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GEOCHEMISTRY OF THE PANTS LAKE INTRUSION, LABRADOR: IMPLICATIONS FOR FUTURE MINERAL EXPLORATION

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ABSTRACT

This report presents and discusses geochemical data from the nickeliferous mafic rocks of the Pants Lake Intrusion (PLI) in Labrador, and is a sequel to an earlier descriptive account, which noted petrological similarities between these and the mafic rocks of the Voisey's Bay area (Voisey's Bay and Mushuau intrusions). These petrological similarities are supported by similarities in their major- and trace-element geochemistry.

The PLI is a relatively primitive, MgO-rich, mafic igneous suite, dominated by olivine gabbro, associated with lesser amounts of troctolite, melagabbro and diabase. The PLI includes two subtly different magma types. The South intrusion is distinguished by higher TiO_2, K_2O and incompatible element contents, and most closely resembles the Voisey's Bay intrusion. The North intrusion more closely resembles the Mushuau intrusion, although it is not an exact match. The three main geological units within the North intrusion probably formed from discrete, yet closely related, batches of magma. Contrasting olivine fractionation trends suggest that the South intrusion was a relatively static chamber whose evolution approached closed-system fractionation, whereas the North intrusion was a more dynamic open-system body that was regularly replenished with fresh, more primitive magma. The parental magma composition(s) for the PLI are hard to estimate, but they were probably more primitive than the diabase units associated with it, which are relatively fractionated.

Mineralized rocks in both the South and North intrusions share all the geochemical characteristics of spatially associated unmineralized rocks, and are thus closely related to them. Unmineralized rocks throughout the PLI have low Ni and Cu contents and low Cu/Zr ratio values, suggesting that the magmas were depleted in metals by sulphide liquids. First-order calculations suggest that at least 15 million tonnes of Ni metal, several times more than is presently known to be contained at Voisey's Bay, remain mostly unaccounted for. The low/metal contents of PLI magmas are in accordance with the modest sulphide metal contents (1 to 3% Ni) observed in mineralized samples, and imply a relatively low/mass-ratio (R) of silicate liquid to sulphide liquid (R=180 to 250) compared to Voisey's Bay (R=600 to >1000). The ubiquitous metal depletion in PLI mafic rocks contrasts with the more localized metal depletion seen at Voisey's Bay, and may indicate that PLI sulphide liquids were not "upgraded" to the same extent by later undepleted magmas. Thus, although large amounts of sulphides may remain undiscovered in the area of the PLI, there may be inherent limits upon their potential grades.

INTRODUCTION

Previous Current Research reports have described sulphide mineralization from both the Nain Plutonic Suite (NPS) and the Harp Lake Intrusive Suite (HLIS; Kerr and Smith, 1997, 2000; Kerr, 1998, 1999), and an overview paper integrating some of this work was recently published (Kerr and Ryan, 2000). To date, there has been no detailed discussion of lithogeochemical data from these areas, aside from general observations related to Ni, Cu and Co contents of mineralized rocks. This article presents and discusses geochemical data from the Pants Lake Intrusion (PLI), which was the focus of a large exploration program from 1995 to 1998. Its purposes are to place these data in the public domain, to make comparisons with published data from mafic intrusions of the Voisey's Bay area, and discuss the

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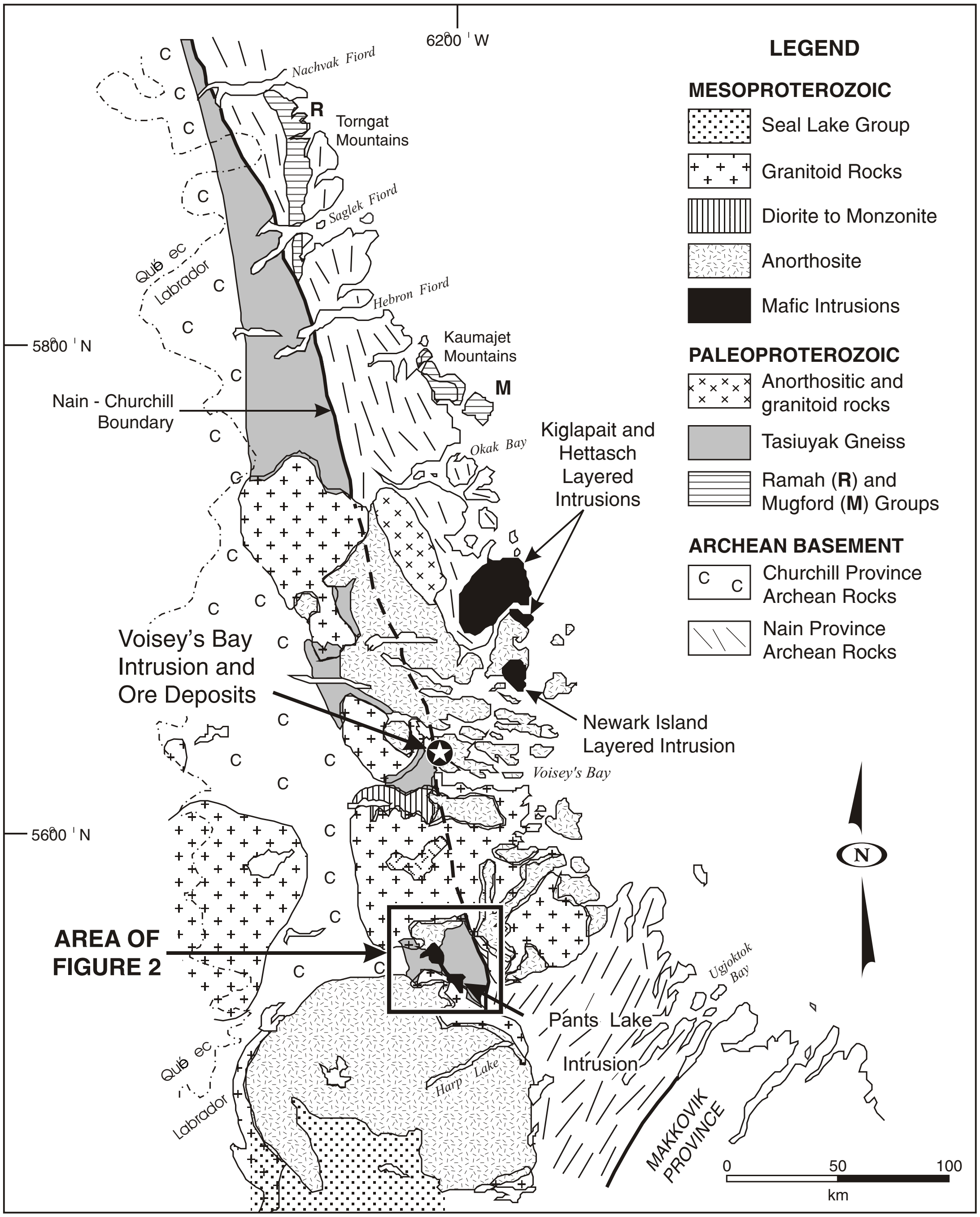

Figure 1. *Generalized geological map of the northern part of Labrador, showing the location of the Pants Lake Intrusion, and other mafic intrusions of the Nain Plutonic Suite.*

implications for mineral exploration. This article is the sequel to a previous descriptive treatment of the geology, petrology and sulphide mineralization of the PLI (Kerr, 1999). It also draws upon a M.Sc. thesis at the University of Toronto (MacDonald, 1999).

REGIONAL GEOLOGICAL FRAMEWORK

The PLI is located within the Churchill Province, about 15 to 25 km west of the major tectonic boundary between the Nain and Churchill provinces (Figures 1 and 2). Archean

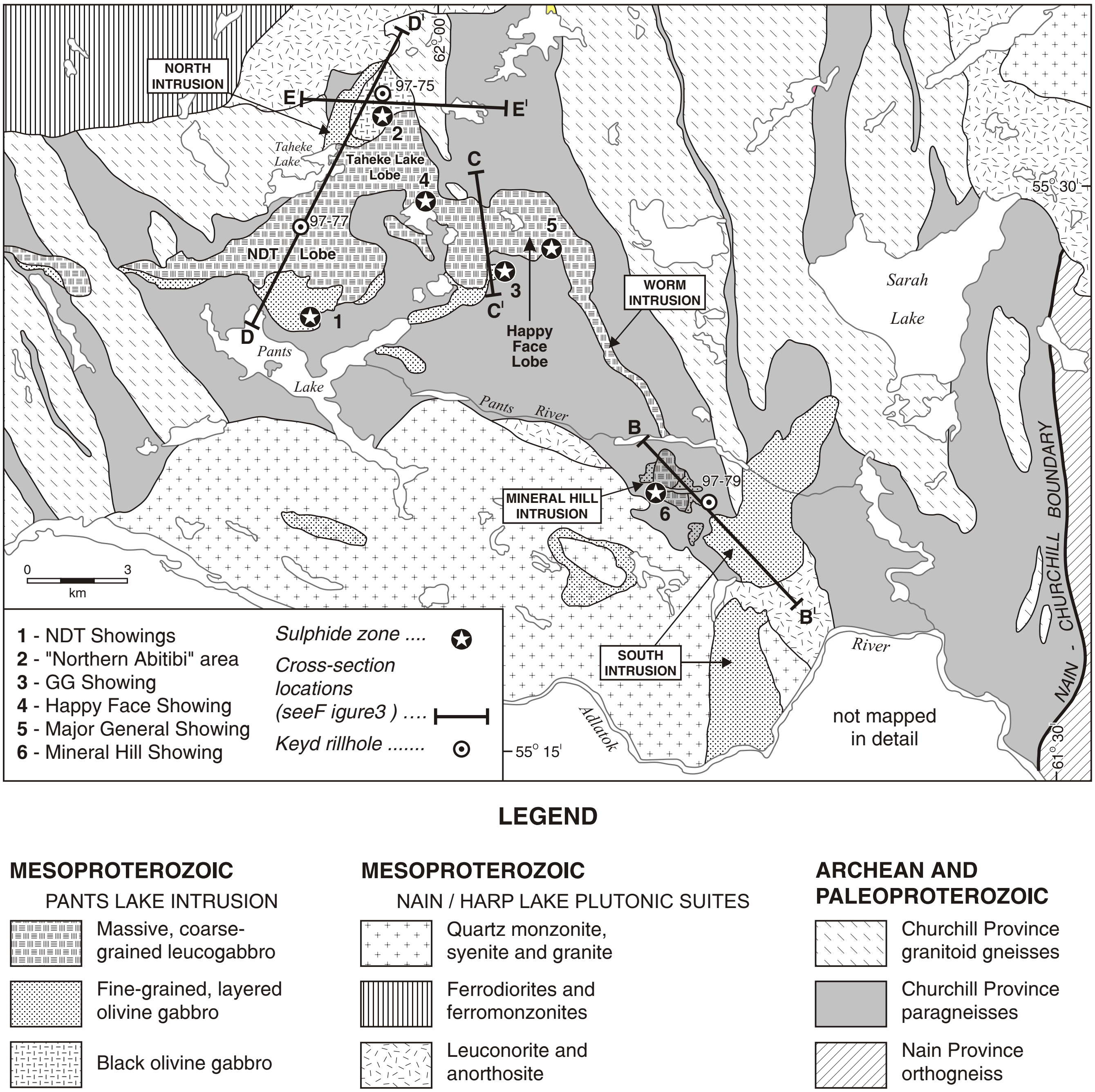

Figure 2. *Geology of the Pants Lake Intrusion and surrounding areas. After Kerr (1999), and based partly upon exploration company data. Cross-sections indicated on the map are illustrated in Figure 3. Drillholes indicated were studied in detail by MacDonald (1999).*

orthogneisses of the Nain Province are present to the east, but the Nain–Churchill boundary itself is poorly exposed. West of the Nain–Churchill boundary, the area is dominated by amphibolite-facies gneisses that form part of the Paleoproterozoic Torngat Orogen (Wardle *et al.*, 1990). These include pelitic to semipelitic, variably sulphide- and/or graphite-bearing paragneisses that are compositionally equivalent to the Tassiuyak gneiss, which hosts part of the Voisey's Bay intrusion (Figure 1). Granitoid orthogneisses, commonly garnetiferous, form several kilometre-scale units within the paragneisses, and exhibit relict igneous textures. The paragneisses and orthogneisses are interleaved on both outcrop and regional scales, and field relationships suggest that many orthogneisses were derived by local anatexis during peak-metamorphic conditions. There is a well-developed northeast–southwest-trending regional foliation, which appears to have been superimposed on an early east–west-trending foliation locally observed in the paragneisses. Undeformed plutonic rocks assigned to the NPS occur in the northwest and northeast of the area (Figure 2), and include coarse-grained leuconorite to anorthosite, iron-rich diorite to monzonite, and granite. Granitic rocks of the HLIS occur to the southwest of the PLI, and are dated imprecisely at ca. 1450 Ma (Emslie, 1980). The granites are intruded by small, sill-like bodies correlated with the PLI, and locally sit beneath its basal contact. This represents the only field constraint on the age of the PLI, although a general lack of crosscutting mafic or felsic dykes implies that it is one of the younger intrusive units in the area. The relationship between the PLI and other NPS plutons is not seen, as the two come into contact in only one place. U–Pb zircon geochronology reported by Smith *et al.* (1999) from the North intrusion indicates an age of 1322 ± 2 Ma, confirming that the PLI is an integral part of the NPS.

GEOLOGY OF THE PANTS LAKE INTRUSION

The following description of the geology of the PLI is condensed from a previous report (Kerr, 1999). The PLI consists of several discrete component intrusions scattered over about 250 km^2 (Figure 2). The largest bodies are referred to as the North and South intrusions, and there are several smaller bodies including the Mineral Hill intrusions, and the Worm intrusion, which may link the North and South intrusions. Exploration drilling demonstrates that all are broadly sheet-like or slab-like in geometry, although their attitudes and internal anatomy vary (*see* Kerr, 1999, for more discussion). Despite their scattered locations, all the intrusions contain essentially the same rock types (albeit in different proportions), suggesting that they are very closely linked. The North intrusion has been the main focus of exploration work, and provided most of the data under consideration.

ROCK TYPES AND PETROLOGY

The PLI contains three main rock types, i.e., 1) fine-grained, layered, olivine gabbro, 2) coarse-grained massive leucogabbro, and 3) black olivine gabbro of variable grain size. Other units include chilled diabase-like rocks, found mostly on a local scale near its external contacts, and peridotite and melagabbro, mostly in the lower part of the South intrusion. There are also several unusual rock types associated with a thin package of sulphide-bearing rocks (termed the Mineralized Sequence), which is best known at the base of the North intrusion. The rock types of the mineralized sequence are discussed separately below.

Fine-grained, layered, olivine gabbro dominates the South intrusion, and forms the lower section of the North intrusion. This is a red-weathering, grey-green to dark grey, fine- to medium-grained (1 to 4 mm), granular rock, consisting essentially of olivine, plagioclase, and clinopyroxene. In some areas, it develops a characteristic "speckly" texture imparted by small plagioclase phenocrysts. Although locally well developed, layering is generally subtle, and subhorizontal or gently dipping, defined by slight variations in olivine and plagioclase content. Typical examples consist of olivine (30 to 60%), plagioclase (40 to 60%; typically An_{50} to An_{55}), clinopyroxene (5 to 30%), minor red biotite, magnetite, and serpentine (after olivine). Orthopyroxene is rare, but locally forms thin rims on olivine. A few examples are true troctolites (i.e., < 5% pyroxene), and these appear to be more common at lower "stratigraphic" levels in the North and South intrusions. Olivine is granular, plagioclase is lath-like, and clinopyroxene is interstitial, subophitic or (more rarely) poikilitic; small olivine grains are included both in plagioclase laths and subophitic clinopyroxene. The texture indicates early formation of olivine, followed by plagioclase, and finally clinopyroxene; magnetite and biotite are also late-crystallizing.

Melagabbro and peridotite occur within the lower part of the South intrusion, and are dominated by cumulus olivine and interstitial to poikilitic plagioclase. Similar rocks occur locally in the lower part of the North intrusion, in the NDT lobe. The troctolitic variants of the fine-grained gabbro and the melagabbro–peridotite unit are, to some extent, gradational, and share a common texture. Both are regarded as olivine-rich cumulates.

Coarse-grained, massive leucogabbro is the dominant rock type on the surface throughout the North intrusion, where it sits above the previously described fine-grained unit. It also occurs in the Mineral Hill intrusions, and in other minor bodies. It is a pale-grey- to white-weathering, coarse-grained, homogeneous, plagioclase-rich rock that has a characteristic seriate to porphyritic texture, defined by stubby (0.5 to 2 cm) plagioclase crystals. The mafic minerals all have an interstitial to subophitic habit, and some variants of this rock type are superficially similar to typical NPS leuconorite and anorthosite, as indicated by the mapping of Hill (1982). Typical examples consist of zoned plagioclase (60 to 80%, typically < An_{55} at the rim), olivine (5 to 20%), clinopyroxene (10 to 20%), minor biotite and variable amounts of magnetite. Both olivine and clinopyroxene are interstitial to subophitic, indicating that they crystallized late, in contrast to the early cumulus olivine of the fine-grained, layered olivine gabbro unit and associated cumulates. Thin rims of orthopyroxene, surrounded by amphibole, occur on olivines in some samples. An altered, hydrated variant of this rock type occurs near the upper contact of the North intrusion.

Black olivine gabbro is presently known only in the North intrusion, and has a restricted outcrop area. In drill-core, it is a medium- to coarse-grained, homogeneous, dark-grey to black rock, which superficially appears ultramafic. However, it contains 60 percent or more dark-grey plagioclase, associated with green olivine and purple-bronze clinopyroxene. The plagioclase is commonly prismatic or tabular, in contrast to the more equant habit typical of the massive leucogabbro; its dark colour appears to be related to numerous tiny iron-oxide inclusions (MacDonald, 1999). Texturally, black olivine gabbro resembles the massive leucogabbro, and generally contains large, optically continuous, interstitial olivine and clinopyroxene crystals. However, it locally also contains early equant cumulus olivines that are surrounded by intercumulus clinopyroxene, but rarely included in plagioclase. A fine-grained variant is a black rock containing poikilitic olivines and clinopyroxenes, which is referred to as poikilitic olivine diabase. Black olivine gabbro was originally considered to be a variant of the massive leucogabbro unit, but logging of key drillholes in the western part of the North intrusion shows that it sits beneath the fine-grained olivine gabbro unit, in contrast to massive leucogabbro, which sits above the fine-grained gabbro (Kerr, 1999; *see* Figure 3).

Diabase is uncommon, but several examples of chilled mafic rocks are associated with the basal contacts of the PLI, located below the rocks of the Mineralized sequence, or forming thin sill-like units in gneisses just below the basal contact. There is also one example of a chilled diabase at the upper contact of the North intrusion, which appears to grade downward into typical coarse-grained massive leucogabbro. Diabase samples are all dominated by fine-grained intergrowths of clinopyroxene and plagioclase, and their olivine contents are hard to estimate.

