineralization has higher Ni/Cu ratios than elsewhere in the PLI, where Ni/Cu is mostly slightly above 1.

The South intrusion mineralized sequence appears to be a gravitational accumulation, where sulphide droplets and gneissic fragments were concentrated by the same process as the cumulus olivine and pyroxene. Variations in tenor may represent changes in the bulk ratio of sulphide liquid to silicate magma ("R-factor"; Naldrett, 1989) as the magma chamber evolved. The basal contact of the South intrusion represents a large and poorly explored area (Figure 3), and its topography is not well known. The metal contents of the sulphides suggest that, if the sulphide liquid was able to accumulate in significant quantities in a suitable trap, the area could provide an attractive exploration target.

NORTH INTRUSION MINERALIZED SEQUENCE

Distribution and General Features

The North intrusion mineralized sequence is exposed in several areas along the southern boundary of the intrusion, and includes the NDT, Happy Face, GG Zone and Major General surface showings. The blind drilling target known as the Northern Abitibi area is another area of extensive mineralization (Figure 2). However, sulphides are not restricted to these localities, as they occur in at least some quantity in almost every drillhole that penetrates the basal contact of the intrusion.

The surface showings are not particularly informative, due to heavy gossan development. All are close to the basal contact of the intrusion. Gneisses below the contact contain local veins and patches of sulphides, but are otherwise unmineralized. The lowermost rocks of the PLI are similarly barren, or contain only very minor sulphide. The showings commonly contain an upper unit that weathers to egg-like or disk-like masses of unweathered rock, surrounded by a friable, recessive matrix. This is underlain by more homogeneous rocks that commonly contain disseminated sulphide. Locally, these have a "knobbly"-weathering texture where resistant nodules about 1 cm across are set in a recessive, sulphide-bearing matrix. In rare fresh samples, this is the "leopard gabbro", consisting of clinopyroxene crystals in mineralized matrix. The sulphide-bearing rocks are in some places overlain by unmineralized fine-grained gabbro, but most commonly lie just below massive, coarse-grained, leucogabbro, which is unmineralized.

Diamond-drill core provides the most useful information about original textures and geological relationships, and much of this section is based on core samples, as reported previously by Kerr (1998a, b). The mineralized sequences show subtle variations from lobe to lobe, and are described separately. However, they all contain the same rock types, which have a persistent stratigraphic arrangement. The upper part of the mineralized sequence is dominated by heterogeneous, breccia- like rocks collectively termed composite gabbro. This is underlain by more homogeneous rocks containing disseminated sulphides, "leopard-textured" gabbro, barren gabbro and (locally) semimassive to massive sulphides. Idealized "stratigraphic sections" through the mineralized sequence in the various parts of the North intrusion are illustrated in Figure 7, but individual sequences may not contain all of the indicated components. However, the two-part division into an upper heterogeneous zone and a lower homogeneous zone is a fundamental characteristic. Smith and Wilton (1998) introduced a more detailed subdivision, which suggested specific names for rock types that probably form part of compositional spectra. The current treatment retains the simpler terminology of Kerr (1998b), but the need for further subdivision is acknowledged.

Composite Gabbro: Petrology and Mineralogy

This simple term is used for a spectrum of rock types that form the upper part of the mineralized sequence (Plate 7a-d). Most variants clearly contain discrete inclusion and matrix components. The inclusions consist of a dark grey to green, fine-grained to aphanitic mafic rock, which forms aligned "bands" and lenses oriented subparallel to the basal contact of the intrusion, representing disk-like, ellipsoidal, inclusions having a strong alignment. The coarser matrix material is a 2 to 10 mm intergrowth of white plagioclase, clinopyroxene and olivine, associated with large clots of intergrown sulphide. Fine-grained sulphide is locally present within the mafic inclusions, but most is associated with the coarser matrix (Plate 7a), which accounts for its recessive weathering. The inclusions in some composite gabbros are "etched" by white, fine-grained, plagioclase rims (Plate 7c). Although inclusions most commonly are ellipsoidal to rounded, some composite gabbros contain angular examples, and the textures in these are more reminiscent of intrusive breccias. There are also variations from rocks with clear, sharp inclusion-matrix contacts to diffuse, blotchy rocks where fine and coarser grained domains appear almost gradational. The proportions of inclusions and matrix vary and composite gabbros can be either "clast-supported" or "matrix-supported" (Plate 7c,d). The relationships are usually clearer in the latter.

Most composite gabbros also contain rounded to amoeboid gneissic inclusions ranging from recognizable rock types (mostly granitoid gneiss) to diffuse grey or blue patches having dark reaction rims (Plate 7d). These are included within the coarser matrix, but also locally appear to be within the fine-grained domains, forming inclusions within inclusions. The amount of such debris varies widely, and in gneiss-rich examples, it becomes difficult to discern fragment-matrix relationships. Larger gneissic fragments locally contain vein-style sulphide mineralization (locally chalcopyrite-rich), which is distinct from the interstitial style of matrix sulphides. Lastly, composite gabbros may also contain exotic sulphide inclusions. These are difficult to verify, but rounded patches of high-grade, Cu-rich sulphide observed in composite gabbro containing pyrrhotite-rich mineralization in hole 97-70 (Plate 7b) are difficult to explain by any other process. This particular example is interpreted as a transported fragment of high-grade mineral-

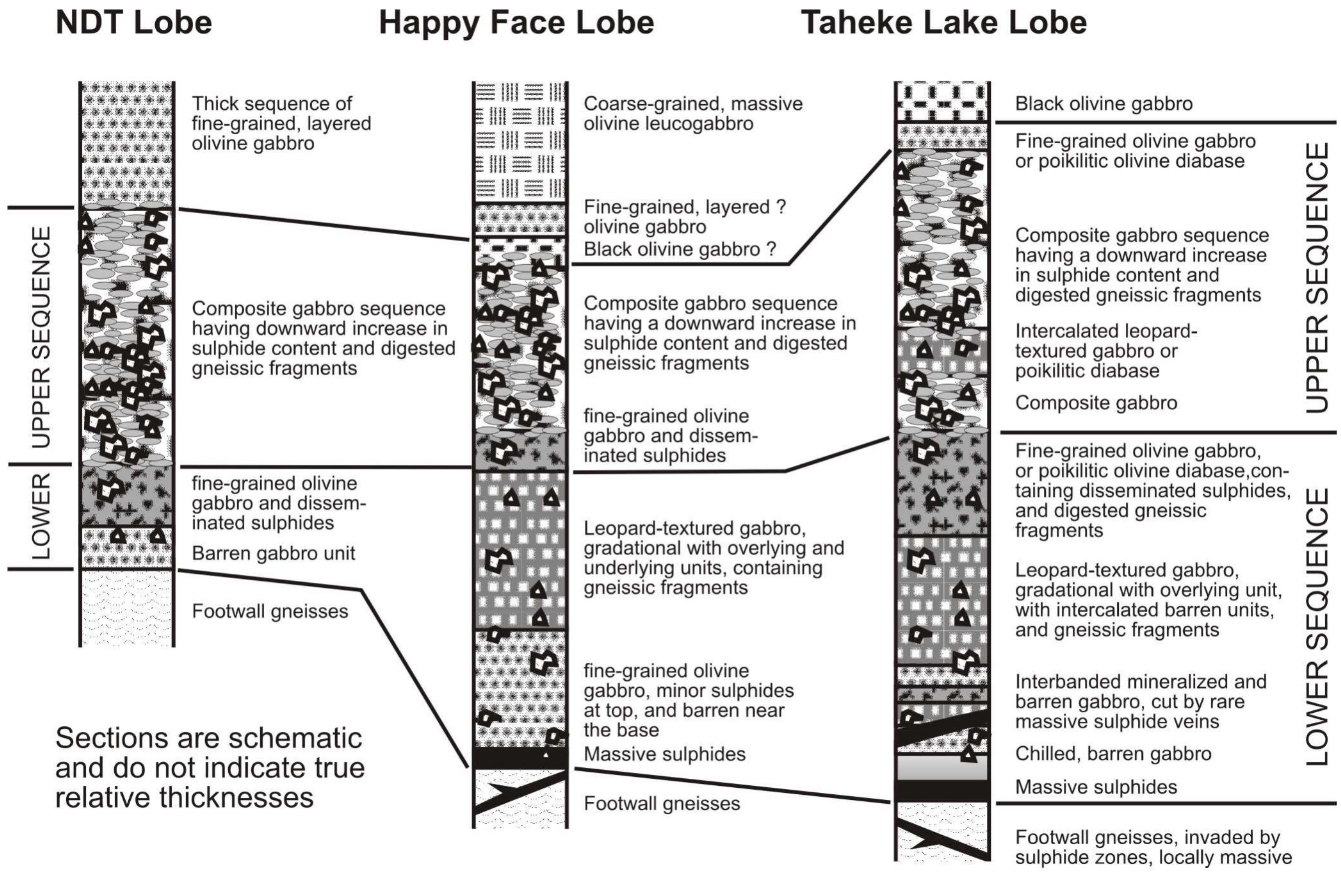


Figure 7. *Idealized stratigraphic sections through the mineralized sequence in various parts of the North intrusion. Note that not all of these components are present in a given section through the mineralized sequence. Diagram is schematic and does not convey true relative thicknesses within or between lobes.*

ization. Copper-rich veins in gneissic fragments likely came from the same type of source. A high-grade, Cu-rich clast was also noted in the thick sulphide intersection from hole 97-96 (K. Sparkes, personal communication, 1998).

Despite their complexity, composite gabbros have common petrographic features. The fine-grained inclusions commonly consist of a granular olivine-rich gabbro or troctolite, containing tiny rounded olivines and later lath-like plagioclase, with lesser late subophitic clinopyroxene (Plate 8a). These inclusions are texturally and mineralogically identical to the layered olivine gabbro unit, but finer grained. In addition to "granular troctolite", some also contain inclusions of a fine-grained diabase-like rock containing poikilitic clinopyroxene and olivine. More rarely, this is the dominant or only inclusion component (Plate 8b). One example from the NDT lobe contained inclusions of fine-grained norite, which has no known counterpart elsewhere in the PLI. The composite gabbro matrix consists of plagioclase, purplish clinopyroxene and grey–green olivine, with variable amounts of biotite, magnetite and sulphides. Its texture is closely similar to that of the massive leucogabbro and black olivine gabbro units, where olivine forms late subophitic to poikilitic crystals (Plate 8c). Sulphides are interstitial to all silicates, and commonly occur in the coarsest parts of the matrix (Plates 7 and 8). The textures of fine-grained "inclusions" and coarser-grained "matrix" are distinct, and their mutual boundaries range from sharp (often marked by a thin rind of fine-grained plagioclase) to fuzzy and gradational. Locally, coarse olivine in matrix is optically continuous with the olivine in inclusions with poikilitic textures.