ANATOMY AND GEOMETRY

Exploration drilling provides information on the three-dimensional geometry of the PLI, which is summarized here by generalized cross-sections (Figure 3; *see* Kerr, 1999, for additional details). The South intrusion is a gently west-dipping, slab-like body up to 600 m thick, which has a basal mafic cumulate zone, and is structurally overlain by at least two sill-like bodies that form the Mineral Hill intrusions (Figure 3a). The South intrusion is dominated by fine-grained olivine gabbro and local interlayered melagabbro and peridotite. The North intrusion has a complex, arcuate shape that probably records northward tilting (or possibly gentle warping) of a sheet-like body that had significant original variations in its thickness and anatomy. These original variations allow its subdivision into three "lobes" (Figure 2). The Happy Face lobe is dominated by massive leucogabbro and has a thin, fine-grained layered sequence at the base, associated with mineralization (Figure 3b). The NDT lobe contains up to 400 m of fine-grained olivine gabbro and a thinner section of massive leucogabbro sitting above it (Figure 3c). The Taheke Lake lobe contains all three units, and the black olivine gabbro sits beneath much of the fine-grained unit (Figure 3d). However, some fine-grained olivine gabbro occurs also at the very base of the body, where it is part of the Mineralized sequence (*see below*). The configuration of the north intrusion to the northwest is unknown, and a high-angle or subvertical feeder system to the intrusion has not been located.

The intrusive relationships between the three main units of the PLI in the North intrusion are equivocal. In outcrop, the contact of fine-grained olivine gabbro and massive leucogabbro units is generally sharp but uninformative; in drill-core, there appear to be vein-like zones of leucogabbro that cut the finer unit below it. The contact between the fine-grained olivine gabbro and black olivine gabbro is a diffuse, gradational zone, in which rounded enclaves of fine-grained material are surrounded by black gabbro; this texture is similar in many respects to "composite gabbro" within the Mineralized sequence (*see below*). Contacts between black olivine gabbro and massive leucogabbro have not been defined on surface or in drill-core.

Ni–Cu SULPHIDE MINERALIZATION

Sulphide mineralization associated with the PLI is described in detail elsewhere (Kerr, 1999). In the South intrusion, disseminated, interstitial, sulphides are associated with melagabbro and peridotite near the base of the body, over significant thicknesses (up to 50 m), but without any significant accumulation. Absolute grades are low, but the sulphide metal contents (i.e., the Ni and Cu in the sulphides have been calculated from the whole-rock geochemical data, where the sulphide content has been estimated from the analysis of elemental sulphur, *see* Kerr, 1999, for explanation) are relatively high, at 2 to 5% Ni and 1 to 3% Cu.

In the North intrusion, a thin (5 to 60 m) Mineralized sequence is invariably present at, or just above, the basal contact (Figure 3). This exhibits a consistent bipartite stratigraphy from lobe to lobe (Figure 4). The upper part of the Mineralized sequence consists of a peculiar breccia-like rock (composite gabbro) in which fine-grained gabbroic or troctolitic enclaves are entrained in a coarser grained, sulphide-bearing matrix. The matrix also contains variably digested gneissic fragments, commonly reacted to plagioclase, corundum and spinel. The mafic enclaves are texturally akin to the fine-grained olivine gabbro unit, whereas the matrix is texturally akin to either massive leucogabbro or black olivine gabbro. Sulphide content, and the proportion of digested gneiss fragments, commonly increases down-

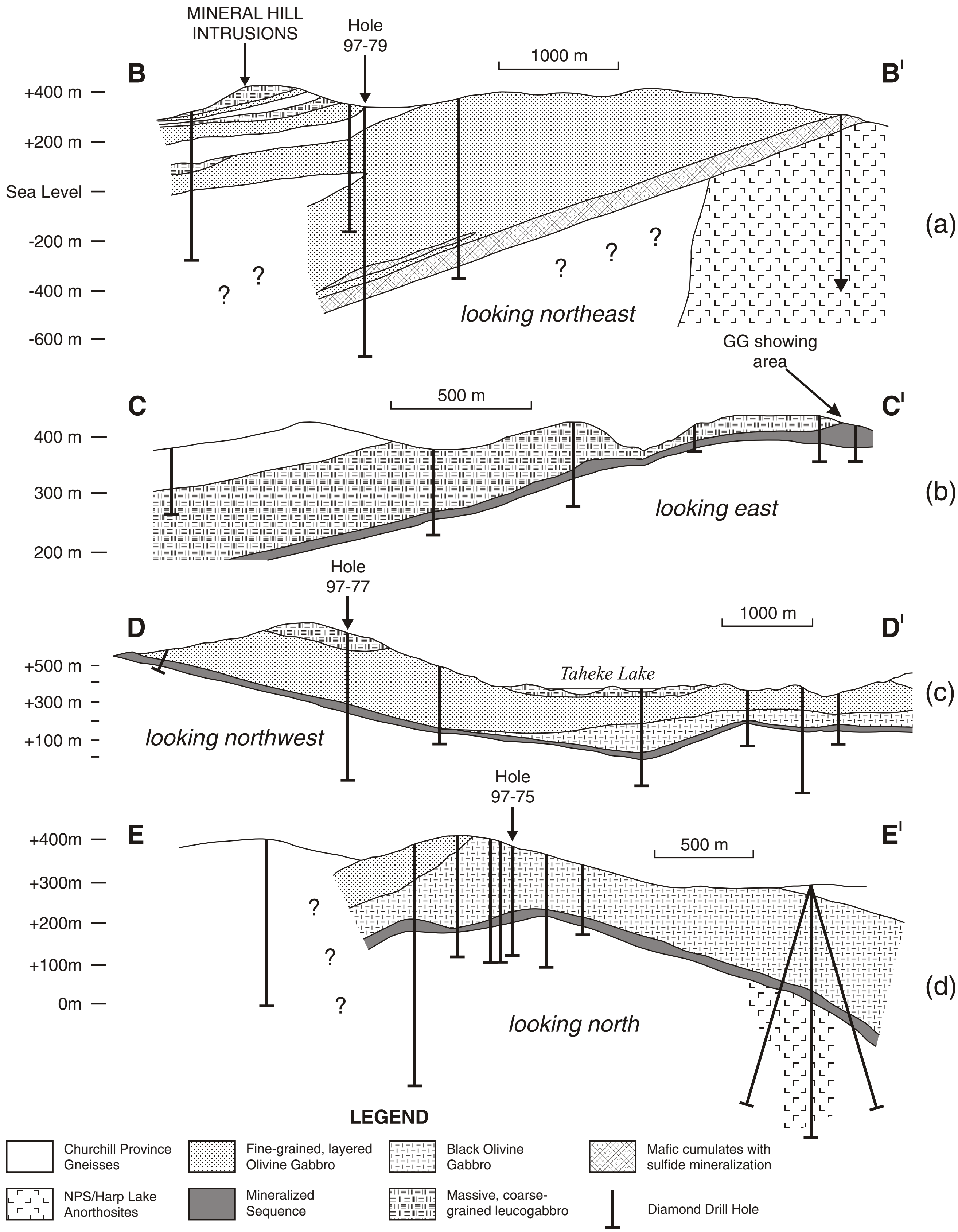

Figure 3. *Simplified cross-sectional views of various parts of the Pants Lake Intrusion, adapted from Kerr (1999); locations as indicated in Figure 2. All sections incorporate twofold vertical exaggeration for clarity.*

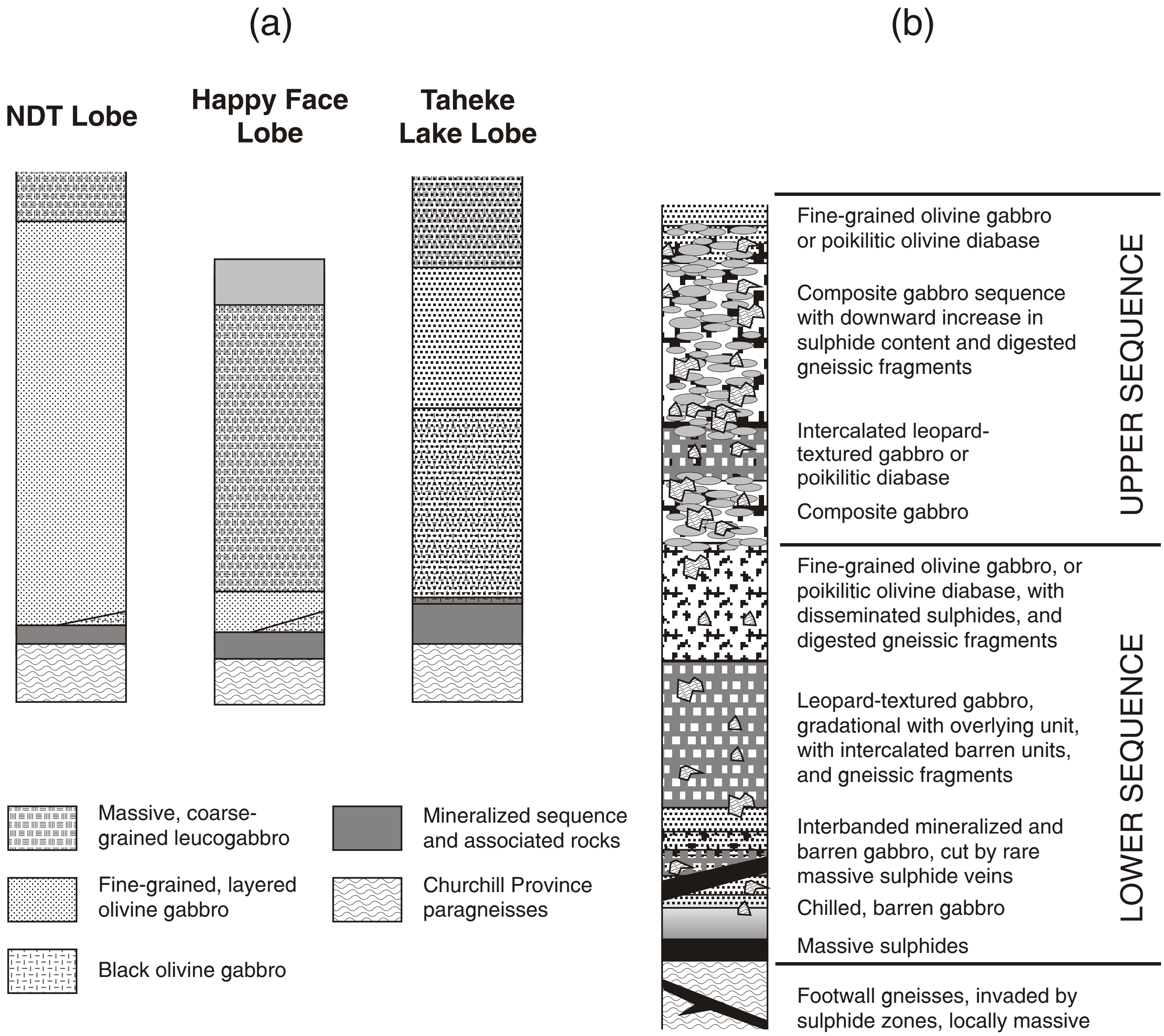

Figure 4. *Schematic illustration of the stratigraphy of the Mineralized sequence in the North intrusion, and its position within the overall stratigraphy of various parts of the intrusion. After Kerr (1999) and Kerr and Ryan (2000).*

ward. This heterogeneous unit passes downward into homogeneous, mineralized fine-grained gabbro, most of which is texturally akin to the fine-grained unit, but including some gneissic debris and variable amounst of disseminated sulphides. This lower sequence commonly includes leopard-textured gabbro, consisting of clinopyroxene oikocrysts in a sulphide-bearing, olivine-rich matrix. Locally, poikilitic olivine diabase (possibly equivalent to black olivine gabbro) containing magmatic sulphide is also present. The lower homogeneous section shows good evidence for gravitational accumulation of sulphides. The lowermost part of the Mineralized sequence is commonly a barren, fine-grained gabbro, which is locally chilled against the basal contact. Massive sulphides, where present, seem to have invaded this contact region and the underlying footwall gneisses. The most spectacular results came from a narrow (1.1 m) footwall zone containing 11.7% Ni and 9.7% Cu, and the thickest massive sulphide intersection to date was 15.7 m of 1.2% Ni, 0.9% Cu and 0.22% Co (Fitzpatrick *et al.*, 1998).

The distinctive rock types of the PLI Mineralized sequence have many affinities to the "basal breccia sequence" and "leopard troctolite" described from the Voisey's Bay deposit (Naldrett *et al.*, 1996; Li and Naldrett, 1999, 2000), and imply the operation of broadly similar genetic processes (Kerr, 1999). However, most of the known mineralization in the PLI is disseminated, and the sulphide metal contents (1.5 to 3% Ni) are lower than at Voisey's Bay

(3 to 5% Ni), although relatively enriched in Cu and Co (Kerr, 1999).

GEOCHEMISTRY OF UNMINERALIZED ROCKS

PREVIOUS GEOCHEMICAL STUDIES

The first geochemical study of the PLI was by Thomas and Morrison (1991), who presented analyses that (on the basis of their descriptions) mostly represent the coarse-grained massive leucogabbro unit. From 1995 to 1998, hundreds of mineralized drill-core samples were analyzed for Co, Ni, Cu and sulphur (Wares *et al.*, 1997; Fitzpatrick *et al.*, 1998), but there were relatively few major- and trace-element analyses of unmineralized gabbros. During the early years of the exploration project, contractual geochemical studies were carried out by Dr. M.R. Wilson, at Memorial University of Newfoundland, but these results are not included in assessment reports, and remain unpublished. MacDonald (1999) completed a geochemical and mineralogical study of three key diamond-drill holes (located in Figure 2). This study concluded that there were compositional differences between the South and North intrusions, some strong similarities between some PLI gabbros and troctolites of the Voisey's Bay intrusion, and evidence for chalcophile element depletion. These initial conclusions are endorsed and amplified by the results of this project, but the larger database permits additional discussion. A detailed study of the Mineralized sequence is currently underway at Memorial University of Newfoundland by R.L. Smith (*in preparation*), and involves whole-rock geochemistry, mineral geochemistry, and isotopic studies. When completed, this should add greatly to the very generalized treatment of the geochemistry of mineralized rocks.

The present database for the PLI consists of about 330 analyses (about 80% from drill core), including about 100 from the Mineralized sequence. Major and trace elements were analyzed at the Department of Mines and Energy laboratory, mostly by Inductively-Coupled Plasma Emission Spectroscopy (ICP-ES), and a subgroup of samples were also analyzed for rare-earth elements (REE) at Memorial University of Newfoundland, by Inductively-Coupled Plasma Mass Spectroscopy (ICP-MS). Detection limits for trace elements at the Mines and Energy laboratory are better than 5 ppm for all, and the precision of analyses is estimated to be better than ± 5% for all except Rb, Mo and Pb, which are generally close to detection limits. For details of accuracy and precision of ICP-MS analyses at Memorial University, see Jenner *et al*. (1990).

SUMMARY OF NUMERICAL DATA

As a first step, the data were grouped on the basis of geographic area and geological unit, and average compositions were calculated (Tables 1 through 5). The first-order geographic divisions were the South intrusion, the Mineral Hill intrusions and the North intrusion. The South intrusion was divided into upper and lower sections, because drill-sections (Figure 3) suggest that it may be a composite body, and the North intrusion was subdivided into its three lobes, as outlined previously. The five main geological units described above were used as a secondary subdivision, i.e., 1) fine-grained layered olivine gabbro, 2) peridotite–melagabbro, 3) coarse-grained massive leucogabbro, 4) black olivine gabbro and 5) diabase and related rocks.

Fine-grained Layered Olivine Gabbro

Table 1 summarizes this unit in various geographic areas. The average major-element compositions are very similar, and the low standard deviations suggest that its composition does not vary widely. Mean SiO_2 ranges from 45.2% in the North intrusion (Taheke Lake lobe) to 47.6% in the South intrusion, and Al_2O_3 and Fe_2O_3 are high in all areas. There are some internal variations in MgO content and Mg/(Mg+Fe), as the Taheke Lake lobe of the North intrusion averages over 15% MgO compared to 10% MgO or less elsewhere. The Taheke Lake lobe also has the lowest mean Na_2O and K_2O contents (< 2% and <0.2% respectively) indicating a less evolved composition. South intrusion gabbros have notably higher mean TiO_2, K_2O and P_2O_5 contents than their counterparts elsewhere, but there are no other clear major-element distinctions. The Mineral Hill intrusion gabbros share some of these characteristics, but their enrichment in TiO_2 and P_2O_5 is less marked. The mean trace-element compositions are closely similar for many elements, but contrasts are shown by Ti (as noted above), Co, Ni, Sr, Ba, La and Ce. Most areas have similar Ni (88 to 120 ppm) and Co (55 to 71 ppm) contents, but the Taheke Lake lobe is distinctly richer in Ni (186 ppm) and Co (100 ppm), consistent with its higher MgO content. The most notable contrast is that South intrusion and Mineral Hill intrusions gabbros contain almost twice as much Ba as those from other areas, and also higher Sr. Lanthanum and Ce are also enriched twofold in the South intrusion and Mineral Hill intrusions, compared to the other areas, as noted previuosly (MacDonald, 1999).

Melagabbro and Peridotite

Table 2 summarizes this unit, represented by 5 samples from the South intrusion and a single sample from the NDT

Table 1. Composition of fine-grained, layered olivine gabbro in various areas

		South Intrusion Lower Section Mean n=7	S.D	South Intrusion Upper Section Mean n=4	S.D	Mineral Hill Intrusion Mean n=9	S.D	North Intrusion NDT Lobe Mean n=34	S.D	North Intrusion Happy Face Lobe Mean n=4	S.D	North Intrusion Taheke L. Lobe Mean n=5	S.D
SiO2	%	47.64	1.14	47.13	0.71	47.37	1.32	46.16	1.38	47.35	0.66	45.22	1.22
TiO2	%	1.57	0.25	1.98	0.58	1.4	0.42	0.89	0.33	1.08	0.11	0.53	0.16
Al2O3	%	18.54	1.67	16.07	1.61	16.44	1.49	17.79	2.68	17.82	1.35	15.21	1.85
Fe2O3	%	11.3	1.69	13.67	1.88	14.02	1.98	12.97	2.52	12.96	1.27	14.04	1.48
MnO	%	0.14	0.03	0.18	0.02	0.18	0.03	0.17	0.03	0.17	0.01	0.17	0.02
MgO	%	8.29	1.46	8.25	1.69	8.43	1.27	9.98	3.21	8.16	0.9	15.19	3.08
CaO	%	8.64	0.32	8.25	0.56	8.66	0.43	9.03	0.98	9.69	0.61	7.65	1.02
Na2O	%	3.37	0.18	3.12	0.5	2.89	0.15	2.65	0.46	2.82	0.17	1.94	0.37
K2O	%	0.52	0.13	0.65	0.16	0.49	0.18	0.29	0.1	0.32	0.04	0.16	0.05
P2O5	%	0.32	0.04	0.37	0.19	0.19	0.09	0.09	0.03	0.11	0.01	0.06	0.02
LOI	%	0.25	0.2	0.79	0.41	0.58	0.34	0.74	1.13	0.5	0.2	0.61	0
Total		100.48		100.06		100.45		100.28		100.74		100.29	
Li	ppm	4	1.3	6.5	0.3	6.2	1.9	5.2	2.7	6.2	0.9	3.8	0.5
Be	ppm	0.4	0.1	0.5	0.1	0.4	0.1	0.3	0.1	0.3	0.1	0.1	0
Sc	ppm	14.6	8.7	23.3	1.8	23.2	7.8	17.6	6.5	25.1	5.8	13.2	2.8
Ti	ppm	9726	1347	12062	3423	8702	2516	5495	1984	6699	754	3295	990
V	ppm	101	46	161	20	152	46	105	36	152	18	74	20
Cr	ppm	102	32	104	35	71	15	60	20	64	14	84	8
Mn	ppm	1043	244	1304	173	1372	222	1268	238	1214	160	1235	127
Co	ppm	55	5	60	14	72	23	76	20	71	19	100	16
Ni	ppm	102	43	61	20	91	79	108	53	121	115	186	42
Cu	ppm	19	12	21	4	66	100	25	9	98	116	13	3
Zn	ppm	85	16	109	15	112	23	94	18	100	8	93	5
Ga	ppm	18	0			19	3	21	4	23	0		
Rb	ppm	4	3	7	1	7	3	4	2	5	2	2	0
Sr	ppm	426	48	354	77	299	56	291	67	292	15	244	35
Y	ppm	15	6	22	1	22	6	16	6	21	4	9	3
Zr	ppm	82	21	113	17	93	35	55	23	70	7	33	11
Nb	ppm	6	2	9	2	5	3	3	1	4	1	2	1
Mo	ppm	1	0	1	0	1	0	1	0	1	0	1	0
Ba	ppm	270	61	309	59	244	91	146	37	160	24	96	24
La	ppm	11	4	13	3	10	5	5	2	6	1	2	1
Ce	ppm	24	7	28	6	24	9	14	5	15	2	8	2
Dy	ppm	2.6	1.1	3.8	0.1	3.5	1.1	2.4	1	3.5	0.5	1.8	0.4
Pb	ppm	1	0	1	0	2	2	1	0	1	0	1	0

lobe of the North intrusion. As expected, this has a primitive major-element composition. Mean SiO_2 is 41%, and it also has high mean Fe_2O_3 (17.8%) and MgO (21.6%) contents. The South intrusion samples are enriched in TiO_2, K_2O and P_2O_5 relative to the North intrusion, as seen in the associated fine-grained gabbro unit (*see above*). The high Co, Ni and Cu in the South intrusion samples are due to interstitial sulphides, whereas the unmineralized North intrusion sample contains only 220 ppm Ni, which is anomalously low for a rock containing over 60% olivine. South intrusion melagabbro samples are richer in Sr, Zr, Ba, La and Ce than the North intrusion sample.

Coarse-Grained Massive Leucogabbro

Table 3 summarizes this unit, which does not occur in the South intrusion, aside from a very thin unit intersected in the uppermost part of hole #97-79. Average major-element compositions are similar in all areas, although there is a subtle variation in SiO_2, Al_2O_3, MgO and CaO. Mean trace-ele-

Table 2. Compositions of melagabbro and peridotite in various areas

		South Intrusion		North Intrusion NDT Lobe
		Mean n=5	S.D	Value n=1
SiO2	%	41.16	1.16	41.06
TiO2	%	1.5	0.2	0.55
Al2O3	%	8.44	1.47	7.24
Fe2O3	%	17.77	1.13	21.24
MnO	%	0.19	0.01	0.265
MgO	%	21.63	1.84	22.47
CaO	%	4.18	0.58	4.13
Na2O	%	1.72	0.4	1.07
K2O	%	0.44	0.08	0.15
P2O5	%	0.34	0.05	0.08
LOI	%	3.05	0.75	1.71
Total		100.41		99.96
Li	ppm	5.7	1.3	6.6
Be	ppm	0.3	0.1	0.1
Sc	ppm	8.7	1.3	19.5
Ti	ppm	9059	978	3394
V	ppm	81	8	84
Cr	ppm	130	10	74
Mn	ppm	1437	122	2093
Co	ppm	149	27	146
Ni	ppm	940	228	220
Cu	ppm	405	200	15
Zn	ppm	116	2	125
Ga	ppm			
Rb	ppm	2	0	2
Sr	ppm	166	33	128
Y	ppm	12	1	13
Zr	ppm	79	9	38
Nb	ppm	4	1	2
Mo	ppm	1	0	1
Ba	ppm	188	38	92
La	ppm	8	1	2
Ce	ppm	22	2	15
Dy	ppm	2.4	0.3	2
Pb	ppm	5	2	3

ment compositions are remarkably similar in all areas, and the Co, Ni and Cu contents are generally very low, typically < 50 ppm for each element. Compared to the fine-grained gabbro unit (Table 1), the massive leucogabbro is richer in Al_2O_3 and CaO, and poorer in Fe_2O_3 and MgO. Such differences are consistent with petrographic data indicating that it is a plagioclase cumulate (MacDonald, 1999; Kerr, 1999).

Black Olivine Gabbro

Table 4 summarizes this unit, which occurs only in the North intrusion. The major-element compositions are similar in the Taheke Lake and Happy Face lobes, and resemble that of the massive leucogabbro (Table 3) aside from slightly higher MgO and variably lower Al_2O_3 and Fe_2O_3. There are no clear differences in trace-element composition between this and the other North intrusion units. Nickel contents of the black olivine gabbro are modest (55 to 82 ppm), but generally higher than those of the massive leucogabbro. The composition of this unit is similar to that of the massive leucogabbro but statistical tests (based on holes #97-75 and #97-77) show that the two are not completely identical (MacDonald, 1999).

Diabase and Related Rocks

Table 5 summarizes this unit. Rapidly cooled rocks such as diabase closely approximate liquid compositions, and may thus provide information about parental magma compositions. Viewed as a group, diabase samples display a similar range of SiO_2 contents to other PLI units (45.6 to 52.0%), but have more variable major- and trace-element compositions.

Analyses from the South intrusion include diabase that appears to intrude the upper section of hole #97-86, and a basal chill zone located beneath the mineralized zone in hole #97-79. Both are distinguished by having high TiO_2 contents (3.4 to 3.8%) and P_2O_5 contents (1.0 to 1.6%) compared to all other diabase samples, and also to the associated South intrusion fine-grained gabbro (Table 1). Samples from basal (chilled) diabases in the North intrusion all have much lower TiO_2 (0.4 to 1.6%) and P_2O_5 (< 0.2%) contents than those of the South intrusion, but similar K_2O contents. A basal (chilled) diabase from the Mineral Hill intrusions has higher TiO_2 than the North intrusion examples, but is much less Ti-enriched than South intrusion diabases. Essentially, the diabases mirror major-element contrasts noted within the associated fine-grained gabbros, but are also compositionally distinct from these rocks. Specifically, they are higher in TiO_2, K_2O and P_2O_5, locally higher in SiO_2 and CaO, poorer in MgO, and locally poorer in Al_2O_3. (Tables 1 and 5). A single (chilled) diabase sample, which is gradational with coarse-grained leucogabbro at the upper contact of the North intrusion (Happy Face lobe), is similar to basal chilled diabases associated with the fine-grained gabbro unit elsewhere in the North intrusion.

Trace-element compositions of the diabase samples are more variable than for other PLI units. Zirconium, Nb, La

Table 3. Compositions of coarse-grained, massive leucogabbro in various areas

		Mineral Hill Intrusion Mean n=5	S.D	Worm Intrusion Mean n=6	S.D	North Intrusion NDT Lobe Mean n=8	S.D	North Intrusion Happy Face Lobe Mean n=17	S.D	North Intrusion Taheke L. Lobe Mean n=3	S.D
SiO2	%	47.54	0.39	47.86	0.33	48.99	1.23	48.51	1	48.7	0.58
TiO2	%	1.3	0.32	1.49	0.62	0.9	0.3	1.06	0.3	0.69	0.2
Al2O3	%	19.01	1.71	17.32	2.87	21.88	3.1	20.41	1.3	23.04	0.7
Fe2O3	%	11.83	1.44	13.73	2.63	9.23	2.98	10.76	1.3	8.33	0.72
MnO	%	0.16	0.02	0.19	0.04	0.12	0.05	0.14	0.03	0.11	0.01
MgO	%	5.81	1.01	6.4	0.99	4.66	1.14	4.93	1.03	4.55	0.08
CaO	%	9.86	0.67	9.39	0.79	10.6	1.38	10.2	0.49	11.1	0.36
Na2O	%	3.13	0.18	3.27	0.23	3.4	0.27	3.27	0.2	3.27	0.05
K2O	%	0.42	0.12	0.45	0.12	0.39	0.21	0.4	0.14	0.25	0.03
P2O5	%	0.13	0.05	0.14	0.04	0.09	0.04	0.12	0.05	0.07	0.02
LOI	%	0.84	0.43	0.26	0.32	0.59	0.81	0.51	0.49	0.24	0.07
Total		100.02		100.46		100.79		100.31		100.39	
Li	ppm	5.7	1.6	6.4	1.6	9	10.8	6.8	2.5	3.9	0.2
Be	ppm	0.5	0	0.4	0.2	0.3	0.1	0.4	0.1	0.2	0.1
Sc	ppm	22.8	4.7	31	16.1	17.8	10	20.1	3.9	14.7	1.4
Ti	ppm	8202	1691	9256	3783	5540	1648	6752	1570	4364	1277
V	ppm	145	31	207	145	109	51	118	34	95	12
Cr	ppm	50	14	39	10	50	57	35	12	40	20
Mn	ppm	1250	149	1406	277	934	314	1115	127	815	134
Co	ppm	51	7	56	6	40	9	45	8	39	2
Ni	ppm	44	23	32	11	30	5	39	13	30	0
Cu	ppm	35	8	42	21	24	6	34	8	20	8
Zn	ppm	104	17	107	21	75	26	92	12	67	7
Ga	ppm	22	2	23	2	21	1	23	2	22	0
Rb	ppm	9	0	5	3	4	2	8	2	5	0
Sr	ppm	334	28	291	42	360	44	349	25	377	3
Y	ppm	22	3	25	7	16	5	23	6	13	4
Zr	ppm	76	20	91	32	58	16	75	31	40	13
Nb	ppm	3	2	5	1	4	1	4	2	3	1
Mo	ppm	1	0	1	0	1	0	1	0	1	0
Ba	ppm	192	51	211	55	157	39	191	53	128	20
La	ppm	8	3	8	3	6	2	8	3	4	1
Ce	ppm	18	5	20	6	14	5	17	5	10	3
Dy	ppm	3.3	0.6	3.9	1.3	2.4	0.9	3.4	1.2	2	0.3
Pb	ppm	3	3	1	0	1	0	1	0	1	0

and Ce are strongly enriched (by factors of 3 to 5) in South intrusion diabases relative to other areas. The Mineral Hill intrusions diabase also shows this enrichment but not to the same extent. As in the case of major-element compositions, it seems to be "intermediate" between the South and North intrusions. Diabases from the NDT lobe have the lowest Zr, Nb and REE contents. The high Ni and Cu contents in sample #AKC1193 are due to small amounts of sulphide; if this is excluded, diabase Ni contents are variable, but generally low (13 to 53 ppm). Compared to spatially associated fine-grained gabbros, the diabases have higher Rb and Ba contents, lower Ni contents, and (in the South intrusion and Mineral Hill intrusions) higher Y, Nb, La and Ce. However, diabases from the NDT lobe have lower Zr, Y and REE contents than the spatially associated fine-grained gabbros. In summary, aside from the NDT lobe, diabases have generally more evolved compositions than associated fine-grained gabbros.

Table 4. Compositions of black olivine gabbro in various areas

		North Intrusion Taheke Lake Lobe Mean n=44	S.D	North Intrusion Happy Face Lobe Mean n=2	S.D
SiO2	%	48.17	1.37	47.47	0.33
TiO2	%	0.94	0.27	1.17	0.02
Al2O3	%	20.11	2.69	17.19	1.2
Fe2O3	%	11.03	2.53	13.53	0.52
MnO	%	0.15	0.03	0.18	0
MgO	%	6.77	2.97	8.76	0.98
CaO	%	10	1.25	9.04	0.48
Na2O	%	3.02	0.39	2.67	0.13
K2O	%	0.33	0.1	0.33	0.03
P2O5	%	0.1	0.03	0.12	0
LOI	%	0.34	0.42	0.1	0
Total		100.82		100.5	
Li	ppm	5.6	1.4	6.5	0.6
Be	ppm	0.3	0.1	0.3	0
Sc	ppm	19.2	6.5	23.5	0.4
Ti	ppm	5844	1569	7329	231
V	ppm	121	38	154	6
Cr	ppm	45	25	55	9
Mn	ppm	1070	242	1311	14
Co	ppm	54	19	70	7
Ni	ppm	55	40	82	18
Cu	ppm	23	8	46	18
Zn	ppm	87	15	105	3
Ga	ppm	22	1		
Rb	ppm	5	2	4	2
Sr	ppm	328	44	283	9
Y	ppm	17	4	21	1
Zr	ppm	60	20	77	3
Nb	ppm	4	1	5	1
Mo	ppm	1	0	1	0
Ba	ppm	153	34	163	6
La	ppm	6	2	6	0
Ce	ppm	13	4	16	1
Dy	ppm	2.8	0.7	3.3	0.1
Pb	ppm	1	0	1	0

GEOCHEMICAL VARIATION TRENDS

Major Elements

Major-element oxides, excluding Fe_2O_3, are negatively correlated with MgO, and have weaker positive correlations against SiO_2. For many elements (e.g., CaO and Al_2O_3; Figure 5a and b), correlation is linear, and all units lie upon a single common trend. Such trends are defined at the high-MgO–low SiO_2 (unfractionated) end by the melagabbro–peridotite unit, and at the low-MgO–high-SiO_2 (fractionated) end by the massive leucogabbro unit. Generally, the latter shows higher Al_2O_3 and CaO, and lower MgO (as noted from analysis tables), but overlaps extensively with both the fine-grained gabbro and black olivine gabbro units. Diabase samples mostly have lower CaO and Al_2O_3 at a given MgO or SiO_2 content (Figure 5a, b). In the CaO–MgO diagram, the PLI data form a well-defined array that lies between tie lines joining plagioclase (An_{60} to An_{55}) and olivine (Fo_{65} to Fo_{75}), reflecting the dominance of olivine and plagioclase, although measured olivine compositions are generally less than Fo_{60} (MacDonald, 1999; *see below*). Diabase samples all lie below the main data array, indicating their lack of cumulus plagioclase. The black olivine gabbro unit shows a wider range of MgO contents than the otherwise similar massive leucogabbro unit.

TiO_2 and Na_2O (Figure 5c, d) separate gabbros from different areas. Fine-grained gabbros from the South intrusion and Mineral Hill intrusions have higher TiO_2 than those from the North intrusion, as do diabase and melagabbro samples. Diabase samples are the most Ti-enriched. Similar trends against MgO are shown by P_2O_5 (not illustrated), which is also strongly enriched in diabase samples. The Na_2O–MgO diagram (Figure 5d) reveals two subparallel trends; an upper (elevated Na_2O) trend defined mainly by the South intrusion, and a lower (depressed Na_2O) trend defined by the remainder of the data, in this case including the Mineral Hill intrusions. Most North intrusion mafic rocks are subalkaline, but many of the South intrusion samples plot within the alkaline field on the (Na_2O+K_2O)–SiO_2 plot (Figure 6a). All show tholeiitic (Fe-enrichment) evolution trends (not illustrated). Magnesium Numbers (i.e., molecular MgO/[MgO+FeO]) for PLI rocks decline from almost 75 in melagabbro to about 30 in the massive leucogabbro unit, but there is considerable overlap between all units (Figure 6b). There is a progressive decrease in Mg Number from melagabbro, through fine-grained olivine gabbro to black olivine gabbro and massive leucogabbro, coupled with a mild increase in SiO_2 (Figure 6b). The black olivine gabbro unit is relatively magnesian (Mg Number generally > 50) compared to the massive leucogabbro unit (Mg Number generally < 50). Most diabase samples have Mg numbers < 50.

The overall distribution of data in Figures 5a and b is very similar to that of the Voisey's Bay intrusion, as defined by Lightfoot and Naldrett (1999) and Li *et al.* (2000). PLI diabase samples plot in the same area as the "conduit assemblage" from Voisey's Bay. In the Al_2O_3 *vs* SiO_2 plot, the PLI data are less tightly grouped than the Voisey's Bay intrusion data (Li *et al.*, 2000). In general, the PLI data more closely resemble the Voisey's Bay intrusion than the spatially associated, but significantly younger, Mushuau intrusion.

Table 5. Compositions of diabase and chilled gabbro in various areas

		South Intrusion			Mineral Hill Intrusion		North Intrusion Area				
		Hole 97-86 Upper Section		Hole 97-79 Basal Chill	Hole 96-48 Basal Chill Zone		NDT Basal Chill	NDT Basal Chill	NDT Basal Chill	Taheke L. Basal Chill	Happy Face Upper Chill
		Mean n=2	S.D	AKC-825	Mean n=2	S.D	AKC-1193	AKC-1208	AKC-1191	AKC-1131	AKC-705
SiO2	%	47.00	0.61	45.56	49.92	0.75	52.01	52.12	49.12	48.41	49.31
TiO2	%	3.42	0.03	3.77	1.72	0.06	0.37	0.81	1.22	1.58	1.06
Al2O3	%	13.84	0.03	16.57	14.96	0.30	18.16	17.57	16.84	16.81	16.69
Fe2O3	%	15.17	0.39	14.48	14.59	0.00	9.91	10.88	13.91	13.45	12.35
MnO	%	0.18	0.01	0.17	0.18	0.01	0.14	0.16	0.19	0.18	0.16
MgO	%	4.22	0.20	6.22	5.68	0.43	7.48	6.56	7.51	6.45	6.30
CaO	%	7.52	0.36	7.84	8.29	0.50	7.54	7.46	8.43	9.19	8.58
Na2O	%	3.89	0.09	3.77	2.86	0.12	2.92	3.01	3.00	2.77	2.96
K2O	%	1.11	0.26	0.89	0.75	0.08	0.94	1.18	0.58	0.55	0.58
P2O5	%	1.59	0.01	0.99	0.23	0.03	0.04	0.03	0.16	0.16	0.15
LOI	%	2.88	0.82	0.19	0.97	0.66	0.71	0.98	n/a	1.79	0.91
Total		100.82		100.45	100.15		100.22	100.76	100.96	101.34	99.05
Li	ppm	5.8	1.2	9.5	6.1	0.2	18.3	30.5	12.7	8.5	3.5
Be	ppm	1.5	0	0.8	0.8	0.1	0.3	0.4	0.4	0.5	0.5
Sc	ppm	24	0.1	18.6	35.6	0.6	15.3	23.8	25.4	33.7	27.4
Ti	ppm	21168	6	22860	11234	650	2276	4939	7342	9468	6994
V	ppm	161	1	153	191	1	87	148	151	212	155
Cr	ppm	37	1	59	64	8	81	71	53	87	97
Mn	ppm	1348	105	1251	1417	84	1031	1151	1374	1233	1285
Co	ppm	44	1	52	49	3	80	55	57	61	53
Ni	ppm	26	1	50	17	3	203	42	13	49	53
Cu	ppm	28	0	25	33	3	236	129	18	53	35
Zn	ppm	124	2	118	127	6	76	80	113	117	108
Ga	ppm			24	1						
Rb	ppm	16	4	8		23	34	23	8	23	
Sr	ppm	266	18	448	297	2	294	277	294	270	309
Y	ppm	42	1	28	33	1	8	8	8	28	23
Zr	ppm	290	5	195	123	8	29	23	29	94	76
Nb	ppm	22	0	17	7	1	1	3	1	5	5
Mo	ppm	2	0	1	1	0	1	1	1	1	1
Ba	ppm	708	124	455	411	57	174	256	174	198	311
La	ppm	60	1	26	18	3	4	4	4	9	17
Ce	ppm	103	1	54	35	4	9	9	9	19	31
Dy	ppm	7	0	5.1	5	0.1	1.1	1.1	1.1	4.9	3.4
Pb	ppm	4	1	1	2	1	2	2	2	1	2

Trace Elements

Scandium, V, Mn and Zn all show flat trends against MgO, or poor correlations. Chromium shows a good correlation with MgO, which is to be expected, but also demonstrates that the South intrusion samples have high Cr even at relatively low MgO (Figure 7a). Both Co and Ni correlate well with MgO, suggesting that they are largely controlled by olivine (Figure 7b and c). Excluding South intrusion melagabbros (omitted from the chart), the highest Ni contents are shown by the fine-grained olivine gabbro and black olivine gabbro, but both these units vary widely. The majority of samples contain less than 100 ppm Co and 150 ppm Ni. In contrast, Cu shows little systematic variation against MgO (Figure 7d), and is low (commonly < 50 ppm) in all units. A few samples that have high Cu contents (> 200 ppm) contain minor amounts of sulphides. Diabase samples have higher Cu contents (> 30 ppm) than many of the gabbro samples.