Composite gabbros also contain gneissic material, which appears as clumps and clots of strained, metamorphic plagioclase. Larger gneiss fragments are dominated by strained, granular plagioclase, possibly associated with quartz and cordierite, surrounded by rims of dark green, granular, hercynitic spinel (Plate 8d). Locally, acicular corundum is present within plagioclase (or cordierite ?) and is visibly replaced by dark green spinel (Plates 8d and 9a). Digested foreign material is present even within samples that lack visible fragments, where scattered crystals of strained plagioclase are incorporated into the matrix igneous texture. Diffuse ring-like zones of dark green spinel represent the outlines of former gneissic fragments. Locally, all

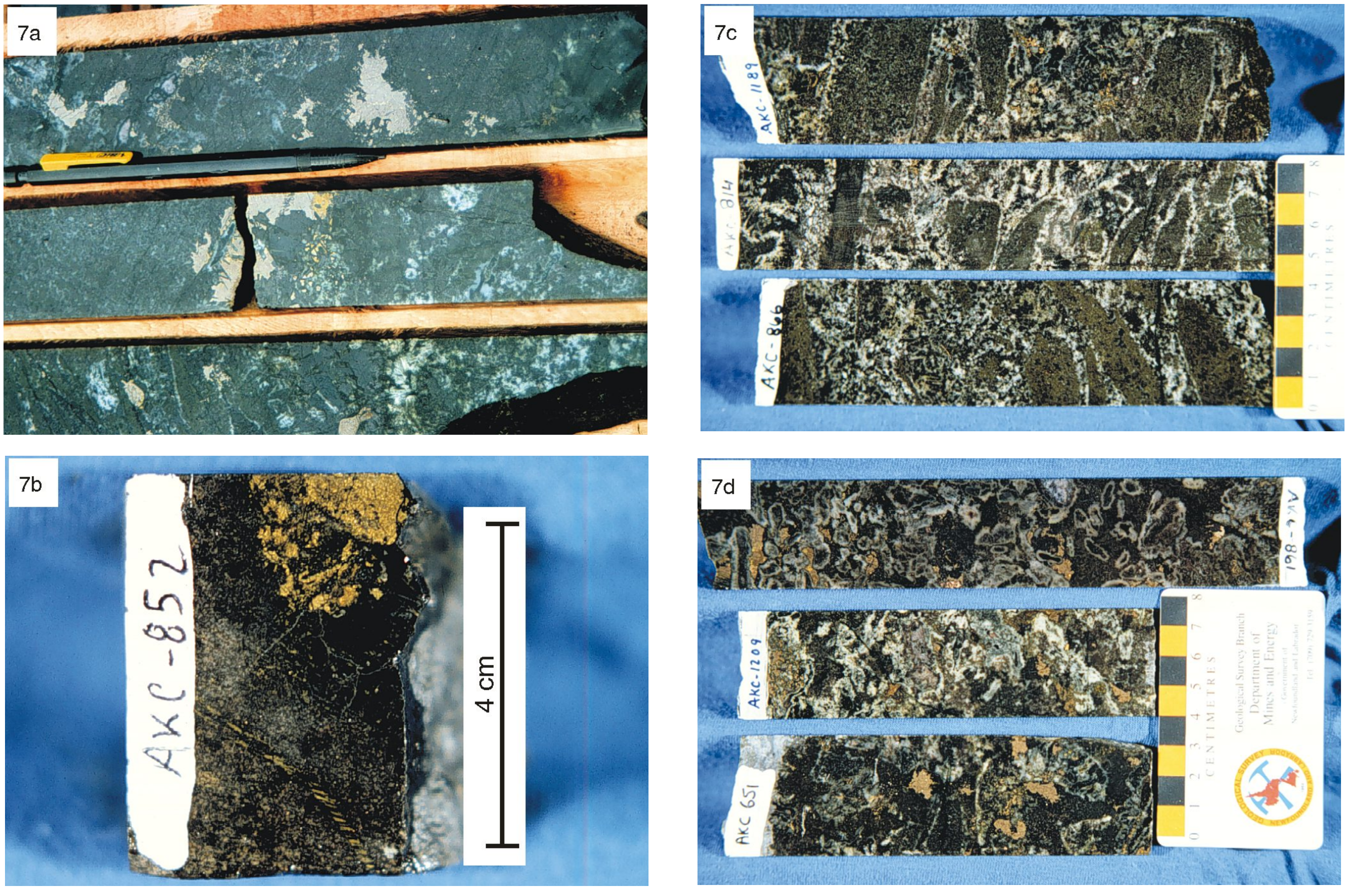


Plate 7. *Examples of composite gabbro from the North intrusion. (A) Typical example of sulphide-rich material in drill core from the NDT showing, illustrating very coarse patches of matrix sulphides. (B) "Exotic" sulphide clast (?) consisting of high-grade, Cu-rich sulphide and associated silicates, hole 97-70. (C) Examples of composite gabbro dominated by fine-grained mafic inclusions in coarse gabbroic matrix, typical of the upper part of the sequence. Upper core sample shows development of discrete zones rich in gneissic debris. Note white plagioclase rims developed on many mafic inclusions. (D) Examples of composite gabbro also containing abundant digested gneissic material and matrix sulphides, typical of the lower part of the sequence.*

igneous phases are riddled with anhedral spinel inclusions (Plate 9b). These unusual textures are regarded as the final stage in the assimilation process, where spinel restite is locally suspended in the magma (cf., Li *et al.*, 1996).

Leopard Gabbro and Related Rock Types

The composite gabbro is almost always underlain by more homogeneous fine- to medium-grained gabbroic rocks that contain disseminated sulphide mineralization. The "leopard gabbro" is the best-known example and is texturally equivalent to the "leopard troctolite" at Voisey's Bay (Naldrett *et al.*, 1996). The leopard gabbro is actually one variant of a range of gabbroic rocks containing disseminated, interstitial mineralization, and is gradational with these closely related rocks.

Leopard gabbro from the GG showing essentially consists of oikocrystic clinopyroxene set in a sulphide-bearing, troctolitic, groundmass (Kerr, 1998a). Examples from other areas fit this basic description, with some variations (Plate 10a). The leopard gabbro is texturally similar to the unmineralized, fine-grained, layered olivine gabbro, which locally shows a similar oikocrystic texture in the absence of sulphides. Sulphides are mostly confined to the groundmass as a late, interstitial phase, but larger patches also occur, which contrast texturally with the groundmass texture (Plate 10b). Some were earlier suggested to be exotic sulphide fragments (Kerr, 1998a), but they could also represent coalesced sulphide droplets. However, the bimodal size distribution is striking, and at least some larger sulphide clots are associated with coarse mafic silicates, including clinopyroxenes with orthopyroxene cores, unknown elsewhere in the PLI.

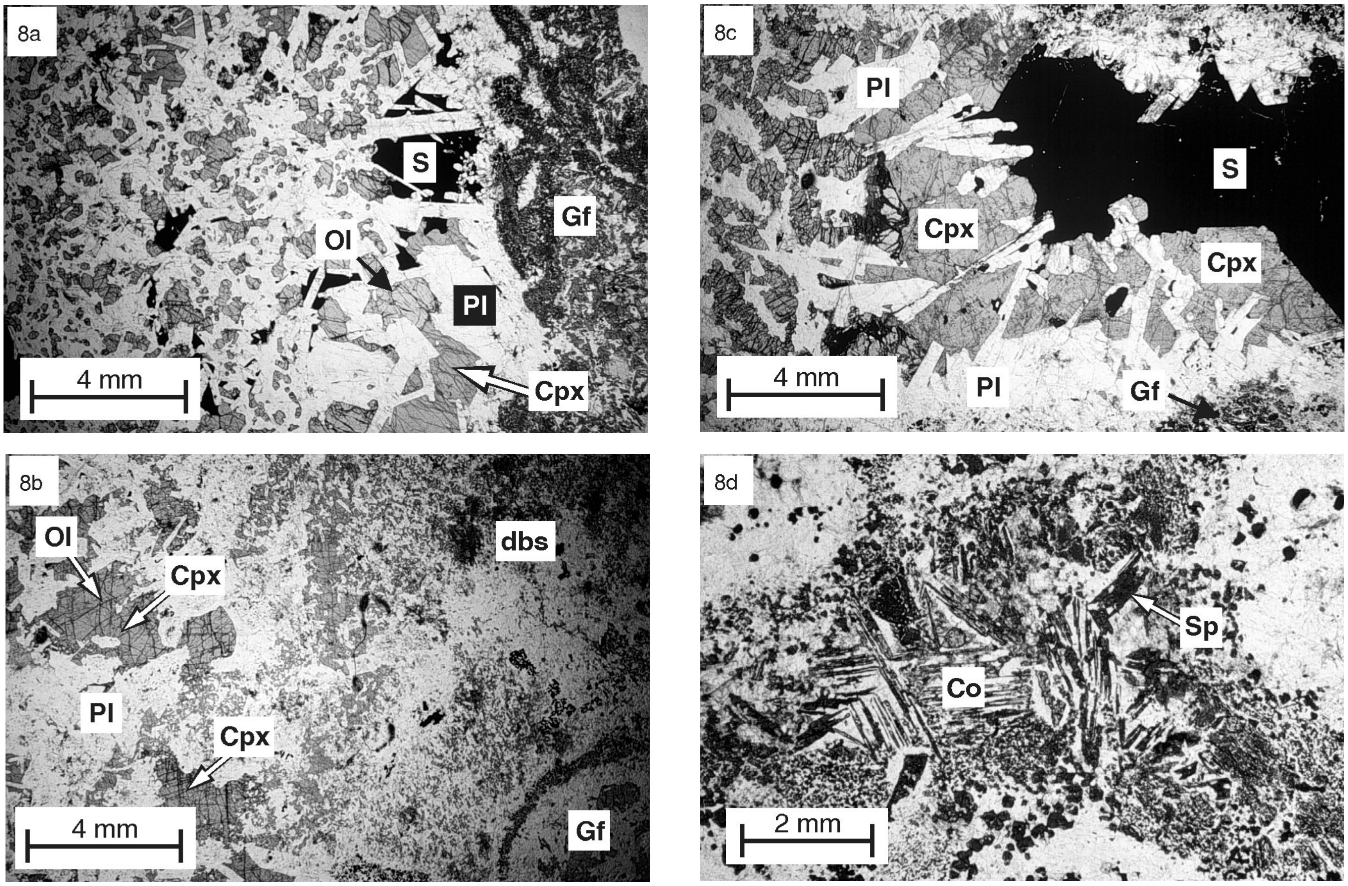


Plate 8. *Petrography of composite gabbro unit. (A) Heterogeneous sample showing three main components; from left to right, these are (i) fine-grained, granular, troctolitic gabbro inclusion, (ii) coarse-grained gabbroic matrix with sulphides and (iii) a metasomatized gneiss fragment containing abundant spinel. (B) Similar, heterogeneous rock, but here containing fine-grained diabase-like inclusions with poikilitic clinopyroxene. Rim of a gneissic fragment at lower right. (C) Coarse-grained matrix material showing interstitial olivine, clinopyroxene and sulphides. (D) Gneissic fragment, showing acicular corundum, reacting to form green spinel. Pseudohexagonal pattern may indicate that parent mineral was largely cordierite, rather than plagioclase. Ol – olivine, Pl – plagioclase, Cpx – clinopyroxene, S – sulphide, Sp – spinel, Co – corundum, Gf – gneiss fragment, dbs = diabase inclusion. All photos are in PPL (plane-polarized light).*