Strontium and Ba show inverse correlations against MgO, consistent with incompatible behaviour during olivine fractionation. Fine-grained gabbros from the South intrusion mostly have higher Sr contents at a given MgO content, but some South intrusion diabases lie within the main data array, as do most samples from the Mineral Hill

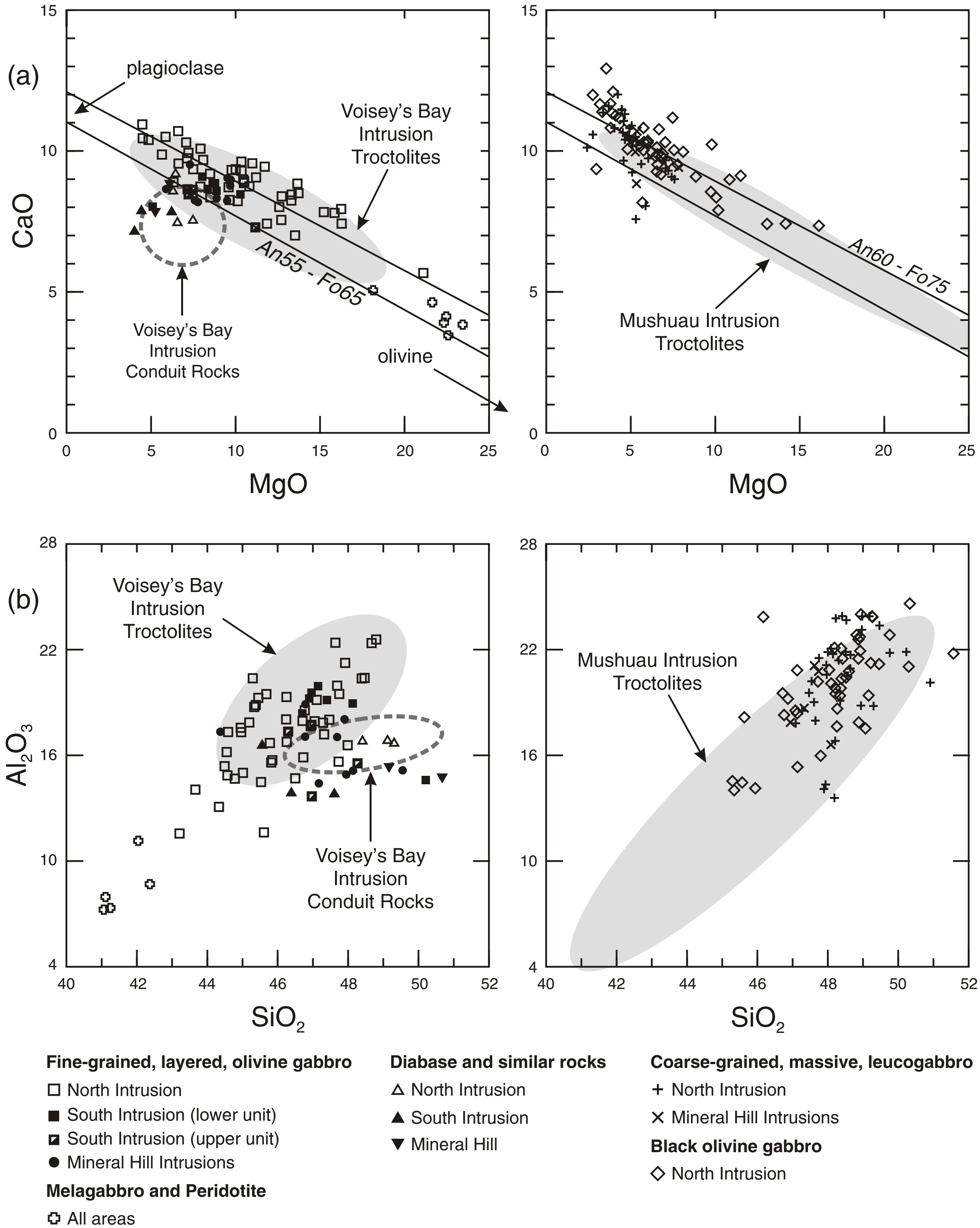

Figure 5. *Selected major-element compositional trends for unmineralized rocks of the Pants Lake Intrusion. (a) CaO vs MgO; comparative data fields after Li* et al. *(2000); (b) Al_2O_3 vs SiO_2; comparative data fields after Li* et al. *(2000); (c) TiO_2 vs MgO; (d) Na_2O vs MgO.*

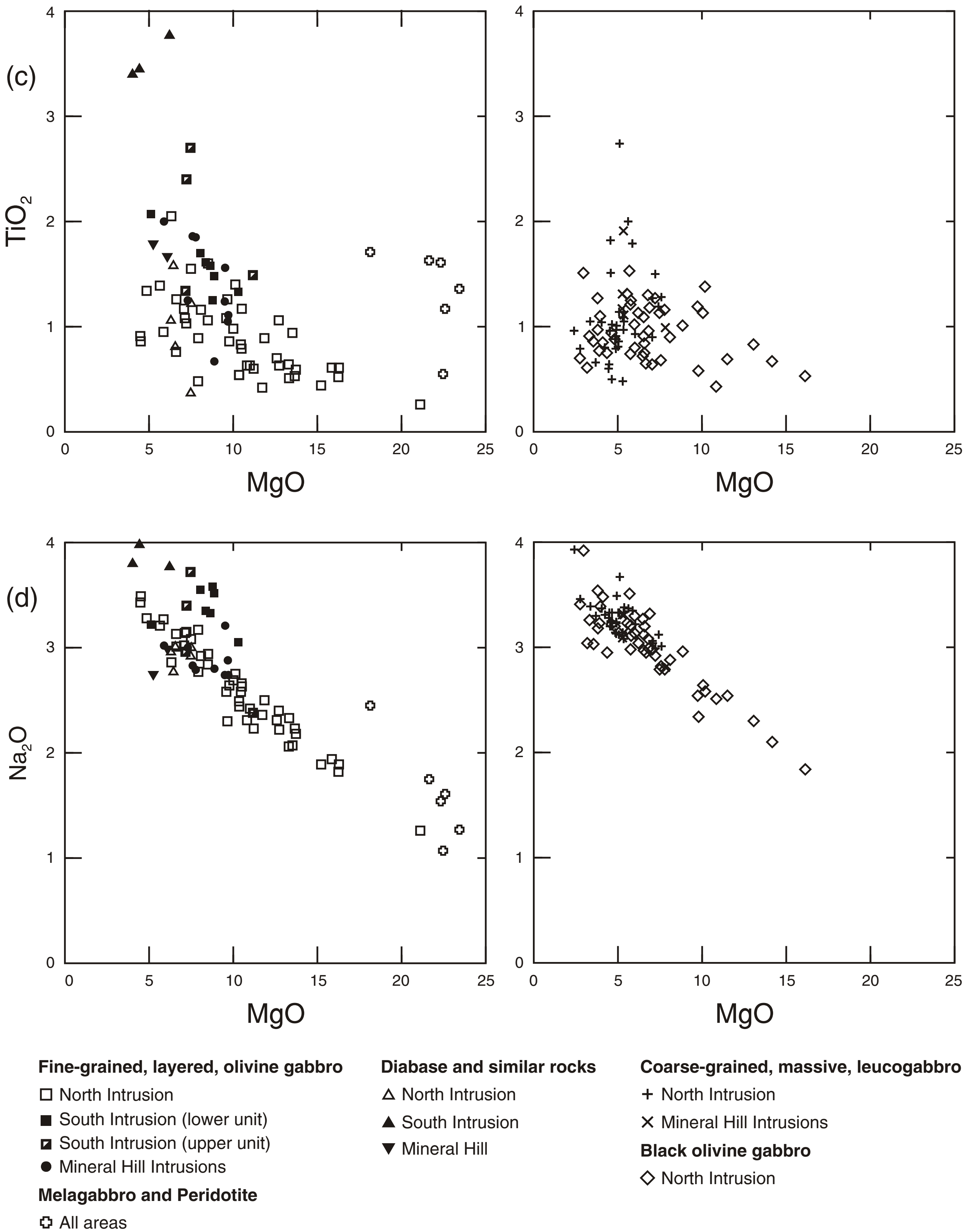

Figure 5. *Continued. Caption on previous page.*

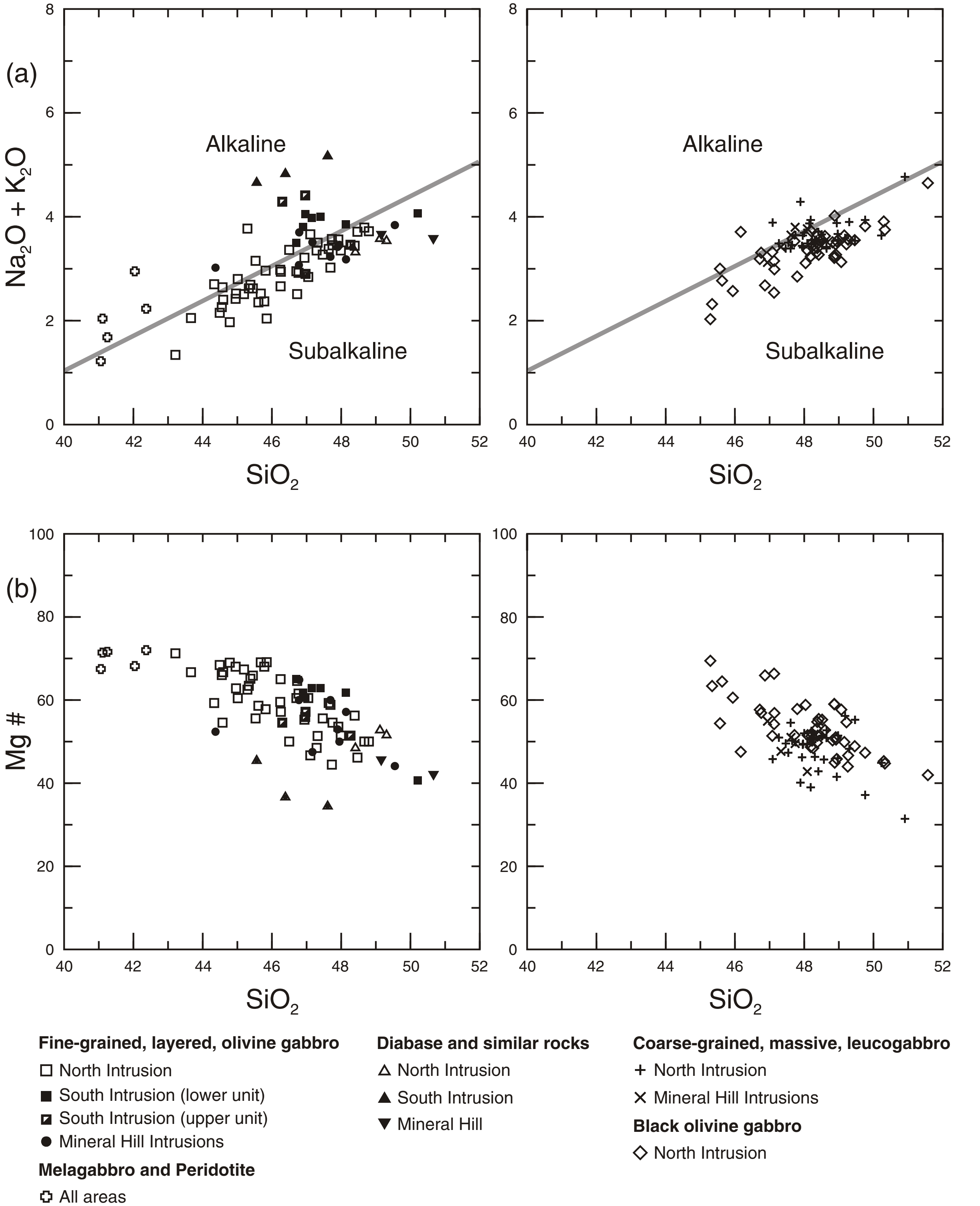

Figure 6. *Selected major-element compositional trends for unmineralized rocks of the Pants Lake Intrusion. (a) Total alkalies vs SiO_2; (b) Mg Number (molecular MgO/[MgO+FeO]) vs SiO_2.*

intrusions (Figure 8a). South intrusion samples also have distinctly higher Ba at a given MgO content (Figure 8b). The differences in the Sr and Ba trends reflect the fact that Sr is highly compatible in plagioclase, whereas Ba is generally incompatible; thus, cumulus plagioclase has a more significant affect upon Sr data.

Niobium has the clearest pattern (Figure 9a) and this most closely resembles the pattern for Ba (Figure 8b). The South intrusion and Mineral Hill intrusions show elevated Nb compared to the North intrusion, and most diabase samples also show Nb enrichment. Zirconium and Y patterns (not illustrated) resemble the Nb trends, but are more scattered. The pattern for Ce (Figure 9b) is shared by other REE's (e.g., La and Dy) and also resembles the pattern for Nb. The South intrusion and some (but not all) Mineral Hill intrusions samples show enrichment in all these REE's relative to the North intrusion.

A plot of Ni vs Cu shows a rather disorganized pattern in which Ni/Cu ratios range from less than 0.5 to over 20 (Figure 10a). This contrasts with the strong covariance of Ni and Cu in mineralized samples (Kerr, 1999; *see* later discussion). The range of Ni/Cu variation in sulphide-free samples is due to cumulus olivine, which contains Ni, but little Cu. Diabase samples, which more closely approach liquid compositions, have low Ni/Cu (0.5 to 2) and an average value of 0.95, slightly lower than the average Ni/Cu of mineralized rocks (Kerr, 1999). Ni/Co changes in a similar manner, from 0.25 to 1.0 in diabase, to > 4.0 in olivine-rich melagabbro (Figure 10b). These values are much lower than those of mineralized rocks, in which Ni/Co averages about 8, albeit with wide variation (Kerr, 1999).

The ratio value of Cu/Zr has been proposed as an indicator of metal depletion caused by sulphide segregation, because the two elements are normally covariant and incompatible, and unaffected by accumulation of either olivine or plagioclase. However, there are potential complications from zircon accumulation in more evolved mafic magmas. Low Cu/Zr and Cu/Hf ratios in PLI mafic rocks were initially noted by MacDonald (1999), who compared the frequency distributions to the data of Lightfoot *et al.* (1994) from the Noril'sk area in Russia. The larger database shows that virtually all unmineralized PLI samples have low Cu/Zr (0.2 to 0.8), and that Cu/Zr is poorly correlated with Ni (Figure 10c). Two diabase samples from the North intrusion have high Cu/Zr, but these are known to contain minor sulphide; all other diabases appear to be Cu-depleted. Cu/Zr < 1 in mafic rocks is generally considered to record the effects of sulphide removal, which affects Cu, but not Zr (e.g., Lightfoot *et al.,* 1994; Li and Naldrett, 1999).

On the basis of samples from holes #97-77 and #97-79. MacDonald (1999) noted that Ce/Yb ratios averaged 22 for the South intrusion versus 7 for the North intrusion, and that Th/Ta ratios averaged 2 for the South intrusion versus 4 for the North intrusion.

The Ce/Y ratio provides a regional indication of the slope of the REE profile; although Y is not a REE, it has similar chondrite-normalized abundances to heavy REE such as Yb or Lu. The contrasts in Ce/Yb previously noted by MacDonald (1999) imply that Ce/Y should be a useful areal discriminant. Ce/Y plotted against [Sr+Ba] provides excellent separation between PLI units and areas (Figure 10d). Fine-grained gabbros from the South intrusion are easily separated by their high Ce/Y and [Sr+Ba], and melagabbro samples from the South intrusion also have high Ce/Y. In this summary diagram, and several others previously discussed, samples from the Mineral Hill intrusions mostly plot with the North intrusion data, rather than with the South intrusion.

Rare-Earth-Element (REE) Profiles

Chondrite-normalized REE patterns of fine-grained olivine gabbro in the North intrusion have gentle slopes, with normalized La/Lu of 2 to 3. Most samples have a positive Eu anomaly, indicating cumulus plagioclase, and the amplitude of the anomaly is inversely correlated with the total REE content (Figure 11a). This is a common pattern in mafic igneous rocks, as cumulus plagioclase dilutes all REE except Eu. A troctolite sample has similar overall REE content to the more common gabbroic rocks. Diabase samples associated with the North intrusion have REE abundances akin to those of the most REE-enriched gabbros, and very similar shapes (Figure 11a).

The South intrusion, fine-grained gabbro unit has a distinctly steeper REE pattern, and a normalized La/Lu ratio of about 6 to 8, at least twice that of the North intrusion (Figure 11b; MacDonald, 1999). Modest positive Eu anomalies are again inversely correlated with total REE content. The upper and lower sections of the South intrusion are essentially identical, although the REE abundances vary slightly. Diabases associated with South intrusion gabbros show strong REE enrichment (up to La = 200 x chondrite), some LREE enrichment, and lack Eu anomalies. The more REE-enriched diabase comes from the upper part of the South intrusion. Melagabbro and peridotite from the South intrusion show the same steep REE pattern as the fine-grained gabbros, but lack Eu anomalies because they have no cumulus plagioclase (Figure 11d).

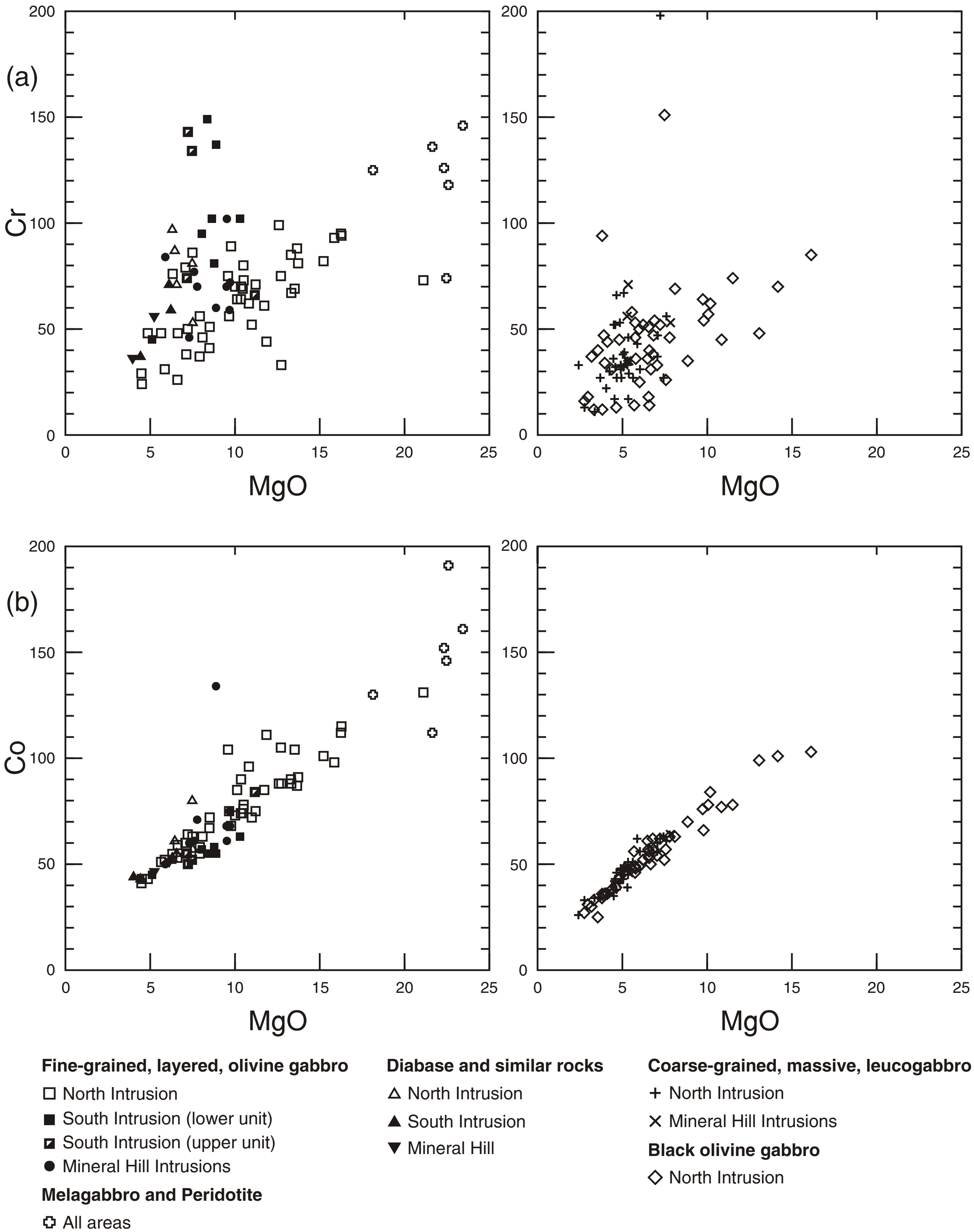

Figure 7. *Trace-element compositional trends for selected transition elements. (a) Cr vs MgO; (b) Co vs MgO; (c) Ni vs MgO; (d) Cu vs MgO.*

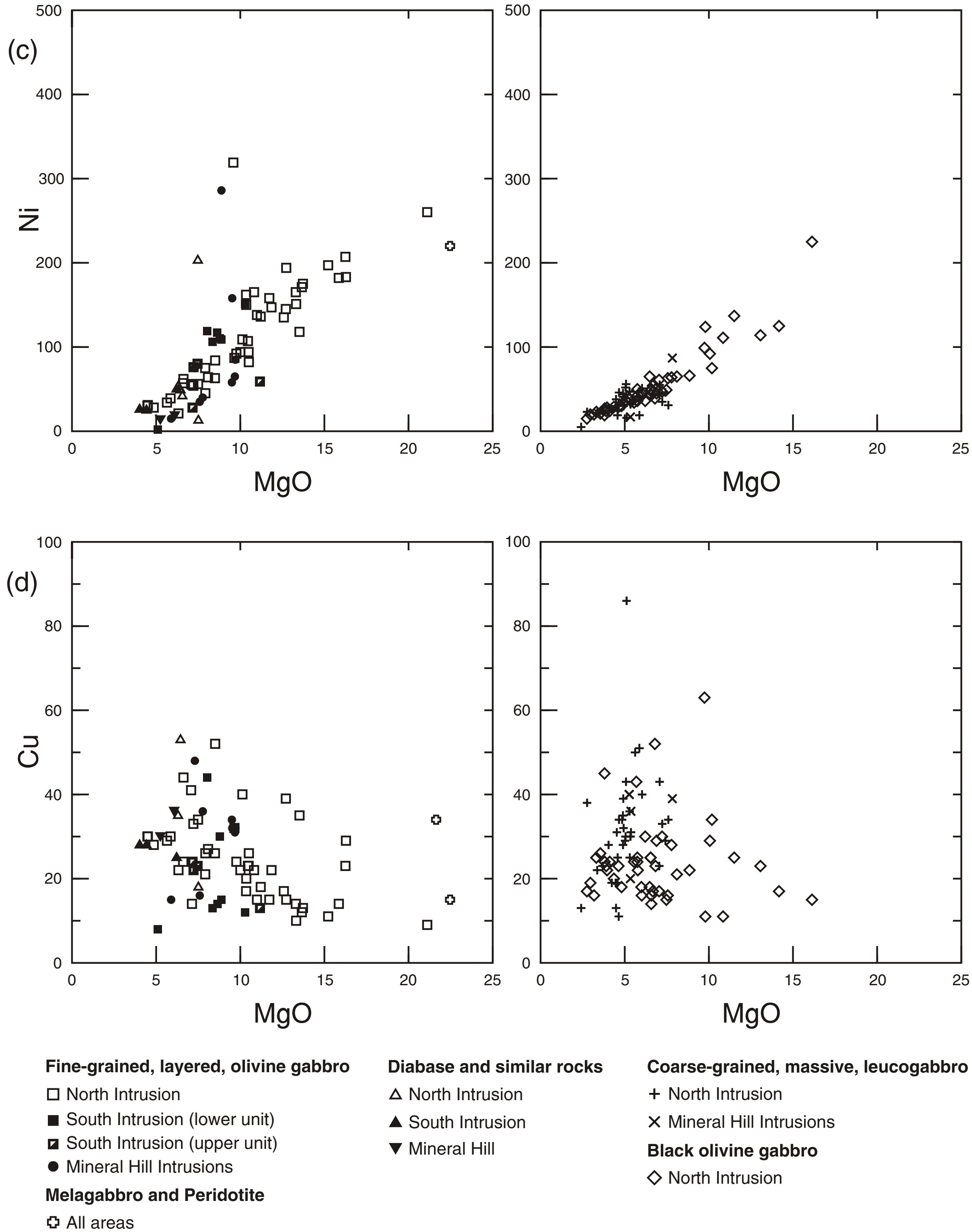

Figure 7. *Continued. See caption on previous page.*

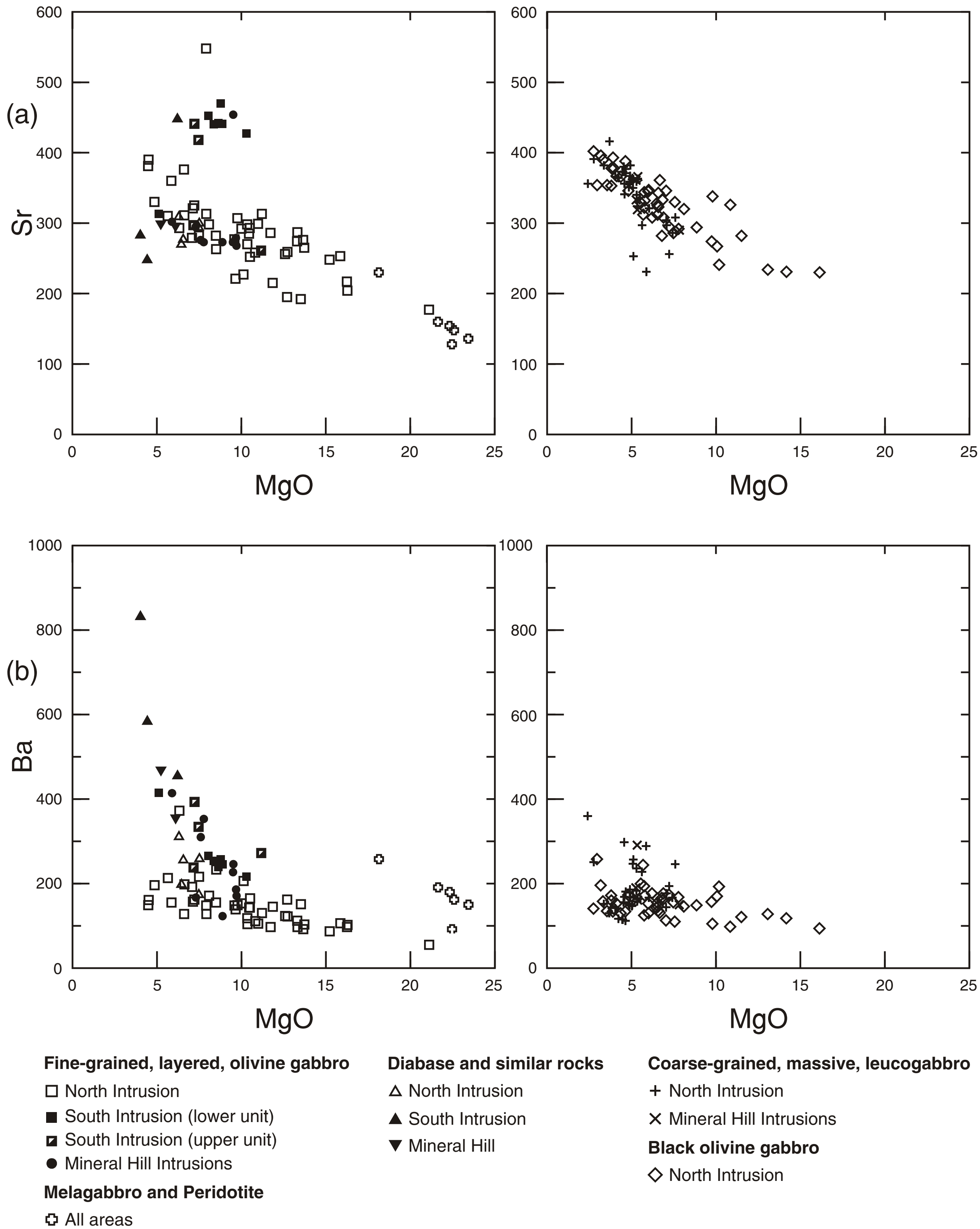

Figure 8. *Trace-element compositional trends for selected lithophile elements. (a) Sr vs MgO; (b) Ba vs MgO.*

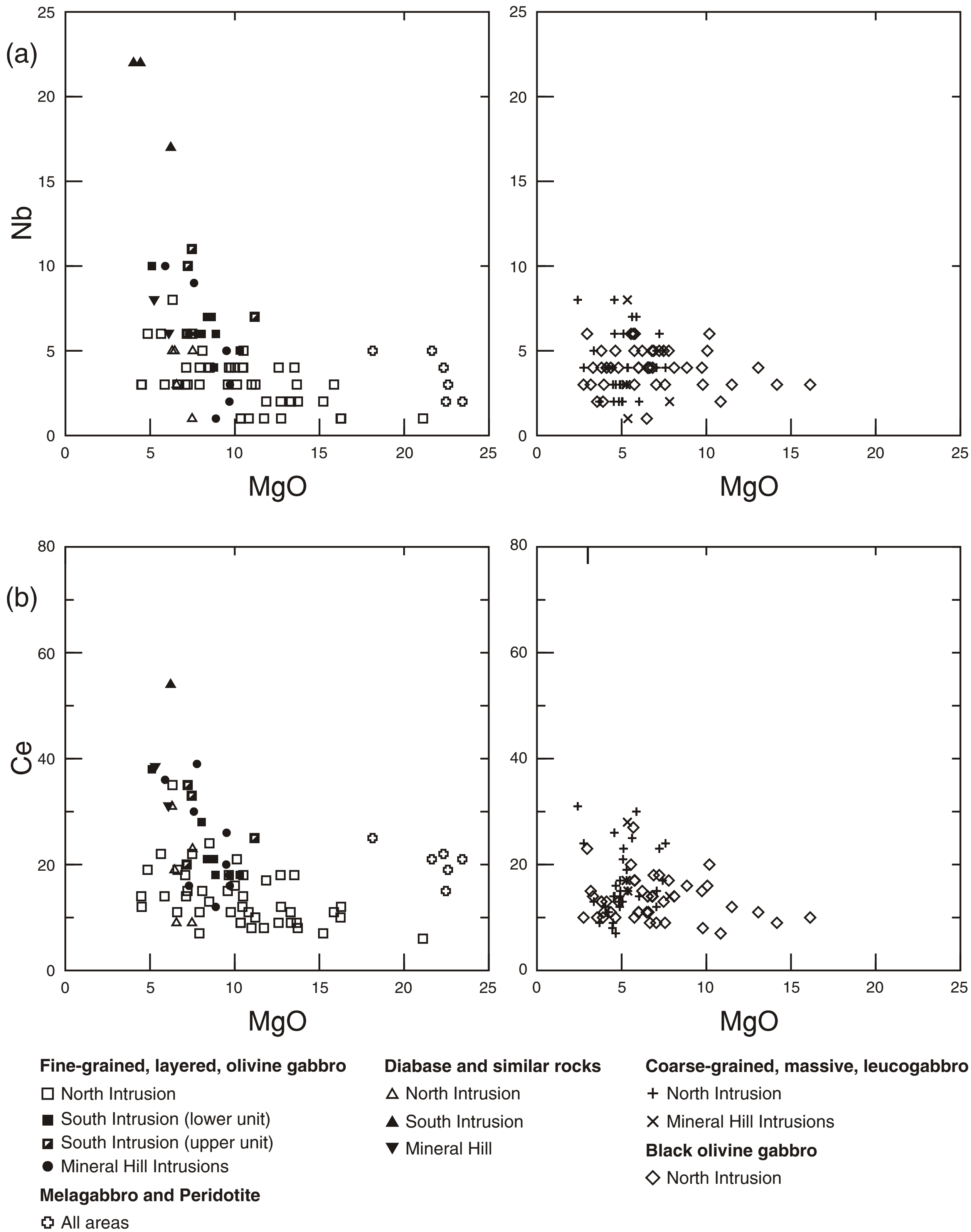

Figure 9. *Trace-element compositional trends for selected high-field-strength and rare-earth-elements. (a) Nb vs MgO; (b) Ce vs MgO.*

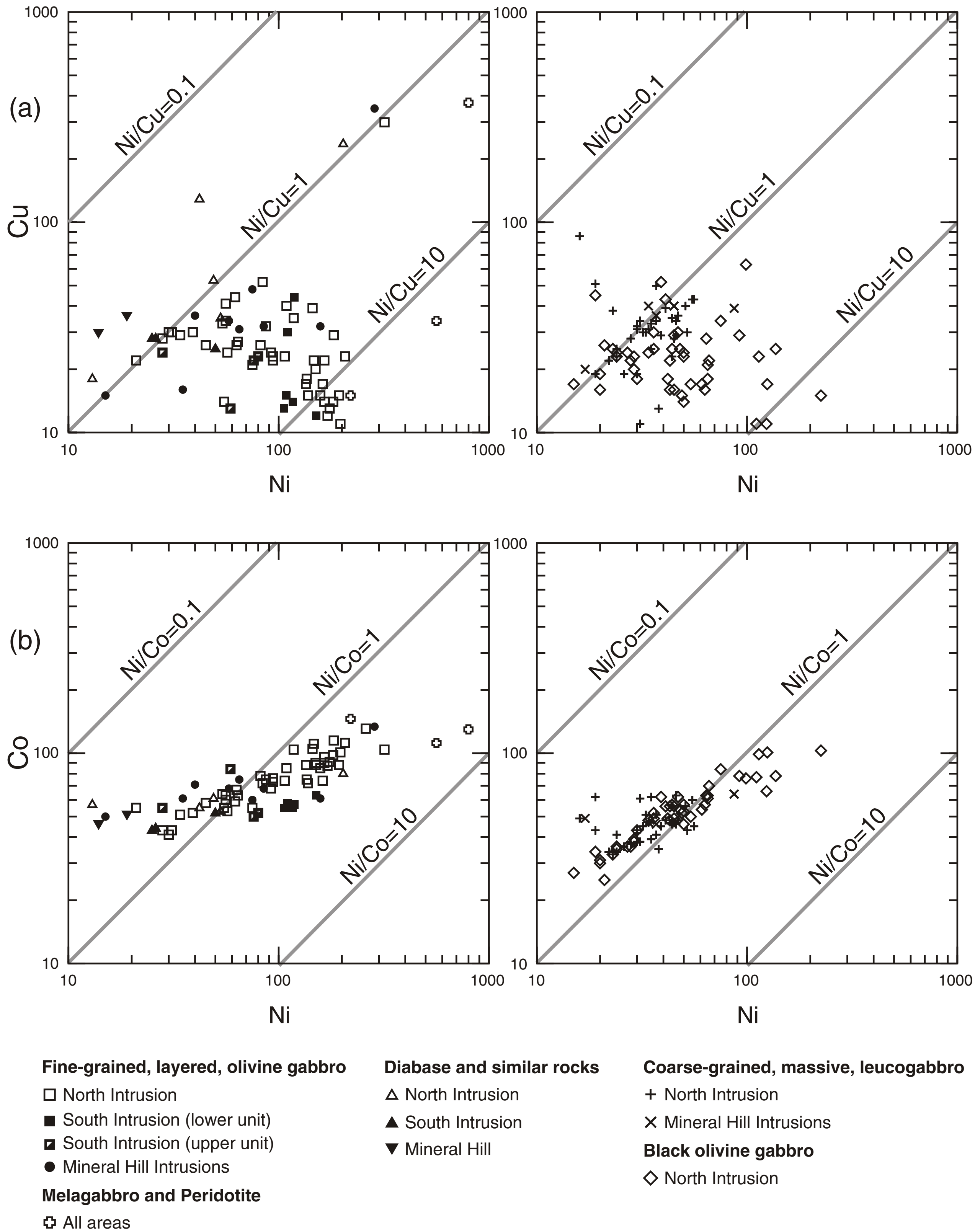

Figure 10. *Variations of selected trace-element ratios. (a) Cu vs Ni; (b) Co vs Ni; (c) Cu/Zr vs Ni; (d) Ce/Y vs [Sr+Ba].*