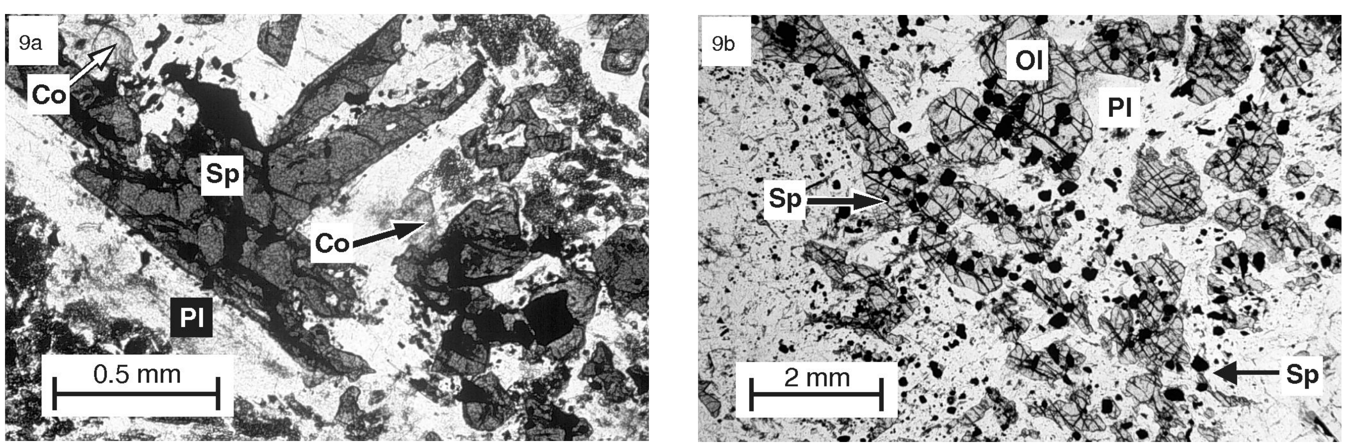


Plate 9. *Reaction textures in gneissic inclusions. (A) Coarse green spinel and associated corundum in the central region of a gneissic fragment. (B) Granular spinel inclusions, seen as tiny dark patches, contained within plagioclase and olivine crystals in composite gabbro matrix. These textures suggest complete disaggregation of restite from assimilated gneisses. Ol – olivine, Pl – plagioclase, Cpx – clinopyroxene, Sp – spinel, Co – corundum. All photos are in PPL (plane-polarized light).*

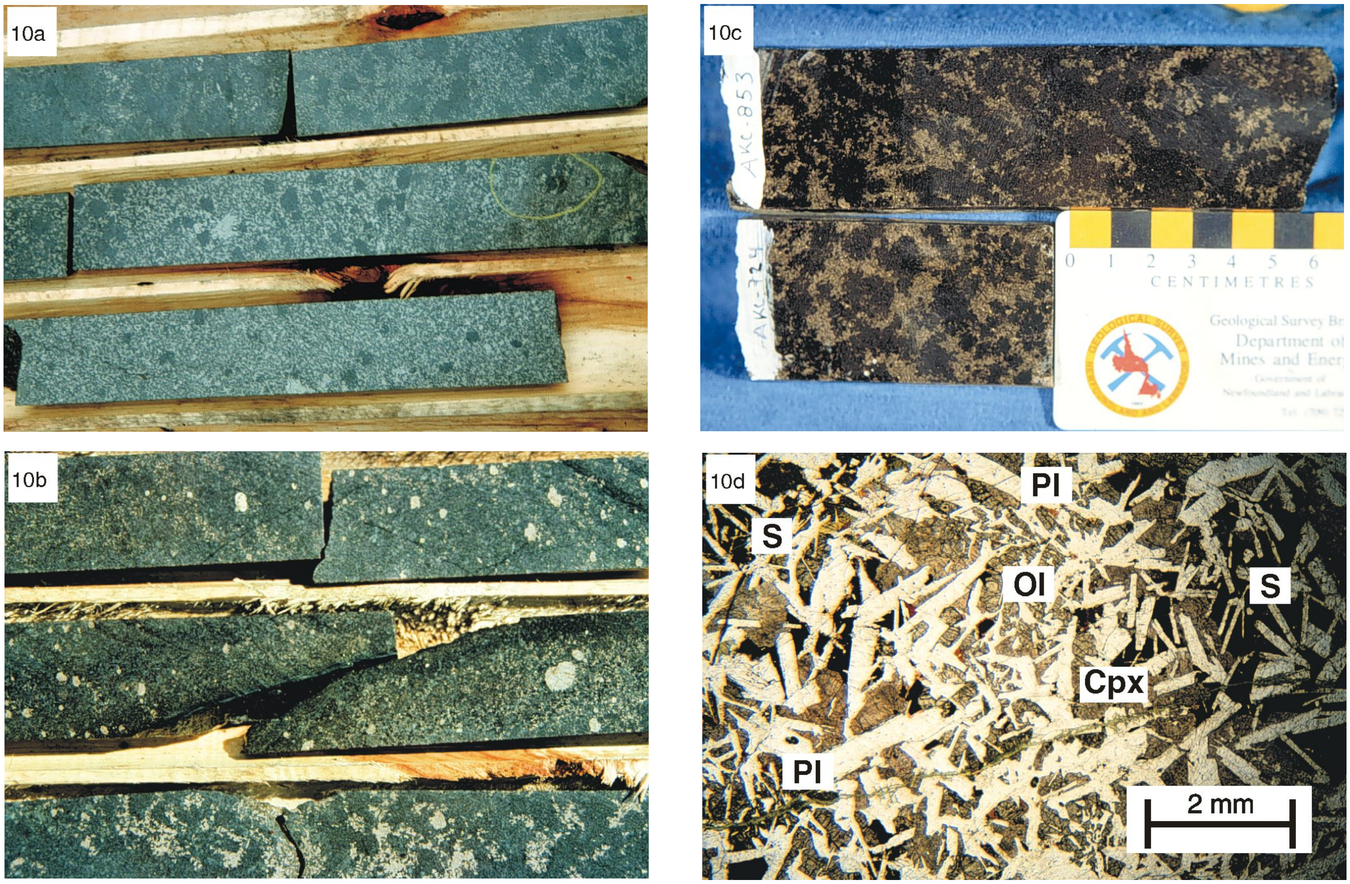


Plate 10. *Examples of more homogeneous mafic rocks from the mineralized sequence of the North intrusion. (A) From top to bottom of photo, a downhole progression from essentially barren gabbro to leopard gabbro, and to semimassive sulphide containing clinopyroxene crystals, hole 98-103. This indicates gravitational sulphide accumulation. (B) Contrasting habits of sulphide mineralization, hole 98-112; note bimodal pattern of very fine-grained interstitial sulphide, and larger, rounded sulphide patches. (C) Drill-core examples of mineralized poikilitic diabase, holes 97-67 and 97-70. (D) Petrography of mineralized poikilitic diabase; note that olivine, clinopyroxene and sulphide all form poikilitic crystals. Ol – olivine, Pl – plagioclase, Cpx – clinopyroxene, S – sulphide. Photo in PPL (plane- polarized light).*

Most leopard gabbros contain gneissic fragments, which resemble those in the overlying composite gabbro, and have reaction rims of granular hercynitic spinel. These ring-like patterns resemble features described in texturally similar rocks at Voisey's Bay (Li *et al.,* 1996). Clots of metamorphic plagioclase and anhedral spinel inclusions in all igneous minerals 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 composite sequence, except close to their mutual boundary, where it may be high.

The leopard gabbro is gradational with other fine-grained gabbros containing dispersed sulphide. Some also contain clinopyroxene oikocrysts, but lack sufficient sulphide to delineate them, but others contain only interstitial clinopyroxene, and are texturally identical to typical fine-grained olivine gabbro. In several drillholes, these rocks are interlayered with typical leopard gabbro, which seems to have formed by gravitational accumulation of sulphides (Plate 10a). Hole 98-103 from the Northern Abitibi area contains at least two "cyclic" units that progress downward from virtually barren gabbro, into disseminated sulphide, incipient leopard texture, and true leopard gabbro. One such unit eventually grades down into semimassive sulphides containing clinopyroxene oikocrysts, that represents an "ultimate" leopard-texture. These features, and the general homogeneity of the rocks, suggest that the lower part of the mineralized sequence represents a relatively "quiet" magmatic environment compared to the upper part.

The more homogeneous mineralized rocks also locally include recognizable fragments of other rock types that were previously mineralized. Hole 96-43 at the GG zone contains xenoliths of coarse-grained clinopyroxene monzonite with interstitial granophyre, which contains invasive magmatic sulphide veins, clearly truncated by the surrounding fine-grained gabbro. The xenoliths do not correspond to any known PLI rock, and are interpreted as older Mesoproterozoic igneous rocks that hosted footwall-style mineralization at some other location prior to becoming entrained in the host magma.

Mineralized Poikilitic Olivine Diabase

The lower part of the mineralized sequence locally also includes another fine-grained, mineralized rock type which is distinct from leopard gabbro (Plate 10c). This has a striking diabase-like texture, in which plagioclase laths are enclosed by a network of larger, poikilitic olivine and clinopyroxene crystals. The plagioclase is typically dark in drill core and contains oxide inclusions. Sulphide mineralization is also interstitial and late, and locally forms poikilitic crystals that include plagioclase (Plate 10d). This may have a textural equivalent in fine-grained, diabase-like inclusions seen in some composite gabbros, but it is also texturally akin to the composite gabbro matrix. It contains scattered digested gneissic inclusions with the usual corundum-spinel reaction products. In drill core, well-preserved examples having lesser amounts of sulphide resemble fine-grained versions of the black olivine gabbro unit. It is very difficult to distinguish from one fine-grained, dark mafic rock from another, and the distribution of this rock type within the mineralized sequences remains poorly known.

Barren Olivine Gabbro

The mineralized rocks described above commonly pass down gradationally into a fine-grained, sulphide-free gabbro. Most examples are texturally identical to the fine-grained, layered olivine gabbro. Chilled versions adjacent to the footwall contact show diabase-like textures and ophitic clinopyroxene, which reflect rapid cooling.

Massive Sulphide

Massive sulphide horizons, where present, are located close to the footwall gneiss contact, and at least some are probably located below its original position, as they contain gneissic inclusions, xenocrystic quartz, and graphite. Relationships between massive sulphides and spatially associated mineralized gabbros are ambiguous. Thin massive sulphide veins cut leopard gabbro and associated rock types, and massive sulphides at the footwall contact are locally isolated from the overlying mineralized sequence by chilled, barren gabbro. Vein-style massive sulphides also commonly cut the gneisses below the footwall contact. These relationships imply that sulphide liquids remained mobile after solidification of the overlying rocks, and have migrated along the footwall contact region. However, hole 97-67 contains a massive sulphide zone with an unusual upper contact against gabbro that may be a two-liquid boundary, as round blobs of sulphide are present in the overlying gabbro and vice-versa (Plate 11a). High-grade sulphide zones, such as the famous hole 75 intersection (11.7% Ni and 9.7% Cu) are mostly known from the footwall region, and small zones of this type are particularly common in the Northern Abitibi area (Plate 11c). Hole 98-131, however, contained massive sulphides with 4.5% Ni and 2.6% Cu at the basal contact of the gabbro.

Massive sulphides display considerable textural variation. Some are coarse-grained, "clean" sulphides consisting of pyrrhotite, chalcopyrite and pentlandite, which locally show "loop textures" (i.e., rings of pentlandite around pyrrhotite crystals) akin to those described from the Eastern Deeps deposit at Voisey's Bay (Naldrett *et al.,* 1996). High-grade footwall sulphide veins have a coarse crystalline texture reminiscent of Voisey's Bay material (Plate 11c), which is also seen in the hole 131 intersection. Lower grade, pyrrhotite-dominated massive sulphides tend to be finer grained and "dirty" having variable grain sizes, texture, abundant silicate inclusions, quartz grains and graphitic patches (Plate 11b). These have either assimilated country rocks through thermal erosion, or are actually partially derived by melting and mobilization of primary sulphides from the metasedimentary gneisses. The sulphide mineral assemblages are also consistent with generation from such a source (A.J. Naldrett, personal communication, 1998; and unpublished consultant reports).

Footwall Gneisses

It is commonly difficult to position the basal contact of the North intrusion precisely, especially if massive sulphides are present. The underlying gneisses have not yet been examined in any detail. The most common rock type is a coarse-grained garnetiferous orthogneiss, which underwent contact metamorphism and reaction for 25 to 50 m below the basal contact. Garnet has been transformed to grey cordierite and/or orthopyroxene pseudomorphs, but is progressively better preserved at depth. A peculiar texture, in which grain boundaries are "etched" by fine-grained biotite and/or amphibole aggregates, is also spatially associated with the contact region. Invasive, vein-style sulphide mineralization is also common in the immediate footwall region. Kerr (1998a) also reported the presence of hercynitic spinel and corundum, which are characteristic of the more digested inclusions seen in the mineralized sequence. The footwall rocks likely 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. They also provide a possible method of evaluating the emplacement depth of the PLI through study of contact metamorphic assemblages.

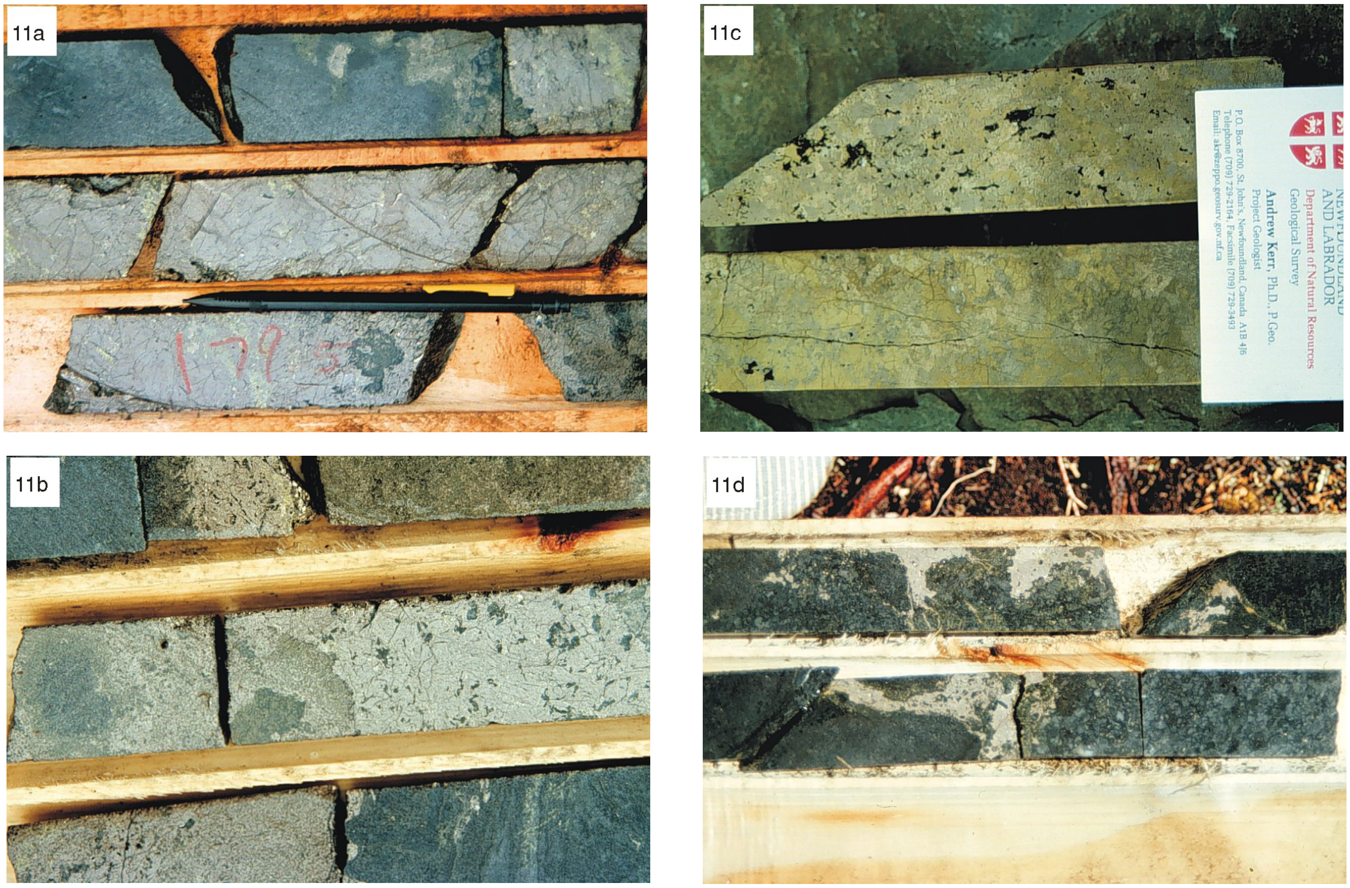


Plate 11. *Examples of massive sulphide intersections from the Taheke Lake lobe of the North intrusion. (A) contact of fine-grained gabbro and massive sulphide zone, hole 97-67. Note the rounded inclusions of sulphide in gabbro, and gabbro in sulphide, which may indicate a two-liquid interface. (B) Heterogeneous massive sulphides, hole 98-101, littered with gneissic debris, and showing contrasts in grain size and texture. Footwall paragneiss at lower right, gabbro at upper left. (C) High-grade massive sulphides (up to 11.8% Ni, 9.7% Cu) from footwall vein in hole 97-75, showing coarse crystalline texture. (D) Sulphide veins invading chilled barren gabbro and footwall gneisses, adjacent to the basal contact of the gabbro, hole 98-109.*

NDT Lobe Mineralized Sequence

The mineralized sequence in the NDT lobe 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 4). Hole 96-04, drilled west of the showings, encountered about 30 m of spectacular composite gabbro, sitting beneath a medium-grained olivine gabbro or troctolite containing cumulus olivine. Gneissic fragments and derived restite become more abundant toward the base, and fine-grained diabase inclusions accompany the dominant granular troctolite. The composite sequence is underlain by only a few metres of homogeneous fine-grained gabbro containing disseminated sulphide. In hole 77, almost 300 m of fine-grained, layered olivine gabbro sits between the base of the massive leucogabbro and the top of mineralized rocks (Figure 4). The lowermost 20 m of the fine-grained unit is a complex mixed zone, including heterogeneous inclusion-rich sections that resemble composite gabbro, albeit without sulphides. Locally, the coarse-grained material appears to be included in finer grained material, which is the reverse of the normal relationship. The main part of the mineralized sequence is dominated by composite gabbro, but this has an unusual "stoped" texture, where inclusions are subangular, but remain strongly aligned. This is underlain by only 1 to 2 m of fine-grained, sulphide-bearing gabbro. Other holes in the NDT lobe display a similar pattern of a relatively thick composite sequence, underlain by a thin zone of homogeneous fine-grained gabbro. In general, the amount of sulphide in the mineralized sequence is low (2 to 7 percent), and massive sulphides are essentially absent. The NDT mineralized sequence has low absolute Ni and Cu contents (< 0.30% combined) reflecting the low sulphide abundance. Nickel contents at 100 percent sulphide are consistent at 1.5 to 2.0% Ni, commonly with equivalent or marginally lower Cu contents (Figure 6).

Happy Face Lobe Mineralized Sequence

In the Happy Face lobe, the North intrusion is a thin sheet dominated by massive leucogabbro, and the mineralized sequence commonly sits just below the base of this upper unit, with no significant intervening thickness of fine-grained gabbro (Figure 4). The mineralized sequence contains the standard pattern of an upper composite gabbro section underlain by more homogeneous rocks. Gneissic fragments are particularly abundant at the base of the composite gabbro section. The lower homogeneous zone is thick (20 m true thickness at the GG showing) and locally shows well-developed leopard texture. A weakly mineralized to barren lower zone is also well developed at the GG showing. Other examples of the mineralized sequence from the Major General and Happy Face showings are similar, but the lower zone of homogeneous rocks is thinner. East of the showing, it is locally absent, and composite gabbro sits directly on gneisses. Composite gabbros at the Major General showing (e.g., hole 96-20) include both granular troctolite and poikilitic diabase inclusions. Two holes that contain the black olivine gabbro unit are of particular interest. In hole 112, medium-grained black olivine gabbro seems to pass directly into composite gabbro, underlain by 5 m of homogeneous gabbro with disseminated sulphide. A similar sequence is seen in hole 80, where the sulphides appear to be pentlandite-rich compared to most other areas. In both holes, the black olivine gabbro appears to sit beneath typical fine-grained, layered olivine gabbro, and the mineralized sequence is isolated from the upper massive leucogabbro.