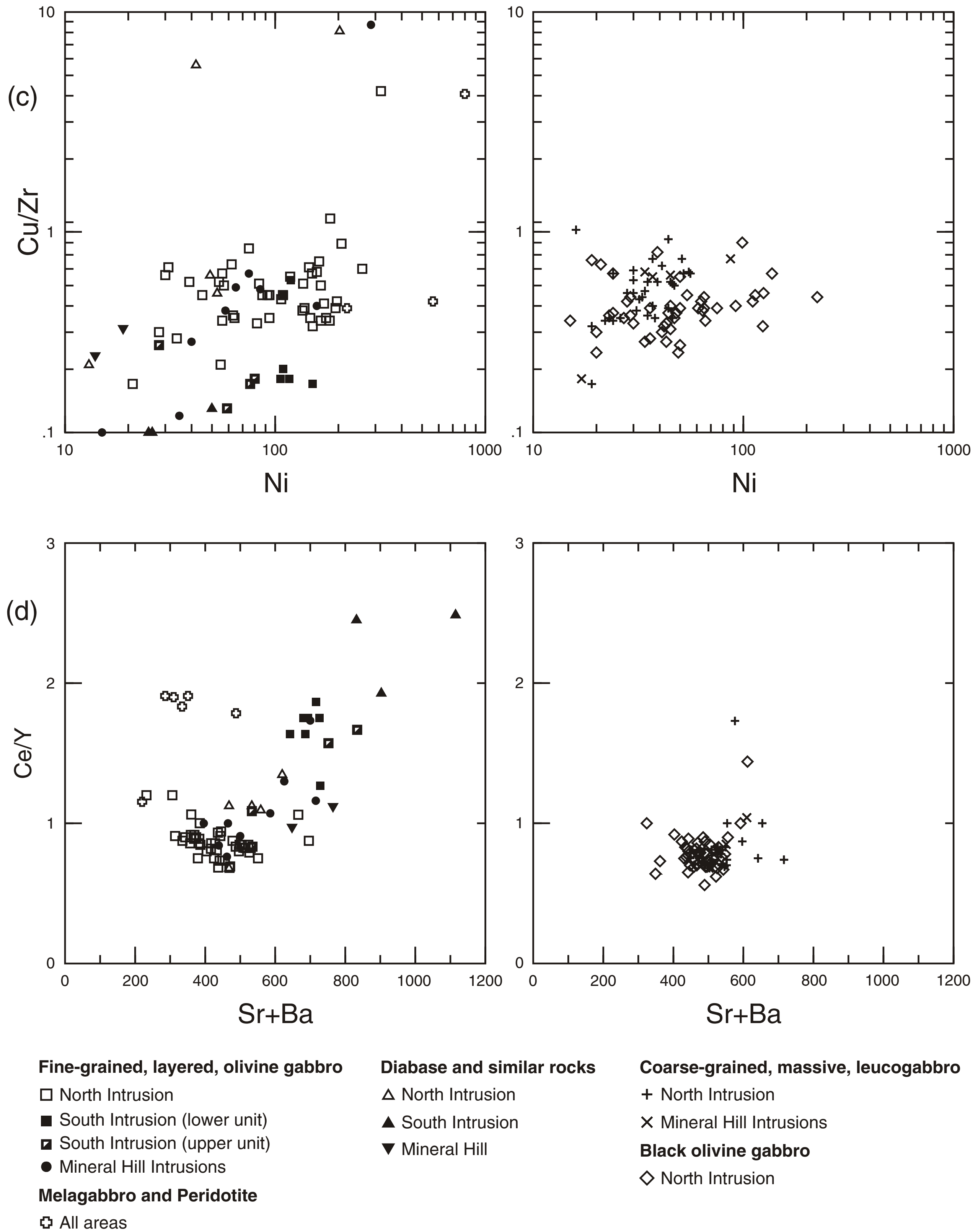

Figure 10. *Continued. See caption on previous page.*

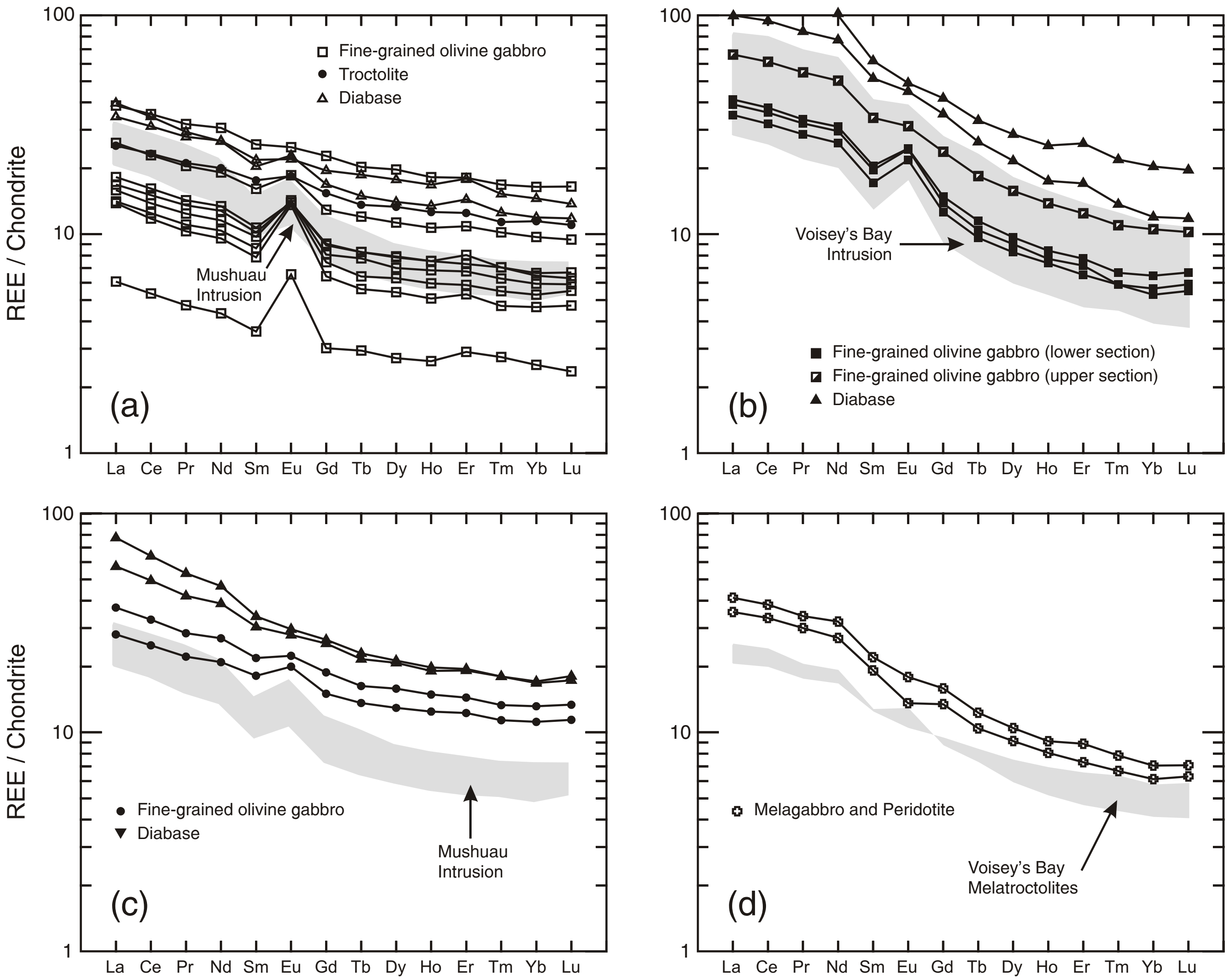

Figure 11. *Rare-earth-element profiles for fine-grained gabbroic rocks and associated diabases in the Pants Lake Intrusion. (a) North intrusion; (b) South intrusion; (c) Mineral Hill intrusions; (d) South intrusion melagabbro and peridotite. Comparative data from Li* et al. *(2000). Normalized to chondrite after Sun and McDonough (1989).*

Fine-grained gabbros from the Mineral Hill intrusions have gently-sloping REE patterns that most closely resemble those from the North intrusion, although they do have higher REE abundances (Figure 11c). They are clearly different from the South intrusion gabbros. Chilled diabase samples that are gradational with fine-grained barren gabbro below the Mineralized sequence have the highest REE abundances, lack Eu anomalies, and show slight LREE enrichment (Figure 11c).

Coarse-grained, massive, leucogabbros from the Happy Face and NDT lobes of the North intrusion have identical REE patterns to the fine-grained gabbro in this area, although they do not show the locally low REE contents caused by cumulus olivine (Figure 12a). Diabase from a chilled zone at the upper contact of the leucogabbro unit (Happy Face lobe) is LREE-enriched, which may reflect gneiss xenoliths noted in drill-core, but its pattern is otherwise identical to that of the coarse-grained leucogabbro. Coarse-grained leucogabbro from the Mineral Hill intrusions is identical to that of the North intrusion (Figure 12b). The REE profile of the black olivine gabbro closely resembles those of other units in the North intrusion. Its overall REE abundances are intermediate between those of the fine-grained olivine gabbro and the coarse-grained leucogabbro, but overlap both (Figure 12c)

The REE profiles for the PLI can be compared with those from the Voisey's Bay and Mushuau intrusions (Emslie, 1996; Lightfoot and Naldrett, 1999; Li *et al.*, 2000). Troctolites from the Voisey's Bay intrusion have distinctly steeper REE profiles than those of the North intrusion

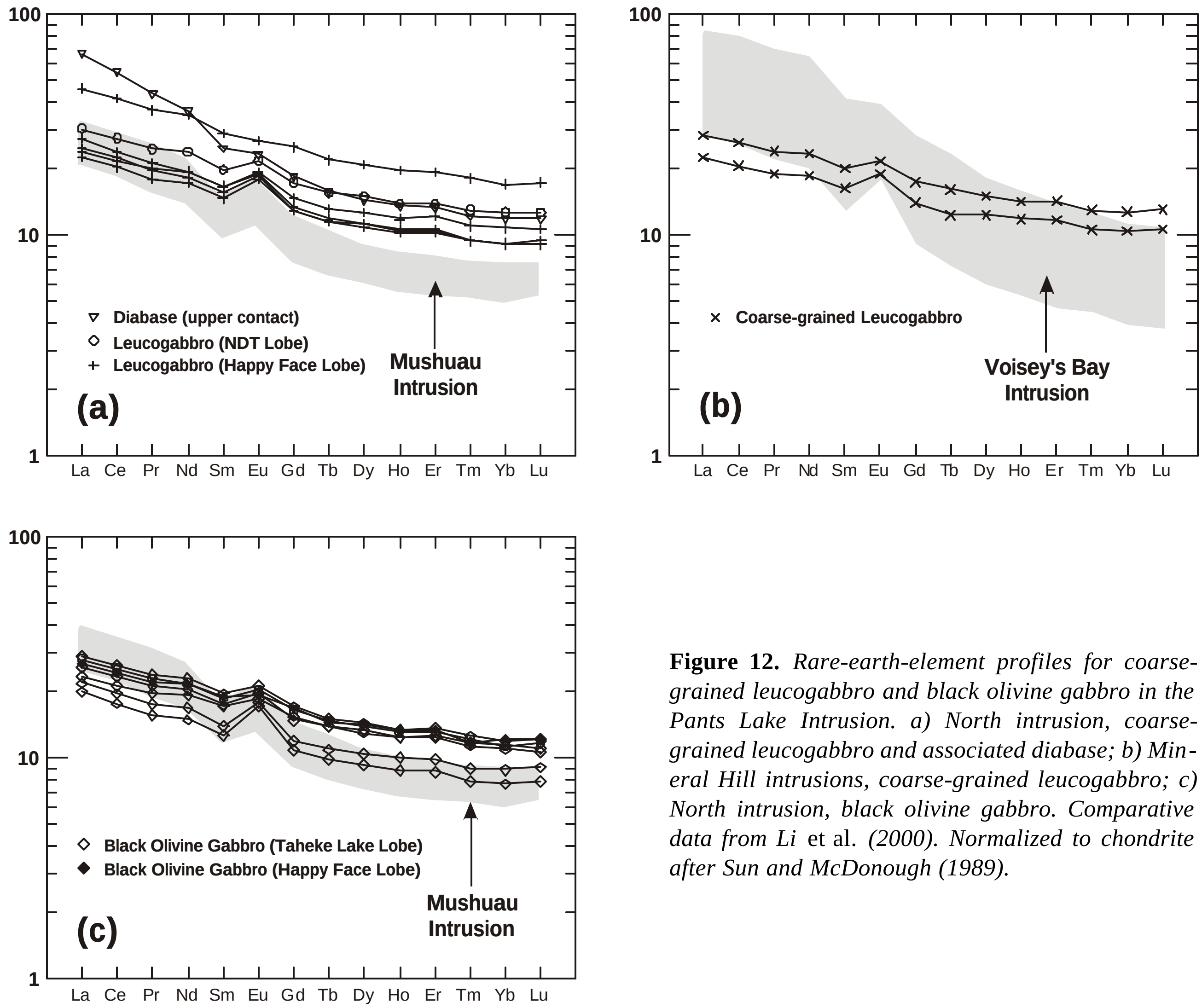

Figure 12. *Rare-earth-element profiles for coarse-grained leucogabbro and black olivine gabbro in the Pants Lake Intrusion. a) North intrusion, coarse-grained leucogabbro and associated diabase; b) Mineral Hill intrusions, coarse-grained leucogabbro; c) North intrusion, black olivine gabbro. Comparative data from Li* et al. *(2000). Normalized to chondrite after Sun and McDonough (1989).*

gabbros, but show the same inverse correlation between their Eu anomalies and total REE content (Figure 11b). In contrast, the Voisey's Bay REE profiles are closely similar to those from the South intrusion (Figure 11b; MacDonald, 1999). Rare-earth-element profiles of melagabbro–peridotite from the PLI South intrusion resemble those of melatroctolite inclusions at Voisey's Bay area (Li *et al.*, 2000), but the PLI samples have higher REE contents (Figure 11d). The PLI North intrusion and Mineral Hill intrusions gabbros, regardless of unit, more closely match the patterns from the Mushuau intrusion (Figures 11a and c; Figure 12).

Trace-element data from Voisey's Bay have commonly been depicted in the form of primitive-mantle-nomalized extended trace-element plots (also known as "spidergrams"). In the author's opinion, trace-element data are far better normalized to chondritic values, but a summary comparison between the PLI and the Voisey's Bay area using the "primitive mantle" method is illustrated in Figure 13. This also emphasizes the strong similarities between South intrusion fine-grained gabbro and troctolites of the Voisey's Bay intrusion, and the more general similarities between the North intrusion and the Mushuau intrusion. There are, however, some differences, notably the deeper negative Ta and Nb anomalies of the PLI rocks. The absence of both U data and reliable Rb and Pb data in PLI samples complicates exact comparisons of the lithophile element (Ba to K) profiles, but data presented by MacDonald (1999) suggest that these elements are indeed generally depleted compared to the Voisey's Bay troctolites.

GEOCHEMISTRY OF MINERALIZED ROCKS

UNIT SUBDIVISIONS

Mineralized rocks in the PLI include melagabbro and peridotite containing disseminated sulphides in the South

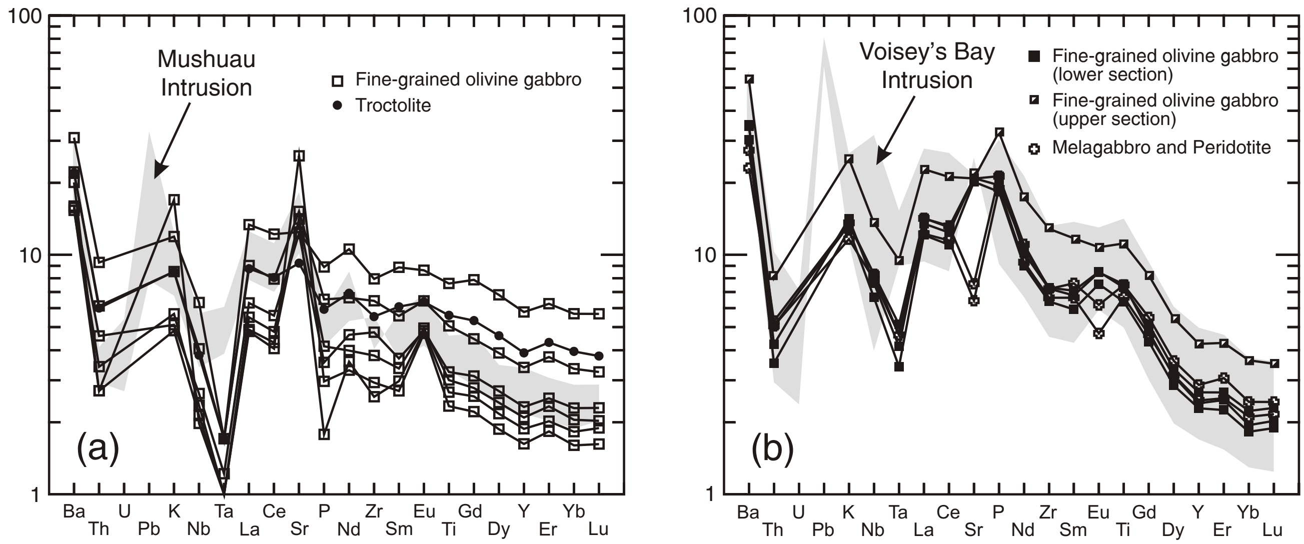

Figure 13. *Primitive-mantle-normalized trace-element patterns for fine-grained gabbro of the Pants Lake Intrusion, in comparison to the Voisey's Bay and Mushuau intrusions. (a) North intrusion; (b) South intrusion. Comparative data from Li* et al. *(2000). Normalized after Sun and McDonough (1989).*

intrusion and the complex and varied sulphide-rich gabbros of the Mineralized sequence in the North intrusion. Most of the data used in the present study come from the latter group. The complete major- and trace-element database consists of about 100 samples, but a large amount of additional data for Ni, Cu, Co and S is available in assessment reports (e.g., Fitzpatrick *et al.*, 1998; *see also* discussion in Kerr, 1999). For the purposes of this discussion, the Mineralized sequence of the North intrusion is divided into four principal units: 1) sulphide-poor composite gabbro, 2) sulphide-rich composite gabbro, 3) leopard-textured gabbro, and 4) undivided, mineralized, fine-grained gabbro. Two additional minor units are also defined, i.e., 5) poikilitic olivine diabase (a fine-grained, variably mineralized, rock that resembles black olivine gabbro), and 6) barren or weakly mineralized gabbro, variably present in the lowermost part of the Mineralized sequence or, more rarely, as thinner units just below the basal contact of the main body. The distinction between the two varieties of composite gabbro is visual and subjective; in most cases, increased sulphide content is accompanied by an increase in the proportion of digested gneiss fragments (Kerr, 1999).

The interpretation of geochemical data in mineralized rocks is inherently more difficult than for sulphide-free samples. Mineralized samples have high Fe_2O_3 contents purely as a consequence of pyrrhotite-dominated sulphides, which in turn depresses percentage values of all other oxides. Trace elements that are not concentrated in sulphides are also diluted in sulphide-rich samples. The ideal approach would be to normalize all data to a sulphide-free state, and correct for the excess Fe_2O_3. Unfortunately, this is impossible because only some of the samples have been analyzed for sulphur.

SUMMARY OF NUMERICAL DATA

Table 6 lists the average compositions of rock types in the Mineralized sequence of the North intrusion; mineralized mafic cumulates from the South intrusion are represented by analyses previously presented in Table 2.

Average compositions of sulphide-poor and sulphide-rich composite gabbro differ little, aside from higher Fe_2O_3 and lower SiO_2 in the latter, probably due to sulphides. Higher mean Al_2O_3 in sulphide-rich varieties may reflect the presence of digested gneiss fragments that are dominated by plagioclase and spinel (Kerr, 1999). The average trace-element compositions are identical, aside from differences in Ni, Cu and Co, obviously due to sulphides. The average compositions of composite gabbro are broadly similar to those of unmineralized gabbros from the North intrusion (Tables 1, 3 and 4), aside from differences related to sulphides. The Al_2O_3 contents are intermediate between those of fine-grained and coarse-grained units, but there are no clear differences in Na_2O or K_2O, or in lithophile trace elements. It thus appears that there is no obvious geochemical signature from digested gneiss fragments in composite gabbros, although it should be noted that extremely fragment-rich varieties were deliberately avoided during sampling.

The average composition for leopard-textured gabbro includes sulphide-rich samples, as indicated by very high Fe_2O_3, Ni, Cu and Co, and it is difficult to compare this to

Table 6. Compositions of mineralized units in the Pants Lake Intrusion

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

unmineralized units in any rigorous way. However, the average composition of undivided, mineralized fine-grained gabbro (generally poorer in sulphides) is similar to that of its unmineralized counterpart (accounting for differences related to sulphides), but has slightly lower Al_2O_3 and a notably higher K_2O content. As K_2O would be diluted by sulphides, this difference may be significant. The barren fine-grained gabbro from the lowermost part of the Mineralized sequence also has higher TiO_2 and K_2O than typical unmineralized fine-grained gabbro, and also has a twofold relative enrichment in La, Ce and Dy. In this respect, it resembles diabase samples, which are commonly more evolved than the fine-grained unit, but it could also have affinities to the rocks of the South intrusion. Poikilitic olivine diabase, interpreted as a fine-grained, variably mineralized variety of black olivine gabbro, is also sulphide-rich, and therefore difficult to compare rigorously to unmineralized units.

GEOCHEMICAL VARIATION TRENDS

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

Differences in trace-element variation trends are mostly connected to the effects of sulphides. In contrast to unmineralized gabbros, Ni and Co are no longer correlated with MgO (Figure 14a and b), but there are strong correlations between Ni and Cu (Figure 14c) and Ni and Co (Figure 14d). The Ni/Cu ratio is constant at slightly more than 1, as previously indicated by Kerr (1999), on the basis of a much larger database including company assay data. The Ni/Co ratios shows a curved trend, from about 1, in weakly mineralized rocks, to about 8, in Ni-rich samples. Note that samples containing more than 10 000 ppm (1%) Ni or Cu have been excluded from these diagrams to avoid compression of the remaining data. These patterns reflect the control of chalcophile elements by the sulphides in mineralized rocks, and the "drowning" of any variation introduced by olivine abundance variations. The differences between Ni/Cu and Ni/Co trends reflect the smaller differences in the the Co contents of olivine and sulphides compared to those for Ni and Cu. The Ni/Cu and Ni/Co ratios indicated by the mineralized rocks resemble those in unmineralized rocks that have low MgO contents, i.e., those that are least affected by cumulus olivine (compare Figure 14c and d with Figure 10a and b). Other trace elements do not yield useful information, although they do show that sulphide-bearing gabbros and the barren gabbro in the lowermost part of the Mineralized sequence tend to have higher REE and Nb contents than unmineralized counterparts.

Rare-earth-element patterns provide a more effective comparison method because their shapes are not affected by sulphides. Composite gabbro samples echo the shapes of REE profiles from fine-grained gabbros in the North intrusion but tend to have higher REE abundances; they most closely resemble the patterns for the black olivine gabbro (Figure 15a and b). One composite gabbro sample shows LREE enrichment, which may be a contamination signature from gneissic debris. Sulphide-bearing gabbros (including leopard-textured rocks) have patterns that resemble those of fine-grained, unmineralized gabbro (Figure 15c and d). As a general statement, REE profiles from the Mineralized sequence resemble those of unmineralized rocks in the North intrusion. A mineralized gabbro from hole #97-79 in the South intrusion shows the steeper REE pattern characteristic of all rocks from this area (Figure 15d).

MINERAL GEOCHEMISTRY

Two studies have examined the geochemistry of silicate minerals in the PLI. Hodder (1997) analyzed olivines, clinopyroxenes and plagioclases from several 1996 drillholes. Olivines ranged from Fo_{41} to Fo_{67}, and most clinopyroxenes proved to be augitic. Plagioclase compositions varied from An_{44} to An_{71}, and larger crystals were zoned, with calcic cores (up to An_{77}). MacDonald (1999) completed a more detailed study of olivine and plagioclase compositions, and the following account is largely drawn from this source. The MgO content of olivine (Forsterite content, or Fo Number), is a valuable fractionation index, which measures Fe-enrichment in mafic magmas. The Ni content of olivines provides valuable indications of depletion by sulphide liquids, and permits calculation of the metal contents of such liquids (Naldrett, 1989). MacDonald (1999) examined three key drillholes (Figure 2); SVB-97-75 (North intrusion; Taheke Lake lobe), SVB-97-77 (North intrusion; NDT lobe) and SVB-97-79 (South intrusion). In the following summary, the term, 'normal trend' is used to describe a decrease in Fo content with stratigraphic height within the intrusion, and, 'reverse trend' is used to describe an increase in Fo content with stratigraphic height.

Hole #97-77 penetrated the deepest section of the NDT lobe, and includes some 300 m of fine-grained, layered olivine gabbro, overlain by a thinner sequence of massive leucogabbro. There is a sharp break in Fo content at the upper boundary of the mineralized sequence, and most of the overlying fine-grained olivine gabbro unit shows a reverse trend from about Fo_{45} to Fo_{67}, followed by a decrease to about Fo_{58} immediately below the contact with massive leucogabbro. Within the lower reverse trend, short intervals show normal trends, followed by reversals. The coarse-grained leucogabbro contains large, zoned olivines that are harder to analyze, but mean compositions suggest an overall normal trend. Hole #97-75, in the Taheke Lake lobe, is dominated by black olivine gabbro, in which olivines tend to be large and zoned. However, average compositions imply that it has a reverse fractionation trend, rather than the normal trend seen in the massive leucogabbro. There is no clear break in Fo content at the top of the mineralized sequence in this hole. Hole #97-79, in the South intrusion, has the most complex pattern. The lowermost part of the hole has modest Fo contents (around An_{55}), which increase to An_{65} to An_{75} in sulphide-bearing melagabbro and peridotite. The overlying thick sequence of fine-grained olivine gabbro is dominated by a normal fractionation trend, with only a few thin intervals showing reverse trend intervals. The uppermost section of the South intrusion (above about 250 m) shows a rather erratic pattern, with no clear overall trend. Variations in Mg Number (i.e., molecular MgO/[MgO+FeO]) from the same samples define broadly similar trends.

Nickel data from olivine analyses are discussed here only in general terms. PLI olivines display the expected strong correlation of Ni and Fo content, and have a wide range of Ni contents, from <100 ppm to about 1200 ppm Ni (A.J. Naldrett, unpublished data). In general, their Ni contents are low compared to those expected for their Fo contents (Fo_{75} to Fo_{35}). Most olivines contain less than 500 ppm Ni, and those with compositions below Fo_{50} generally con-

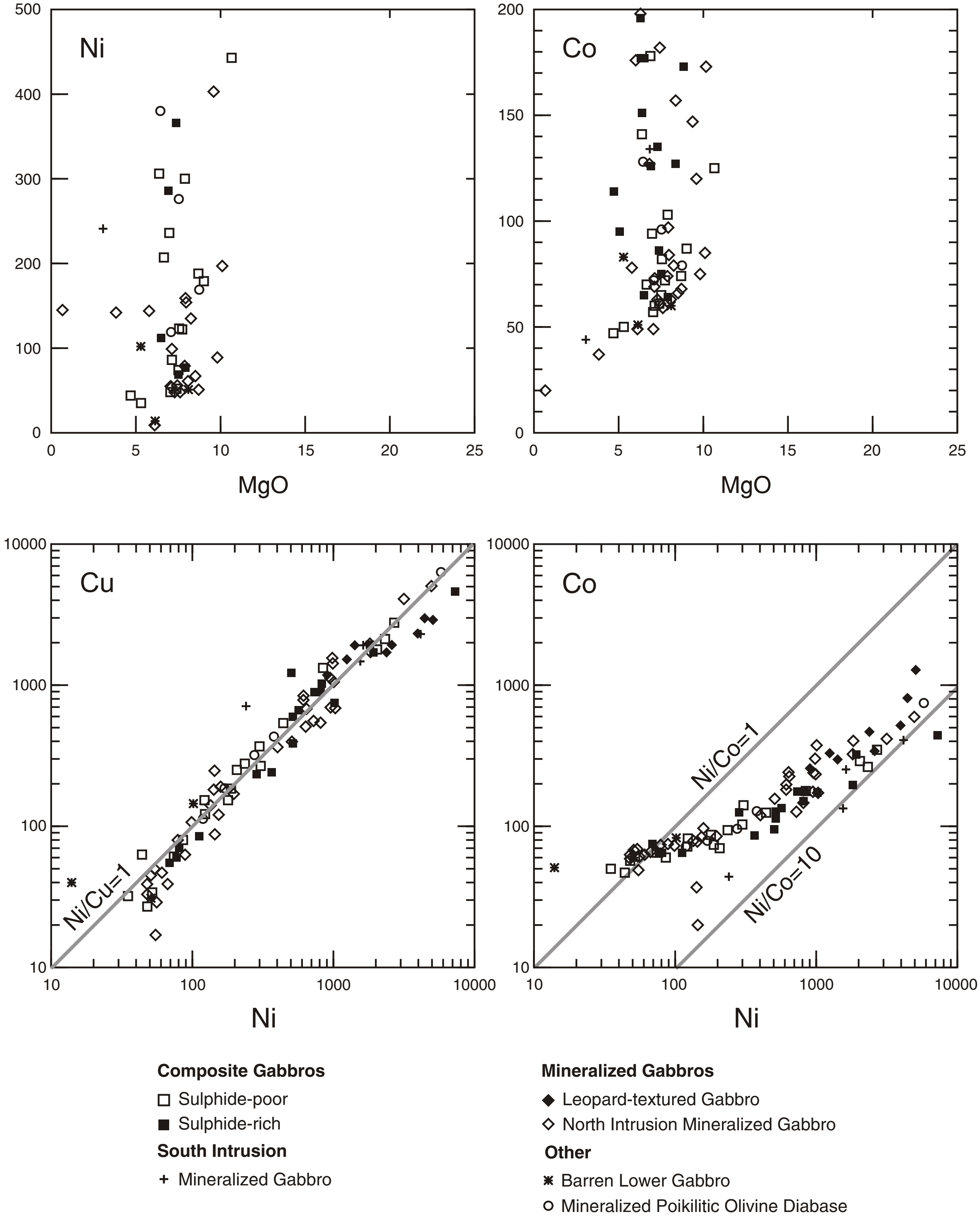

Figure 14. *Variation of chalcophile elements in mineralized rocks. (a) Ni vs MgO; (b) Co vs MgO; (c) Cu vs Ni; (d) Co vs Ni. Compare to patterns in Figure 7 and Figure 10.*

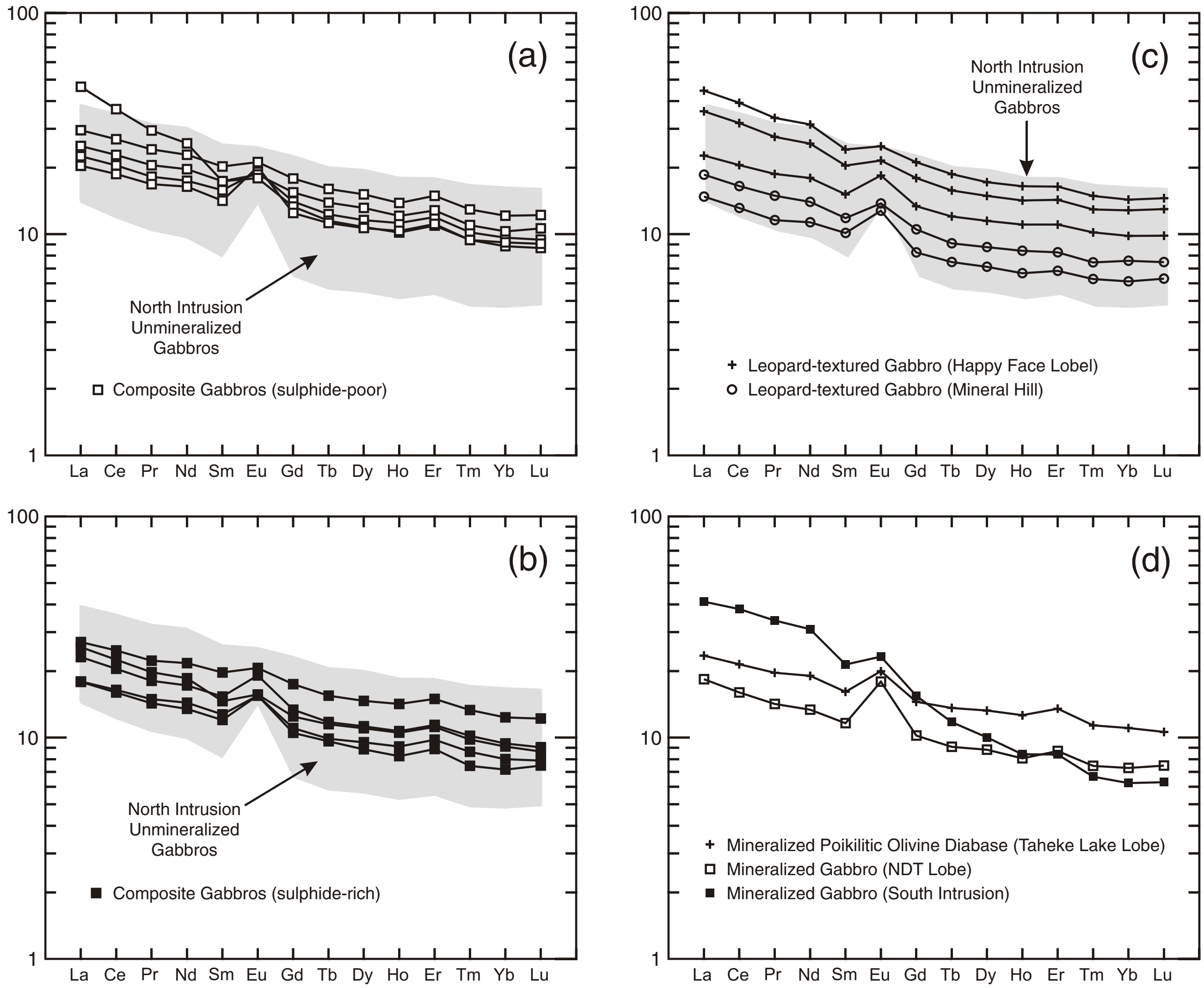

Figure 15. *Rare-earth-element profiles for mineralized rock types in the Pants Lake Intrusion. (a) North intrusion, sulphide-poor composite gabbro; (b) North intrusion, sulphide-rich composite gabbro; (c) Leopard-textured gabbro, various areas; (d) Mineralized gabbros, various areas. Comparative data from Figure 11. Normalized to chondrite. After Sun and McDonough (1989).*

tain < 300 ppm Ni. Most of the PLI olivines plot well below the ranges of Ni contents predicted for fractional crystallization of olivine and plagioclase in sulphide-free systems, i.e., the olivines have been depleted in nickel.

DISCUSSION

Some aspects of geochemical variations within the PLI are incompletely understood, and more data may be required to resolve specific points, but several important conclusions can be formulated on the basis of data presented here, and by MacDonald (1999).

COMPARISONS BETWEEN UNITS WITHIN THE PANTS LAKE INTRUSION

Geochemical data from the PLI point mostly to the common affinity of its rock types, rather than to contrasts between them. Regardless of unit assignment, these rocks share essentially the same component minerals, in similar proportions, and it is not surprising that their geochemical traits are similar. However, within this broad consanguinuity, there are subtle but systematic geochemical contrasts that point to different origins for the South and North intrusions. If the South intrusion is set aside, the geochemical similarities between different units of the PLI elsewhere are compelling and it would be very hard to distinguish any of them on the basis of geochemistry alone.

There is a general progression from "primitive" melagabbro and peridotite, through the fine-grained olivine gabbro, to massive leucogabbro, which has the most "evolved" composition (e.g., Figures 5 and 6). The black olivine gabbro overlaps both of these units, but is generally less "evolved" than the latter. As most of these rocks are of cumulate origin, such patterns do not necessarily indicate differences in parent magma compositions because they may be controlled simply by mineral proportions. However, there are textural differences between these units that suggest differences in the order of phase crystallization (Kerr, 1999), and there are also contrasts in the fractionation trends of olivine within different units and areas of the PLI (MacDonald, 1999). Therefore, it is reasonable to conclude that the North intrusion units crystallized from discrete, but closely related, batches of mafic magma. The trace-element data lead to essentially the same conclusion (Figures 7 to 10). The REE abundances of individual samples are controlled mostly by the amount of cumulus plagioclase, but the REE profiles of all units in the North intrusion are essentially identical, aside from the magnitude of positive Eu anomalies (Figures 11 and 12). This is strong evidence that they developed from genetically related magmas. The REE data also suggest that the Mineral Hill intrusions also belong to this group, although they do have some traits that superficially resemble those of the South intrusion.

CONTRASTS BETWEEN THE SOUTH AND NORTH INTRUSIONS

Fine-grained olivine gabbros from the South intrusion are consistently enriched in TiO_2, K_2O, Na_2O and P_2O_5 (Figures 5 and 6), and variably enriched in Cr, Sr, Ba, Nb, Zr, Y, La and Ce (Figures 7 to 10), compared to their counterparts elsewhere. Identical relative enrichment is shown by melagabbro and peridotite, which represent mafic cumulates associated with the fine-grained gabbro unit, and by associated diabases that likely represent chilled liquids (*see below*). Rare-earth-element profiles for all South intrusion units are distinctly steeper and LREE-enriched compared to those of the North intrusion (MacDonald, 1999; Figures 11 and 12). Also, the olivine compositional data show that the South intrusion has a different olivine fractionation trend from the North intrusion, which argues against any direct correlation between the two bodies (MacDonald, 1999, *see below*). Thus, although the rock types of the South intrusion are similar to those of the North intrusion, it seems to have formed from a genetically distinct magma. Given such differences, and the fact that the South Intrusion has not been dated precisely, it could be of different age to the 1322 Ma North Intrusion.

SIGNIFICANCE OF MAGMATIC EVOLUTION TRENDS

The South intrusion mostly displays a normal olivine fractionation trend, in which olivine becomes more Fe-rich and less Mg-rich with stratigraphic height. Trends of this type are characteristic of situations that approach closed-system fractionation, where a batch of magma crystallizes in place following emplacement, and the residual magma is progressively enriched in iron. This observation fits well with the recognition of mafic cumulates toward the base of the South intrusion, which would be expected to form in such an environment. Minor stratigraphic increases in the Mg content of olivines indicate that there were some minor influxes of new magma, with more primitive compositions. The limited data from the coarse-grained leucogabbro of the North intrusion suggests that this developed in a similar manner, i.e., it crystallized in a relatively static environment.