Absolute grades 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. The higher absolute grades represent rocks having a wide range of sulphide contents, from around 20 to 75 percent or more. When recalculated to 100 percent sulphide (*see* appendix), the samples resolve into two overlapping groups (Figure 6), and the highest metal values come from composite gabbro samples in the upper part of the sequence, where sulphides locally contain up to 3.9% Ni and 3.1% Cu (in hole 97-80). The Leopard gabbro and similar rocks in the lower part of the mineralized sequence show 0.6 to 1.8% Ni and 0.5 to 1.4% Cu at 100 percent sulphide, with the best values at the GG zone itself. The contrast in tenor through the mineralized sequence appears to be independent of sulphide content, i.e., samples with similar sulphide contents show contrasting tenors. A general tendency for samples with small amounts of disseminated sulphide to show higher metal contents than samples with higher sulphide contents has been noted in other studies (e.g., Barnes *et al.*, 1996) but this does not seem to be the only factor at work here.

Taheke Lake Lobe Mineralized Sequences

In the Taheke Lake lobe, the mineralized sequence sits at or just below the base of the black olivine gabbro unit, which occurs at surface in the east, but sits beneath fine-grained, layered olivine gabbro in the west (Figure 4). There are marked variations in the thickness of the mineralized sequence in this area, and it is thickest in hole 97-70, where nearby drillholes indicate a progressive thickening to the northeast.

The mineralized sequence shows the familiar division into an upper section dominated by composite gabbro, underlain by more homogeneous gabbros containing disseminated sulphide, which are locally leopard textured (Figure 7). In general, the composite section is thicker than the more homogeneous zone, with almost 50 m of composite gabbro in hole 70. In hole 97-67, fine-grained gabbro containing granular, cumulus olivine sits between the base of the black olivine gabbro and the top of the composite gabbro, but the underlying homogeneous section includes mineralized poikilitic olivine diabase that is texturally similar to black olivine gabbro and composite gabbro matrix. Some other holes in this area show a similar pattern, but elsewhere the black gabbro passes directly into composite gabbro, and in one example it passes straight down into poikilitic olivine diabase with interstitial sulphide. The composite gabbro section shows a marked downhole increase in gneissic debris, and possibly also in sulphide content. The more homogeneous gabbros beneath the composite section show gravitational sulphide accumulation in the development of leopard gabbro (e.g., hole 97-103, *see* above discussion, also Plate 10a). The transition from composite to homogeneous sequences locally shows "interbedding" of the two rock types, suggesting that there must be 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, invade chilled basal gabbro and overlying leopard gabbro.

The Taheke Lake lobe shows the greatest variations in absolute metal grades, which range up to 11.8% Ni, 9.7% Cu and 0.43% Co in the famous hole 75 intersection. The highest absolute grades that can be spatially linked to the mineralized sequence are 4.5% Ni and 2.6% Cu in a thin zone from hole 98-131, which contains only about 60 percent sulphides, indicating sulphide metal contents of 8.7% Ni and 5% Cu (Donner Minerals, Press Release, November 17, 1998). Most of the disseminated mineralization contains 1.5 to 2.0% Ni and 1.2 to 1.8% Cu at 100 percent sulphides (Figure 6). The data from the Taheke Lake lobe also illustrate grade contrasts within the mineralized sequence. Samples from the more homogeneous lower section have lower Ni and Cu contents at 100 percent sulphide, but this pattern is far from universal. Anomalously high metal contents, from 2.7 to 6% Ni and 3.3 to 8.5% Cu at 100 percent sulphide, occur in the lower part of the thick mineralized sequence in hole 70. Although high-grade sulphide fragments were observed in one part of this interval, their frequency does not seem high enough to fully explain this result, or the tendency for low Ni/Cu ratios in part of this hole.

MINERAL HILL MINERALIZED SEQUENCES

The Mineral Hill area has seen only limited exploration since 1996, and its mineralized sequence is not well documented. Most of the drillholes examined to date (including 96-36, described previously by Kerr, 1998a) are dominated by relatively homogeneous, fine- to medium-grained gabbro containing evenly dispersed magmatic sulphide. These mineralized rocks resemble the fine-grained gabbro in the north intrusion, and contain euhedral to granular cumulus olivine. Clinopyroxene oikocrysts, and typical leopard texture, are developed sporadically. The mineralized gabbros also contain scattered gneissic fragments, which exhibit the green spinel rims seen in the north. Locally, spinel forms inclusions in all igneous phases, and strained metamorphic plagioclase masquerades as an igneous phase. However, despite this evidence for contamination, none of these rocks show the extreme complexity of composite gabbros seen in the north. However, holes 96-45, 48 and 49 are described as containing heterogeneous rocks with fine- and coarse-grained domains, containing sulphides, that sit above the main mineralized zone. These zones are relatively thin, and were not sampled, but they are probably similar to the composite gabbro sequence present in the north.

Despite their fairly high sulphide contents, locally > 20 percent, mineralized samples from these zones have low grades, typically less than 0.3% combined Ni and Cu. Recalculation of disseminated mineralization indicates low tenors of 0.2 to 0.8% Ni and 0.1 to 0.6% Cu (Figure 6), but the amount of data is small. Minor sulphide intersections in the upper sections of holes 79 and 94 (South intrusion; *see* Figure 3) show similarly low values, as does a sulphide zone in one of the "stacked" sheets in hole 110. Overall, these grades resemble those obtained from the lower part of the mineralized sequence in some parts of the North intrusion. The tenor of sulphides in any composite sequence at Mineral Hill is presently unknown.

GEOCHEMICAL CHARACTERISTICS OF SULPHIDE MINERALIZATION

The mineralization in the PLI shows a marked geochemical coherency. Both disseminated and more massive sulphide mineralization from the PLI North intrusion shows consistent Ni/Cu ratios of slightly greater than 1, and high correlation of Ni and Cu (Figure 8 left). Some high-grade sulphide intersections (notably hole 75) also lie on this trend, but others are anomalously rich in either Ni or Cu, suggesting that a fractionation process was involved in their generation. The South intrusion mineralized sequence shows distinctly higher Ni/Cu, commonly >2.0, aside from material at its very base (Figure 6). Mineralization from Voisey's Bay itself mostly shows Ni/Cu ratios >2.0, in the same range as the South intrusion (Figure 8 right). However, massive sulphides at the Voisey's Bay deposit commonly contain 4% Ni or more, which is higher than most calculated sulphide metal contents from PLI mineralization (Figure 6). The PLI mineralization also shows low Ni/Co ratios (average 8 to 9) and, for a given Ni content, the sulphides contain significantly more Co than at Voisey's Bay. Nickel/cobalt ratios for the Reid Brook Zone are closest to those from PLI mineralization. The South intrusion mineralized sequence also maintains a fairly low Ni/Co ratio. Comparisons of Co data at 100 percent sulphides have not been attempted, as these are sensitive to assumptions about correction factors for silicate material; however, the empirical data from massive sulphide zones in the PLI implies values in the 0.2 to 0.3 percent range. Higher Co values can result from enrichment of Co in the source magma, or from lower R-factors during sulphide segregation because the sulphide/magma partition coefficients for Co are less than those for Ni and Cu (Naldrett, 1989).

SUMMARY AND DISCUSSION

The final section of the report is intended to highlight some of the points that emerge from the work conducted to date, and also to provide a general evaluation of some of the parallels and divergences between the study area and Voisey's Bay itself. These are of necessity preliminary, as detailed accounts of the Voisey's Bay area are only now entering the publication stage. The discussion here is not intended to provide a full and exhaustive treatment, but to provide a starting point for more detailed studies.

PETROLOGY AND COMPOSITION OF THE PANTS LAKE INTRUSION

The PLI consists dominantly of olivine gabbro, although it does include some troctolites. However, these are uncommon, and more homogeneous examples are probably cumulate rocks related to the layered olivine gabbro. Also, many of the fine-grained mafic inclusions observed in composite gabbro consist of granular troctolite and olivine-rich gabbro. The most primitive and magnesian member of the PLI is the fine-grained, layered, olivine gabbro. The massive leucogabbro and black olivine gabbro units are gen-

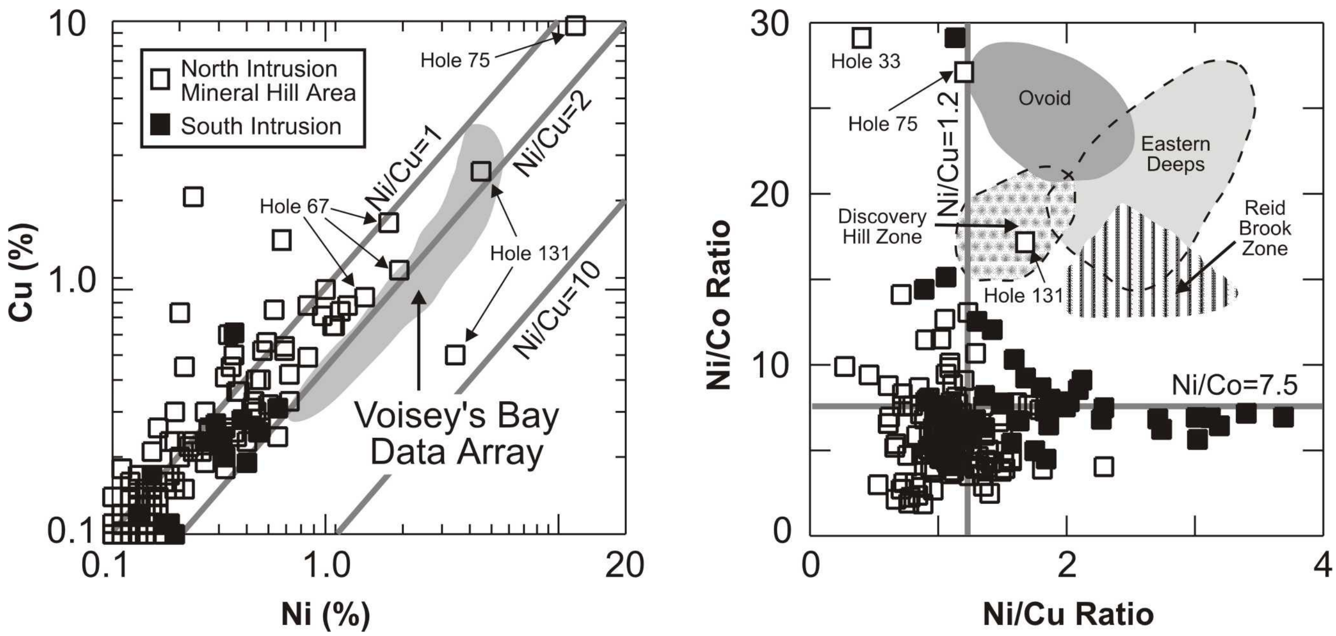


Figure 8. *Nickel–copper–cobalt relationships in the PLI mineralization, compared to the Voisey's Bay area. (Left) Cu–Ni plot. (Right) Ni/Co–Ni/Cu plot. Both diagrams use absolute Ni, Cu and Co contents, not the 100 percent sulphide values employed in Figure 6. Fields for Voisey's Bay data are derived from assay results from Diamond Fields Resources and Voisey's Bay Nickel Company press releases, from 1995 to 1998, and may not be fully representative of their characteristics, especially for the Reid Brook zone.*

erally more pyroxene-rich, and contain olivine of late, interstitial to poikilitic type, which contrasts with the granular olivine of the fine-grained layered unit.

All units of the PLI represent relatively primitive, unevolved mafic rocks in comparison to the leucocratic norite and anorthosite that predominates amongst Mesoproterozoic suites in Labrador. Its general features invite comparison with the "troctolitic" rocks of the Voisey's Bay district, and it is similar to the northern part of the Reid Brook intrusion (now known as the Mushua intrusion), which consists of an early layered unit and a later, massive leucocratic unit, dated at 1317 and 1313 Ma respectively (Amelin *et al.,* 1997, 1998). Mineralization at Voisey's Bay is linked to a slightly older 1333 Ma unit (the Voisey's Bay intrusion), which consists mostly of more massive troctolites. Most of the mafic rocks in the Voisey's Bay area contain variable amounts of clinopyroxene, and many are olivine gabbro if classified strictly. Distinctions between "troctolite" and "olivine gabbro" intrusions are probably not significant and, at least in terms of major-element geochemistry, the PLI certainly resembles some of the Voisey's Bay area troctolitic rocks (Emslie, 1996; A. Kerr, B. Ryan, unpublished data). Geochronological data, as referenced earlier, indicate that the PLI was emplaced during the same time interval.

REGIONAL SETTING OF THE PLI

The PLI was emplaced in a static environment into dominantly metasedimentary gneisses of the Churchill Province, which locally carry significant primary sulphide and graphite. The lithological assemblage is similar to the Tasiuyak gneiss farther north (Figure 1), but is less strongly mylonitized. The Tasiuyak gneiss surrounds some of the Voisey's Bay deposits, and has been implicated as a source of sulphur in the ores and of gneissic fragments seen in host troctolites (e.g., Naldrett *et al.,* 1996). Stable isotope data are ambiguous, but certainly permit a significant contribution of sulphur from the Tasiuyak gneiss (Ripley *et al.,* 1997, 1998). The presence of similar sulphide-bearing gneisses in the environment of the PLI implies that a crustal source of sulphur (if needed) is readily available. A contamination signature attributed to the effects of the Tasiuyak gneiss is also one of the principal isotopic characteristics of the Voisey's Bay intrusion, compared to the Mushua intrusion (Amelin *et al.,* 1998), and may therefore be an important factor in ore genesis. Although equivalent data are not yet available for the PLI, there is certainly field and petrographic evidence for such contamination.

The mafic magmas that host the Voisey's Bay deposits are considered to have ascended through structures related to the Nain Province–Churchill Province boundary, which is depicted as passing through the deposit area (Ryan *et al.*, 1995; Naldrett *et al.*, 1996). In the area of the PLI, the equivalent boundary lies 10 to 20 km to the east. However, it is far from clear that the true Nain Province–Churchill Province boundary lies at Voisey's Bay, as some of the "Nain gneisses" in this area could be Archean basement of the Churchill Province (Ryan, 1996, personal communication, 1998). Prevailing models for the genesis of magmatic sulphide deposits, which emphasize the importance of an external sulphur source, imply that it is more important to be on the correct side of the Nain–Churchill boundary than right on top of it.

GEOMETRY, SIZE AND EROSION LEVEL OF THE PLI

Component bodies of the PLI are flat-lying or inclined sheet-like intrusions, but their dimensions vary considerably. The South intrusion is a slab-like, chamber over 500 m thick, and the North intrusion is also locally more than 400 m thick. Both represent significant volumes of mafic magma, and thus significant potential sources for Ni and Cu. The geometry of the North intrusion is complex, and far from fully resolved, but it is clear that the intrusion includes significant subsurface extensions. Other parts of the PLI represent fairly small bodies, with true thicknesses less than 200 m, and locally less than 100 m, but they must be connected in some way to the larger bodies, as they contain essentially identical rock types and mineralization.

The combination of an original sheet-like geometry and erosion means that there are large areas, particularly in the north, where basal contacts lie at or close to the erosion surface. This resembles Voisey's Bay, where the basal contacts of the Mushua and Voisey's Bay intrusions are similarly exposed, but the total surface and shallow subsurface extent of basal contact regions is much more extensive in the PLI. This is an important indicator of potential, because most magmatic Ni–Cu deposits are associated with the basal regions of genetically associated intrusions (Naldrett, 1989). The original dimensions of PLI intrusions are fairly well constrained, because their roof zones are exposed and penetrated by drilling. In the case of Voisey's Bay, the original dimensions of the intrusion(s) are totally unknown, and could conceivably have been much larger, perhaps on the scale of the Kiglapait intrusion (Figure 1). A second difference is that steeply inclined to vertical feeder conduit systems have not yet been identified in the PLI. Conduit systems of this type, however, could occur in many areas beneath the North and South intrusions, and would be extremely difficult to detect by vertical drilling. As discussed above, there is a possible candidate for a low-angle feeder system northwest of Taheke Lake (hole 98-111; P. Moore and K. Sparkes, personal communication, 1998). The identification of feeder systems is likely to be important, because all significant mineralization at Voisey's Bay appears to be within, or linked to, discrete feeder structures (Naldrett *et al.*, 1996; Evans-Lamswood *et al.*, 1998).

CONTAMINATION OF THE PLI BY METASEDIMENTARY GNEISSES

Most of the PLI consists of homogeneous gabbro, which generally lacks inclusions or xenoliths of country rock. Preliminary analysis of geochemical data (A. Kerr, unpublished data) does not show compelling evidence for extensive crustal contamination in these "normal" rocks. However, the rocks of the mineralized sequences in all areas must be contaminated because numerous, variably digested gneissic fragments, including recognizable metasedimentary rocks, provide evidence for incorporation of this material. Complex reactions, which involve the generation of corundum and hercynitic spinel, indicate metasomatic transformation of inclusions, and contamination of the host magma. Strained metamorphic plagioclase masquerading as an igneous phase, and dispersed spinel inclusions in all igneous phases, indicates that even some relatively homogeneous members of the mineralized sequence must be contaminated. Contamination is known to be widespread in the mineralized rocks of the Voisey's Bay area, and the "basal breccia sequence" (to which the composite gabbros are possibly equivalent, *see below*) is in part defined by digested gneissic inclusions. The corundum and spinel-generating reactions observed in composite gabbro resemble those noted in contaminated rocks at Voisey's Bay (Naldrett *et al.*, 1996; Li *et al.*, 1996). Contamination by metasedimentary material is also the main distinction between the extensively mineralized Voisey's Bay troctolites and the lesser known Mushua troctolites (Amelin *et al.*, 1998).

NATURE AND STRATIGRAPHY OF MINERALIZED SEQUENCES

Comparisons between the mineralized sequences of the PLI and those of the Voisey's Bay area are hampered by a lack of published information concerning the latter. However, most of the 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, 1998; Evans-Lamswood *et al.*, 1998). Although there is persistent disseminated sulphide in the basal region of the Eastern Deeps troctolite body, the most extensive mineralization is at the entry point of a feeder sheet (Naldrett *et al.*, 1996; Evans-Lamswood *et al.*, 1998). Drilling to date has not clearly identified comparable conduit systems in the PLI. The Worm intrusion, superficially the most obvious candidate, has a stratigraphy that is closely similar to connected parts of the North intrusion, and may simply be a dipping extension of it. The thin gabbro intersection northeast of Taheke Lake may also be a candidate, but its relationship to the main part of the gabbro has yet to be established.

The distribution and overall pattern of mineralized sequences in the PLI may differ from the Voisey's Bay region. In the South intrusion, a basal mineralized sequence is associated with mafic cumulate rocks, and may have developed through gravitational segregation of sulphide. In the North intrusion, there is a remarkably persistent mineralized sequence at the base of the body. Although much of the drilling that defines it was targeted on geophysical (notably EM) responses, the consistency of its stratigraphy and common chemical patterns implies that there is some basal mineralization everywhere. The internal stratigraphy consists of an upper composite gabbro sequence, rich in gneissic debris, underlain by more homogeneous gabbroic rocks containing disseminated sulphides, which are locally isolated from the footwall contact by barren gabbro (Figure 7). It is difficult to escape the conclusion that mineralization occurred as part of a single broad event, or closely spaced, correlative events, throughout the North intrusion.

The stratigraphic arrangement of the different parts of the mineralized sequence is also distinct. At Voisey's Bay, the basal breccia sequence (similar to composite gabbro) is the lower unit in the feeder sheet, and more homogeneous sulphide-bearing rocks (including leopard troctolite) sit above it (e.g., Naldrett *et al.,* 1996). More recent discussion suggests that there may be more complex vertical- and lateral-facies variations in the feeder system, related to changes in fluid-dynamic environment (Evans-Lamswood *et al.*, 1998). However, the PLI mineralized sequence has the opposite stratigraphy, with composite gabbro almost everywhere sitting above leopard gabbro and related rocks, and it does not show signs of strong regional lateral-facies variations, although they are certainly present at a local level, as indicated by alternation of composite gabbro and leopard gabbro in some drillholes.

NATURE AND SIGNIFICANCE OF COMPOSITE GABBRO

These rocks are the common thread in the North intrusion mineralization, and must be fundamental in its development. Composite gabbro appears to have many affinities to the "basal breccia sequence" at the Voisey's Bay deposit (Naldrett *et al.,* 1996), but the two rock types may not be direct equivalents. Detailed comparisons are presently hampered by a lack of published petrographic information from the Voisey's Bay area.

The preferred interpretation for composite gabbro sequences involves mixing processes where a sulphide- and fragment-rich magmatic pulse is emplaced into (or passes through) partly consolidated and/or partly solidified mafic magma. The inclusion–matrix textures observed in drill core resemble those observed in outcrops where mixing is inferred to involve the "freezing" of one magma against another (e.g., Vernon, 1984; Weibe, 1987), which commonly results in contradictory intrusive relationships. The "spectral variation" amongst composite gabbros (Plate 7) reflects a variety of controls, but the most important are the compositional and thermal state of end-members, and the degree of mixing, which are interdependent. Although there are examples where inclusions appear to have been derived from largely solid rocks (e.g., hole 97-77), most inclusions were likely at least semi-liquid, and froze when entrained by the matrix magma. Blotchy, "curdled" rocks where matrix–inclusion relationships are indistinct represent advanced stages of mixing and hybridization, whereas the process has been more commonly been arrested. Gravitational and/or fluid dynamic effects also influence the characteristics of these rocks, in particular the abundance of gneissic fragments and sulphides. The most xenolith-rich and sulphide-rich variants are commonly in the lower part of the composite sequence, implying gravitational settling. Composite gabbro almost invariably shows a strong alignment of inclusions and locally shows apparent clast imbrication. The fabric in these rocks is commonly subparallel to the base of the intrusion, and it is suggested to result from lateral flow.

The fine-grained domains could be derived locally from the layered olivine gabbro unit, (which they closely resemble) or from other mafic magmas in the intrusion pathway. Given that some composite gabbros contain different types of mafic inclusions, it is more likely that they come from several different sources. The affinity of the coarser, sulphide-bearing matrix is harder to establish but, in textural and mineralogical terms, it resembles both the massive leucogabbro and black olivine gabbro units, as it contains their distinctive late, interstitial to poikilitic olivine crystals. The contrast in olivine habit (granular and early in inclusions, poikilitic and late in matrix) suggests that the two components represent different magmas, albeit of similar general composition. Plagioclase rims developed around inclusions in some examples may record initial crystallization of the matrix magma, which must have had plagioclase on its liquidus before olivine and pyroxene, on textural evidence.

The gneissic fragments in composite gabbro must include some local material, but their digestion and reaction implies that most have come from elsewhere, and had protracted residence times in the magma. As discussed above, these xenoliths have experienced reactions similar to those documented at Voisey's Bay (Naldrett *et al.*, 1996; Li *et al.*, 1996), and they provide direct indications of extensive and pervasive contamination.

The identity of the matrix material in the composite gabbro is of fundamental importance, because the sulphide mineralization is always associated with it. In the Happy Face lobe and the Worm intrusion, the mineralized sequence sits just below the massive leucogabbro unit, which led Kerr (1998b) to suggest a link between the two. However, elsewhere there is no such spatial association, and composite gabbro sits below fine-grained, layered olivine gabbro or black olivine gabbro. The black olivine gabbro locally passes straight down into composite gabbro, and also into a finer grained sulphide-bearing rock having a similar poikilitic olivine texture. Field work and drill core examination in 1998 suggests that the black olivine gabbro may be more widespread than originally thought, and its finer grained variants are very difficult to identify. Finally, it may be significant that composite gabbro-like rocks are locally developed outside the mineralized sequence, notably at the upper contact of the black olivine gabbro in the Taheke Lake lobe. Although these generally lack gneissic fragments, they do contain minor sulphides. These "upper" composite intervals are interpreted to record mixing between black gabbro parent magma and fine-grained olivine gabbro, although the order of emplacement is not entirely clear. If the black olivine gabbro is equivalent to the composite gabbro matrix, understanding its distribution in the North intrusion is crucial in further exploration work.

NATURE AND SIGNIFICANCE OF THE LOWER MINERALIZED SEQUENCE

In the relatively static environment represented by the lower part of the mineralized sequence, sulphides were able to settle gravitationally, and crystallized as late, interstitial material. The equivalent rock in the Voisey's Bay area (leopard troctolite) is interpreted to form by rapid growth of clinopyroxene crystals in sulphide-bearing magma, in which sulphide is "pushed aside" into interstitial areas (Naldrett *et al.*, 1996). An alternate origin for this texture is the introduction of sulphides into a partially crystalline magma in which clinopyroxene and olivine crystals were already forming. Kerr (1998b) suggested that the lower homogeneous part of the mineralized sequence formed in this way, i.e., that sulphides (and fragmental debris) from the composite gabbro unit "rained down" into preexisting, partly crystallized, fine-grained olivine gabbro parent magma. The latter was cooler and completely solidified near the basal contact, resulting in a lower barren gabbro into which sulphides did not penetrate.

This remains a possible explanation for the persistent stratigraphy of the mineralized sequence, and for the unusual leopard gabbro texture, but it does not fully explain the observed variation in metal contents (Figure 6). Sulphides in the composite gabbro commonly show higher Ni and Cu contents (1.5 to 3.0%) compared to those in the underlying rocks (0.4 to 1%). Sulphide introduced into a preexisting magma should not suffer significant loss of Ni, and would more likely increase its Ni content, because its R-factor is raised, and some of the sulphur would likely dissolve in an undersaturated magma, leading to higher Ni concentrations in that which remains. An alternative explanation, also suggested by Kerr (1998b) is that the lower mineralized sequence represents a separate (probably earlier) pulse of sulphide-bearing magma. This interpretation still permits some interaction between mineralized pulses, and fits with the local presence of disseminated mineralization in composite gabbro inclusions. It also allows the presence of "exotic" sulphide fragments in the composite gabbro, although the problems in verifying these are undiminished.

It is too early to speculate, in detail, about the relative timing of mineralization, or to propose any type of model. However, it seems likely that the mineralized sequence(s) represent fairly early influxes of magma, as they are situated near the base of the intrusions. However, the normal laws of stratigraphic superposition do not apply in magmatic environments, and there was undoubtedly some resident magma in the chamber at the time of their arrival.

POTENTIAL FOR MASSIVE SULPHIDE MINERALIZATION

The most obvious contrast between the Voisey's Bay and PLI areas is that exploration activity in the latter has not yet resulted in the discovery of any large, potentially economic, concentrations of massive sulphides such as the Ovoid or Eastern Deeps deposits. However, the Voisey's Bay deposits occur in a small and intensely explored area, which represents but a tiny fraction of the total subsurface target area in the PLI (Figure 9). Magmatic sulphide deposits present formidable challenges to exploration, particularly in blind environments, as they are small and lack associated alteration haloes. Results to date, although obviously not those that were hoped for, do not entirely diminish the potential of the PLI for economic discoveries.

The evaluation of "potential grade" is a critical step in exploration. Recalculation of assays from sulphide zones to 100 percent sulphides indicates the "grade ceiling" for associated massive sulphide mineralization, should it occur. The empirical and calculated data from the PLI indicate that most sulphides contain maximum values of around 2% Ni, slightly less Cu, and around 0.2% Co (Figure 6). These agree well with the better massive sulphide intersections, but many massive sulphide intersections show significantly lower absolute grades of 1.0 to 1.2% Ni, which are not fully explicable through silicate dilution. In summary, most of the present data suggests that potential massive sulphides would not show the high Ni grades (4% or more) known from Voisey's Bay, but would probably have higher Co contents, which may in part compensate.

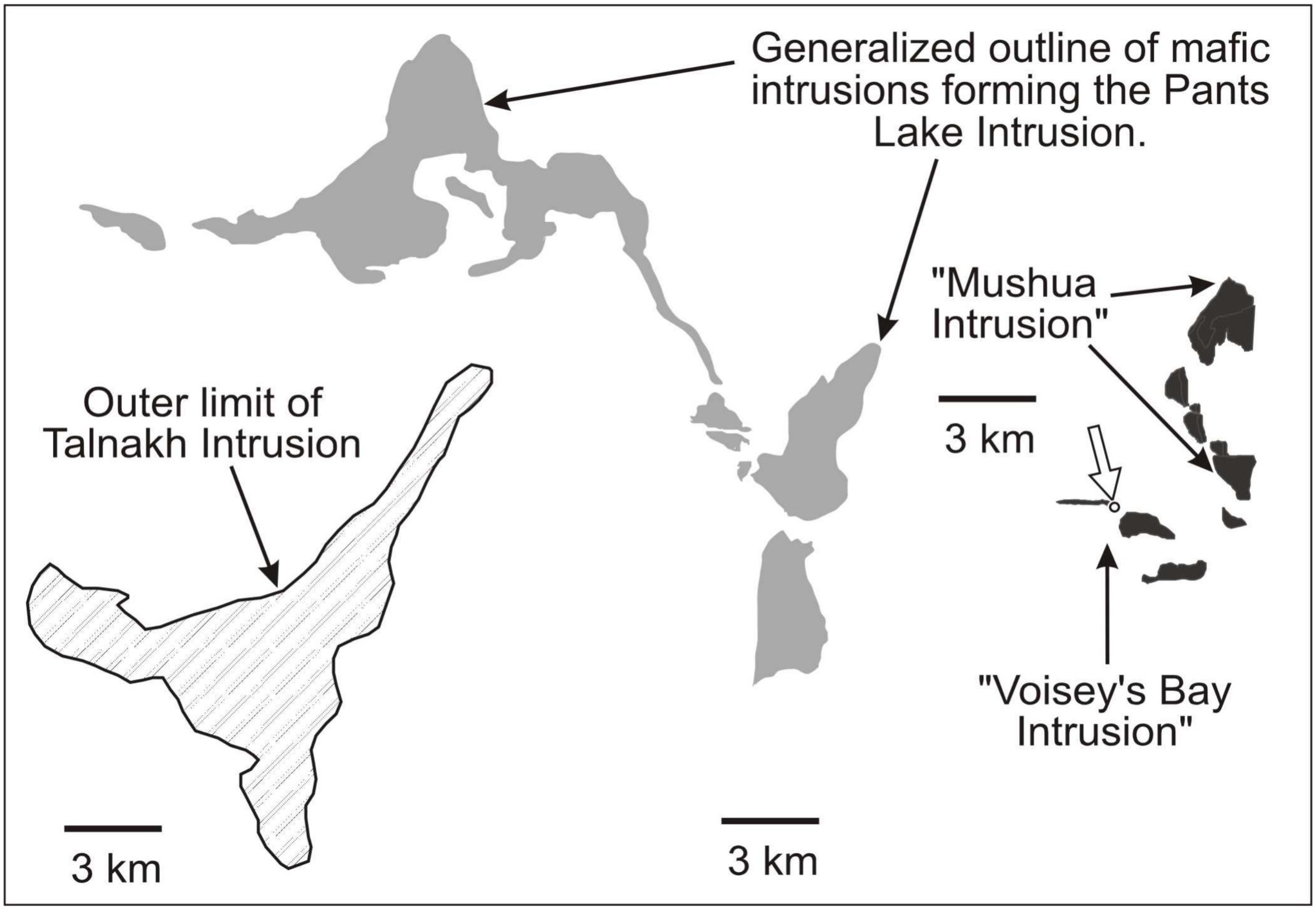


Figure 9. *Comparisons of the size of the target intrusion at the Voisey's Bay project and the Pants Lake intrusion, as it is currently defined. For comparison, the outcrop area of the Talnakh intrusion in the Norilsk district is also shown. The Ovoid deposit is all but invisible at this scale, located at the head of the arrow (top right).*

There are, however, scattered indications of sulphides that are richer in metals, notably in the Happy Face and Taheke Lake lobes, where Ni and Cu are locally both above 3% in selected holes. There are also higher Ni and Cu tenors in parts of the South intrusion mineralized sequence. The possibility that there were two discrete episodes of mineralization lends uncertainty to the identification of a specific massive sulphide zone, for some may be connected to an earlier (?) metal-poor episode. Lastly, if there were two episodes of mineralization marked by a change in tenor, could there have been a third with still higher metal values?

Although the famous hole 75 intersection shows exactly the same Ni/Cu ratio as all other mineralization, other higher-grade massive sulphide intersections, with the possible exception of hole 131, have disturbed Ni/Cu ratios (Figure 8) suggesting that they result from fractionation of sulphide liquids. Although such rich material is unlikely to be widespread, it represents an attractive target in conjunction with larger, lower grade deposits. Finally, the fractionation process is by itself significant, as it by definition involves the extraction of a small aliquot from something that is significantly larger. To use a suitable alcoholic analogy, a small amount of fine brandy is made (indirectly) from grapes, but a substantially larger quantity of champagne must first be made as an intermediate step. As indicated by Figure 9, the vineyard is large and by no means fully explored at this stage.

CONCLUSIONS

Continued exploration in the area, university research projects and future activity by the Geological Survey will develop and expand, or perhaps disprove entirely, some of the early views expressed here. However, this area clearly demonstrates that potential environments for magmatic sulphide deposits are *not restricted* to the immediate Voisey's Bay area, and the distinctive rock types and processes observed and inferred at Voisey's Bay prevail in at least one other part of Labrador. Although areally extensive compared to the Reid Brook intrusion, the PLI remains a small and inconsequential body at the scale of Labrador, and rocks of this affinity may outcrop or lie in the shallow subsurface in other parts of this hinterland.

ACKNOWLEDGMENTS

This report includes significant direct and indirect contributions from Teck Corporation and Donner Minerals staff involved in the 1996 to 1998 exploration programs. In alphabetical order, I wish to thank Kelly Emon, Dennis Fitzpatrick, Steve House, Floyd House, Harvey Keats, Tom Lane, Heather MacDonald, Guy McGillivray, Paul Moore, Trevor Rice, Rod Smith and Kerry Sparkes. The work on which this article is based would not have been possible without their efforts, and its contents were improved by their input in the field and during preparation. Kerry, Paul and Harvey contributed directly to the contents of the article through reviews and suggestions. I also acknowledge valuable discussions with A.J. Naldrett.

Much of the work discussed in this report is based on information from studies of drill core, and our free access to this (and other) material is greatly appreciated. The camp management staff, particularly Bing Lovang and George Small, are also thanked for their hospitality and assistance. Canadian Helicopters, and particularly pilot Luc Gauthier, are thanked for their invaluable services. Joanne Shwetz and John Hinchey are acknowledged for their able, cheerful and tolerant assistance to the senior author in 1997 and 1998. Lastly, Carl von Einsiedel (RAM Exploration) is acknowledged for his work in developing the project in 1995, and for encouraging the Geological Survey to become involved in the project area. Richard Wardle is thanked for reviewing the article.

REFERENCES

Amelin, Y., Li, C. and Naldrett, A.J.
1998: Contrasting assimilation patterns in the Voisey's Bay Complex and Mushua Complex, Labrador, Canada, indicated by Nd–Pb–Sr isotope systematics. Geological Society of America, 1998 Annual Meeting, Toronto, Ontario, Abstract.

1997: Multistage evolution of the Voisey's Bay Complex, Labrador, Canada, revealed by U–Pb systematics of zircon, baddeleyite and apatite. American Geophysical Union, 1997 Fall Meeting, San Francisco, CA, Abstract.

Barnes, S.J., Zientek, M.L. and Severson, M.J.
1996: Ni, Cu, Au and platinum-group element contents of sulphides associated with intraplate magmatism: A synthesis. Canadian Journal of Earth Sciences, Volume 34, pages 337-351.

Emslie, R.F.
1980: Geology and petrology of the Harp Lake Complex, central Labrador: an example of Elsonian magmatism. Geological Survey of Canada, Bulletin 293, 136 pages.

1996: Troctolitic rocks of the Reid Brook Intrusion, Nain Plutonic Suite, Voisey Bay area, Labrador. *In* Current Research, Part C. Geological Survey of Canada, Report 96-1C, pages 183- 196.

Evans-Lamswood, D.M., Butt, D.P., Jackson, R.S., Lee, D.V., Muggridge, M.G., Wheeler, R.I. and Wilton, D.
1998: Physical controls on the distribution of sulphides in the Voisey's Bay Ni–Cu–Co deposit, Labrador. Geological Society of America, 1998 Annual Meeting, Toronto, Ontario, Abstract.

Fitzpatrick, D., Moore, P., Mac Gillivray, G., House, S. and Emon, K.
1998: Report of work, South Voisey's Bay Project, Central Labrador: Core program. Teck Explorations Ltd. Confidential assessment report submitted to the Department of Mines and Energy.

Hill, J.D.
1982: Geology of the Flowers River–Notokwanon River area, Labrador. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 82-6, 137 pages.

Hodder, S.L.
1997: A drill core analysis and petrographic study of Ni–Cu bearing gabbros, South Voisey's Bay area, Labrador. Unpublished B.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland.

Kerr, A.
1998a: Petrology of magmatic sulphide mineralization in northern Labrador: preliminary results. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 98-1, pages 53-75.

1998b: Preliminary report on petrographic studies, South Voisey's Bay project area, Labrador. Confidential report provided to Donner Minerals and Teck Corporation, April 1998.

Kerr, A. and Smith, J.L.
1997a: The search for magmatic Ni–Cu–Co mineraliza-

tion in northern Labrador: A summary of active exploration programs. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 97-1, pages 73-93.

1997b: A summary of 1997 mineral exploration activities in the northern Labrador nickel play. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report of Activities for 1997, pages 21-25.

1998: A summary of 1998 mineral exploration activity in northern Labrador. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report of Activities for 1998, pages 16-21.

Li, C., Naldrett, A.J. and Krstic, S.
1996: The Voisey's Bay Ni–Cu–Co deposit: crustal contamination and petrological variation. Geological Society of America, 1996 Annual Meeting, Denver, Colorado, Abstract.

Li, C., Amelin, Y. and Naldrett, A.J.
1998: U–Pb geochronology of the Mushua troctolite complex at Voisey's Bay, northern Labrador, Canada. Geological Society of America, 1998 Annual Meeting, Toronto, Ontario, Abstract.

Naldrett, A.J.
1989: Magmatic Sulphide Deposits. Clarendon/Oxford University Press, Oxford, United Kingdom.

Naldrett, A.J., Keats, H., Sparkes, K. and Moore, R.
1996: Geology of the Voisey's Bay Ni–Cu–Co deposit, Labrador, Canada. Exploration and Mining Geology Journal, Volume 5, pages 169-175.

Naldrett, A.J., Li, C., Asif, M. and Amelin, Y.
1998: The Voisey's Bay Ni–Cu–Co deposit, Labrador, Canada: A model for ore genesis. Geological Society of America, 1998 Annual Meeting, Toronto, Ontario, Abstract.

Ripley, E.M., Young-Rok, P., Li, C. and Naldrett, A.J.
1997: Sulfur and oxygen isotope studies of the Voisey's Bay Ni–Cu–Co deposit, Labrador, Canada. American Geophysical Union, 1997 Fall Meeting, San Francisco, CA, Abstract.

Ripley, E.M., Young-Rok, P., Naldrett, A.J. and Li, C.
1998: Oxygen isotope studies of the Voisey's Bay Ni–Cu–Co Deposit. Geological Society of America, 1998 Annual Meeting, Toronto, Ontario, Abstract.

Ryan, A.B.
1990: Nain–Nutak Compilation Map. Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-44, scale 1:500 000.

1996: Commentary on the location of the Nain–Churchill boundary in the Nain area. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 96-1, pages 109-131.

Ryan, B., Wardle, R.J., Gower, C.F. and Nunn, G.
1995: Nickel–copper sulphide mineralization in Labrador: The Voisey Bay discovery and its exploration implications. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 95-1, pages 177-204.

Smith, R.L. and Wilton, D.H.C.
1998: Preliminary investigation of the mineralized and contaminated sequence of the Pants Lake Intrusion, South Voisey's Bay Project, Labrador. Canadian Institute of Mining, Metallurgy and Petroleum, Newfoundland Branch, Annual Meeting, November 1998. Program with Abstracts, page 7.

Thomas, A. and Morrison, R.S.
1991: Geological map of the central part of the Ugjoktok River (NTS 13N/5 and parts of 13M/8 and 13N/6), Labrador (with accompanying notes). Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 91-160, scale 1:50 000.

Vernon, R.H.
1984: Microgranitoid enclaves in granites – globules of hybrid magma quenched in a plutonic environment. Nature, Volume 309, no. 5967, pages 438-439

Wares, R.
1997: South Voisey's Bay Project: Summary report and proposed exploration program Donner Resources. Confidential assessment report submitted to Department of Mines and Energy.

Weibe, R.A.
1987: Evidence for stratification of basic, silicic and hybrid magmas in the Newark Island layered intrusion, Nain, Labrador. Geology, Volume 15, pages 349-352.

APPENDIX: CALCULATION OF SULPHIDE TENOR

Recalculation of analytical data to 100 percent sulphide is based on the premise that Ni, Cu and Co are essentially contained in the sulphide phases. Thus, if the sulphide content of a mineralized rock is known, the "potential grade" of massive sulphide accumulations can be readily calculated. In addition to predictions of economic interest, the method provides a consistent method for comparison of rocks with different sulphide contents from different areas or units. The sulphide content is provided by the ratio between elemental sulphur content and the theoretical value for pure pyrrhotite (FeS; 36.5 weight % S). Here, a slightly lower value of 35 percent sulphur is used, to account for other sulphide minerals such as chalcopyrite and pentlandite, and to keep estimates conservative. For example, the sulphide contents and Ni content at 100 percent sulphide are:

Sulphide Content % = ((weight % S) / 35) x 100
Ni (100 % sulphide) = Ni x (35 / weight % S)

The method is complicated somewhat by the presence of Ni, Cu and Co in olivine and, to a lesser extent, pyroxene. These force a correction for metals in silicates to be applied, although this is often negligible. There are several methods for correction, some of which involve assumptions about the percentage of olivine and its Ni content. In this study, a simple empirical correction is used, by assuming that sulphide-free gabbro contains 100 ppm each of Ni and Cu and 50 ppm Co. These values were doubled for the South intrusion data, because the ultramafic host rocks are richer in olivine and pyroxene. These values are actually higher than the observed average values for PLI unmineralized rocks and drill core, and also agree well with the "worst" assay results from rocks with only minute traces of sulphide. The correction method is a simple mass balance calculation, using the percentages of sulphide and silicate. The conservative values for Ni, Cu and Co in sulphide-free rocks again help to ensure that results are not unduly optimistic. For Ni and Cu, the corrections are trivial, unless the sulphide content is very low, but for Co they are larger, because Co is an order of magnitude less abundant in the sulphide phase. Thus, 100% sulphide values for Co are very sensitive to correction assumptions, and are less reliable.

In assessing data, a negative correlation between calculated Ni and Cu in sulphides and the amount of sulphides is commonly observed. There is also significantly greater scatter at low sulphide abundances. These have also been noted in other studies also (e.g., Barnes *et al.*, 1996), and reflect several factors. Decreased analytical accuracy for sulphur and increased uncertainties for silicate corrections are partly responsible, but there are also real variations that are probably due to local R-factor variations where small amounts of sulphide were present in isolation. Most of the data in Figure 6, aside from some South intrusion material, represents samples containing 2 wt % or more sulphur, which translates to minimum sulphide contents of about 6%.