In contrast, the fine-grained gabbro and black olivine gabbro units of the North intrusion are dominated by reverse olivine fractionation trends, in which the olivines become more magnesian with stratigraphic height. Trends of this type are more consistent with open-system behaviour, in which there are frequent influxes of "primitive" fresh magma. Minor stratigraphic decreases in the Mg content of olivines reflect short interludes of static crystallization between influxes, and a normal olivine fractionation trend in the upper part of the fine-grained unit (in hole #97-77) suggests that the magma supply eventually diminished, and the remaining magma crystallized under generally closed-system conditions. The relatively dynamic environment indicated by reverse fractionation trends in the North intrusion suggests that large amounts of magma may have "moved through" the North intrusion en route to some other location, perhaps to the surface, or to a higher (now eroded ?) magma chamber.

DIABASE UNITS AND PARENTAL MAGMA COMPOSITIONS

Rapidly chilled rocks such as diabases represent closer approaches to liquid compositions than coarser grained cumulate rocks, but they do not necessarily represent *parental* liquid compositions. They may represent relatively fractionated magmas derived from a deeper evolving magma chamber, and/or they may be more influenced by crustal contamination. PLI diabase samples mostly have more evolved major-element compositions and higher incompatible-element contents than the spatially associated fine-grained gabbros. This is predictable, because the latter are dominated by cumulus olivine and plagioclase that exclude most trace elements, other than Co, Ni and Eu. These rocks are essentially mixtures of cumulus minerals and trapped residual liquid (containing REE), and their REE contents will generally be depressed from those of the original magma because they are diluted.

North intrusion diabases have REE contents akin to those of the more REE-enriched fine-grained gabbros (Figure 11a), but most of the latter have lower REE contents, which are inversely correlated with the magnitude of the positive Eu anomaly. However, the Eu anomaly does not become apparent until total REE contents are about half those observed in diabase (Figure 11a). The size of the Eu anomaly is a direct measure of the amount of cumulus plagioclase, and the presence of cumulus olivine is shown by the higher Ni content of fine-grained gabbros compared to the diabases (Tables 1 and 5; Figure 7). There is a similar relationship between diabase and fine-grained gabbro in the Mineral Hill intrusions (Figure 11c), and also between the coarse-grained leucogabbro unit and its associated chilled diabase in the North intrusion (Figure 12). However, in this case, the diabase is LREE-enriched, probably due to contamination effects. In the South intrusion, the most evolved diabase contains 7 times as much REE as olivine-rich melagabbro cumulates (Figure 11b and d), which resembles the total range of REE contents in the North intrusion data. However, diabase from the upper part of the South intrusion has a much more evolved composition than the unit at its base. None of the diabase samples show negative Eu anomalies, which indicates that these magmas had not experienced significant plagioclase fractionation. However, some diabase samples have low Ni contents, which suggests some olivine fractionation in their history. Diabases also have lower Mg contents than many of the gabbro samples (Figure 6).

The geochemical data show that the diabases are closely related to the other units of the PLI, but they also suggest that at least some represent pulses of magma that were more fractionated than those that gave rise to much of the fine-grained gabbro unit. As a group, they probably do not characterize parental liquids to the PLI, although they do provide broader general constraints, in that parental magmas were certainly no more fractionated than diabase compositions. MacDonald (1999) calculated model parental liquids for the North and South intrusions by removing 50 percent cumulus plagioclase from mean compositions defined by whole-rock data. This exercise produced model compositions of "ferropicritic" affinity, which had high MgO (13 to 18%), high FeO (20%), very low Al_2O_3 (6 to 9%) and low SiO_2 (41 to 43%). However, these are probably too primitive because the effects of cumulus olivine were not taken into account. The major-element compositions of the PLI parent magmas likely lay somewhere between these model compositions and the least fractionated diabase samples, which contain 6 to 8% MgO, 13 to 15% FeO, 14 to 17% Al_2O_3 and 46 to 48% SiO_2 (Table 5), but they are otherwise difficult to constrain.

COMPARISONS TO THE VOISEY'S BAY AND MUSHUAU INTRUSIONS

The PLI and the troctolites of the Voisey's Bay area may not be siblings, but they are certainly kinfolk. Table 7 lists the average compositions of the principal units of the Pants Lake, Voisey's Bay and Mushuau intrusions (comparative data from Li *et al.*, 2000). The mean major-element composition of the PLI fine-grained layered olivine gabbro unit is similar to those of the "normal troctolite" (NT) and "variable-textured troctolite" (VTT) units at Voisey's Bay, and there is a particularly good match with the South intrusion compositions. The only obvious differences in trace-element composition are the higher Ni, Cu and Sr contents of the Voisey's Bay rocks compared to the PLI. However, the high Ni and Cu values in the VTT reflect minor sulphide mineralization in these and do not indicate magmatic concentrations. Melagabbro from the PLI more closely resembles the melatroctolite of the Mushuau intrusion than the melatroctolite inclusions from the Voisey's Bay intrusion, which are significantly richer in magnesium.

Geochemical variation diagrams show a good correspondence between the PLI and both the Voisey's Bay and Mushuau intrusions for some major elements (Figure 5). More rigorous comparisons are impossible because only average compositions are presently available for the Voisey's Bay area (Li *et al.*, 2000). In general, the PLI shows more similarity to the trends of the Voisey's Bay intrusion than to those of the Mushuau intrusion. REE profiles from South intrusion units closely match those of the Voisey's Bay intrusion (MacDonald, 1999; Figure 11), but profiles from the North intrusion more closely resemble those of the Mushuau intrusion (Figures 11 and 12). Extended trace-element profiles (normalized to primitive mantle) lead to essentially the same conclusions (Figure 13).

Lightfoot and Naldrett (1999) and Li *et al.* (2000) partly attribute the differences between the Mushuau and Voisey's Bay intrusions to differing contamination histories, suggesting that assimilation and digestion of the Tasiuyak (metasedimentary) gneisses in the Voisey's Bay intrusion led to its greater relative enrichment in light REE and incompatible major and trace elements. If this interpretation is adopted, it suggests that the South intrusion magmas experienced a greater amount of contamination from the country-rock gneisses than those of the North intrusion. If magma compositions are directly linked to their mineral potential (which may not necessarily be so), such similarities highlight the South intrusion as a target for further exploration. As noted by Kerr (1999), sulphides associated with this body have high metal contents and Ni/Cu ratios akin to values from Voisey's Bay. The South intrusion has, to date, received much less exploration attention than the more accessible North intrusion.

Table 7. Comparison between the Pants Lake Intrusion and troctolitic rocks of the Voisey's Bay area

		Melagabbro	Fine-grained, layered olivine gabbro			Lcgabbro	Black Gabbro		Voisey's Bay Intrusion			Mushuau Intrusion	
		All Areas	South Intrusion	North Intr. NDT/HF	North Intr. Taheke L.	North Intrusion	North Intrusion	Normal Troctolite	Variable Troctolite	Conduit Rocks	Mela-Troctolite	Mela-Troctolite	Variable Troctolite
		Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
		n=6	n=10	n=38	n=5	n=28	n=46	n=102	n=48	n=11	n=21	n=10	n=8
SiO2	%	41.14	47.5	46.29	45.22	48.67	48.14	46.79	45.18	41.26	43.46	41.57	48.9
TiO2	%	1.34	1.75	0.91	0.53	0.97	0.95	1.32	1.08	2.14	0.75	0.63	0.88
Al2O3	%	8.24	18.04	17.79	15.21	21.11	19.98	19.38	18.94	16.72	7.34	9.41	18.7
Fe2O3	%	18.35	11.71	12.97	14.04	10.06	11.14	9.28	11.3	18.89	13.83	19.33	12.2
MnO	%	0.20	0.15	0.17	0.17	0.13	0.15	0.1	0.1	0.12	0.18	0.21	0.11
MgO	%	21.77	7.99	9.79	15.19	4.81	6.86	9.71	9.61	6.69	23.23	21.47	7.98
CaO	%	4.17	8.62	9.10	7.65	10.41	9.96	8.78	8.22	7.16	5.95	4.18	6.9
Na2O	%	1.61	3.37	2.67	1.94	3.31	3.00	2.91	2.86	2.79	0.84	1.52	3.4
K2O	%	0.39	0.57	0.29	0.16	0.38	0.33	0.37	0.34	0.62	0.36	0.18	0.33
P2O5	%	0.30	0.35	0.09	0.06	0.11	0.10	0.24	0.2	0.29	0.13	0.08	0.11
LOI	%	2.83	0.43	0.71	0.61	0.50	0.33	0.01	0.4	2.02	2.63	0.6	0.35
Total		100.34	100.29	100.33	100.29	100.46	100.81	99.01	98.3	98.69	98.78	99.3	99.86
Li	ppm	5.9	4.8	5.3	3.8	7.1	5.6						
Be	ppm	0.3	0.4	0.3	0.1	0.4	0.3						
Sc	ppm	10.5	17.1	18.4	13.2	18.9	19.4	11	9	9.6	23.2	12.8	15.3
Ti	ppm	8115	10752	5622	3295	6150	5909						
V	ppm	82	120	110	74	113	122	73	65	97	122	71	105
Cr	ppm	121	106	60	84	40	45	121	150	119	2113	267	311
Mn	ppm	1546	1104	1262	1235	1031	1080						
Co	ppm	149	55	75	100	43	55	53	111	223	102	131	119
Ni	ppm	820	90	109	186	35	56	244	1948	3067	1287	684	1104
Cu	ppm	340	21	33	13	30	24	36	847	1570	146	42	721
Zn	ppm	118	90	95	93	84	88	67	77	107	97	107	101
Ga	ppm	0	18	21		22	21	15	15	16	9	10	16
Rb	ppm	2	5	4	2	7	5	4	4	14	13	2	4
Sr	ppm	160	414	291	244	355	326	530	539	498	102	189	341
Y	ppm	12	17	17	9	20	17	9	8	10	11	9	14
Zr	ppm	72	93	57	33	66	61	64	51	67	45	55	4
Nb	ppm	4	7	3	2	4	4	3	3	5	3	2	4
Mo	ppm	1	1	1	1	1	1						
Ba	ppm	172	286	147	96	175	153	212	184	265	93	99	189
La	ppm	7	12	5	2	7	6	7	6	9	5	5	8
Ce	ppm	21	25	14	8	15	13	17	15	22	12	11	18
Dy	ppm	2.3	2.9	2.5	1.8	3.0	2.8	1.7	1.5	1.9	1.9	1.5	2.3
Pb	ppm	5	1	1	1	1	1	2	11	22	7	1	5

AFFINITIES OF MINERALIZED ROCKS

It is clear from their overall geochemistry and REE patterns that mineralized melagabbro and peridotite in the South intrusion are related to unmineralized gabbros in the body, and probably formed as mafic cumulates. This is consistent with the relationships seen in the drill-core and thin section, and in reconstructed cross-sections of the South intrusion (Kerr, 1999; Figure 4). Data from the Mineralized sequence of the North intrusion are harder to interpret. Nevertheless, the average compositions of both the upper and lower parts of the Mineralized sequence resemble those of other parts of the North intrusion, if differences in Fe_2O_3 and chalcophile elements (due to sulphides) are set aside (Table 6). The REE profiles of almost all Mineralized sequence rocks are identical to those of unmineralized North intrusion units, and indicate a close genetic relationship between the two.

Composite gabbros are mostly indistinguishable from the more homogeneous gabbroic rocks. This is not surprising in the case of sulphide-poor varieties that contain few or no digested gneissic fragments because these rocks essentially consist of troctolitic inclusions in a gabbroic matrix (Kerr, 1999), and would not be expected to show distinct compositions. However, it is surprising that sulphide-rich composite gabbros, which contain many fragments of digested gneiss, show little geochemical evidence of such material. Only one sample shows the light REE enrichment that would be expected from numerous paragneiss inclusions (Figure 15). Petrographic studies suggest that most digested gneiss fragments are dominated by fine-grained calcic plagioclase and hercynitic spinel (Kerr, 1999). Gneissic inclusions associated with the Voisey's Bay deposit are very similar and are interpreted to represent the residual end-products of a series of reactions that apparently enriched magmas in SiO_2, Na_2O, K_2O, and incompatible trace-elements (Li and Naldrett, 2000). The geochemical contribution of the residual spinel–plagioclase assemblages is mostly restricted to CaO, Al_2O_3, MgO and Fe_2O_3, which are abundant components of the host mafic magmas and also vary independently as a function of the proportions of igneous minerals and sulphides. Thus, it is perhaps not so surprising that geochemical signatures from digested gneiss fragments are elusive, especially if the data cannot be corrected for sulphides. Li and Naldrett (2000) were able to demonstrate some subtle major-element contrasts between inclusion-rich and inclusion-free samples at Voisey's Bay, but their data were corrected for sulphides, and their study was aimed specifically at inclusion-rich samples. The lack of a contamination signature in PLI composite gabbros implies that digestion and reaction of the gneiss xenoliths was not a purely local process, but instead occurred elsewhere, presumably at greater depths. The contaminants released by the transformation of the gneisses were dispersed into a much larger volume of magma and likely contribute to the overall, regional geochemical traits of the PLI. Similar conclusions were reached by Li and Naldrett (2000) for the very similar inclusion-rich rocks from the Voisey's Bay intrusion.

SIGNIFICANCE OF METAL DEPLETION SIGNATURES

The gabbroic rocks of the PLI appear to have been depleted in chalcophile elements by the segregation of sulphide liquids. Virtually all of the unmineralized rocks have low Ni and Cu contents, and most contain less than 100 ppm of each element. Unmineralized rocks that have higher Ni contents are generally those that contain greater amounts of olivine, as indicated by MgO–Ni correlations, and the lowest Ni contents (<40 ppm) are mostly from plagioclase-rich samples, such as the massive leucogabbro unit. Diabase samples, which provide minimum values for the Ni contents of the parental magmas, generally contain 50 ppm Ni or less. Given that virtually all PLI gabbros are olivine-bearing, these whole-rock Ni contents are unusually low. MacDonald (1999) noted low Cu/Zr and Cu/Hf ratios and the larger database presented here confirms that this is indeed a regional feature. Virtually all unmineralized rocks have Cu/Zr << 1, and many are strongly depleted in Cu relative to Zr (Figure 10). Based on results from Voisey's Bay and elsewhere, this is an indication of metal depletion due to sulphides (Lightfoot *et al.*, 1994; Li and Naldrett, 1999). Finally, results from mineral geochemistry studies (A.J. Naldrett, unpublished data) indicate that most olivines are depleted in Ni relative to expected fractionation paths for sulphide-free systems. This pervasive, ubiquitous depletion differs from that observed at Voisey's Bay (Li and Naldrett, 1999), where only a few rocks, mostly a minor olivine–gabbro unit and equivalent gabbroic rocks in the feeder conduit, show conspicuous Ni depletion in olivines. In contrast, most of the troctolitic rocks at Voisey's Bay appear to be mildly depleted or essentially undepleted.

The scale of the depletion signature in the PLI implies that large amounts of magma have been "processed" for metals by sulphides, and places some general constraints on the amounts of Ni and Cu that have been extracted, and on the potential size and grade of undiscovered sulphide deposits. However, assumptions must first be made about the initial Ni contents of the PLI magmas prior to their depletion by sulphide liquids. The Ni content of mid-ocean ridge basalts is commonly estimated to be about 150 ppm, and Morse *et al.* (1991) estimated the bulk Ni content of the Kiglapait Intrusion magma at about 125 ± 25 ppm. "Normal" (i.e., unmineralized) troctolite from the Voisey's Bay intrusion, which has encountered little metal depletion on the basis of olivine studies (Li and Naldrett, 1999), has an average Ni content of approximately 250 ppm. Although this value may be biased upward by the presence of cumulus olivine, it provides a reasonable upper limit for any calculation. The very consistent Ni/Cu ratio observed in PLI mineralized samples implies that initial magmatic Cu contents were slightly less than the magmatic Ni contents.

Assuming an initial Ni content of 150 ppm, and a final Ni content of 50 ppm after depletion, PLI mafic magmas have lost about 67% of their Ni to sulphide liquids. One cubic kilometre of mafic magma containing 150 ppm Ni contains about 0.45 million tonnes of Ni metal (assuming a density of 3.0) and would thus lose 0.3 million tonnes of Ni metal if its bulk Ni content was decreased to 50 ppm. The presently exposed surface area of the PLI is about 50 km^2, and parts of it are several hundred metres thick; it is also known to be present over large areas in the subsurface, and has presumably also been partly eroded over large areas. As discussed above, much larger amounts of magma may have passed through parts of the North intrusion. A first-order estimate of at least 50 km^3 of metal-depleted magma implies that at least 15 million tonnes of Ni metal, and similar amounts of copper, are missing. The equivalent calculation based on a higher initial magmatic Ni content of 250 ppm doubles this estimate to 30 million tonnes of missing Ni metal. In comparison, the total amount of Ni metal in the Voisey's Bay deposits (based on the 1999 resource figures released by INCO) is approximately 2 million tonnes.

If PLI mineralization is assumed to cover 50 km^2, at an average thickness of 10 m, and an average grade of 0.25% Ni (all of which are certainly overestimates), this would account for 3.75 million tonnes of the missing Ni metal, or about 25 percent of the most conservative estimate above. Thus, although the PLI may, in fact, contain a substantial quantity of metals in disseminated form, this still falls well short of the total amount of metal missing from the magmas. Such calculations, although simplistic and preliminary, certainly provide a rationale for further exploration in this region. However, the recognition of excess missing metal does not provide clues as to its actual location, nor does it indicate if sulphides are present in massive or disseminated form.

The apparently low Ni content of PLI mafic magmas, and their ubiquitous depletion, also carries implications with respect to the potential grade of sulphide accumulations. Sulphide liquid-silicate liquid partition coefficients for Ni (D) are generally considered to be between 300 and 500 in basaltic systems (e.g., Naldrett, 1989; Barnes and Maier, 1999). Assuming a final (depleted) magmatic Ni content of 50 ppm, this indicates that associated sulphide liquids should have had Ni contents of 15,000 to 30,000 ppm, i.e., 1.5% to 3.0% Ni. This is in good agreement with the observed range of sulphide Ni contents in mineralized samples from the PLI, which cluster strongly in the vicinity of 2% Ni, within an overall range extending from 0.5% to greater than 10% (Kerr, 1999). The strong depletion of Ni in PLI mafic rocks is also consistent with a relatively low mass ratio between silicate magma and sulphide liquid, a parameter commonly termed the "R-factor". Conspicuous depletion is characteristic of situations where the R-factor is significantly less than 1000, and results in relatively low-grade sulphides. Assuming the initial Ni content of the magmas to be about 150 ppm (as outlined above), the R-factor required to produce a sulphide liquid with a given Ni content can be readily calculated, after Naldrett (1989). The results are dependent on the value chosen for sulphide liquid - silicate liquid partition coefficients (D), but this has only a limited influence. To produce a sulphide liquid containing 2% Ni, the R-factor was probably between 180 (D=500) and 250 (D=300), slightly higher than a previous estimate by MacDonald (1999), who used a higher partition coefficient. In comparison, the Voisey's Bay sulphides, which contain about 4% Ni, would require R-factors from 600 (D=500) to almost 2000 (D=300), assuming the same initial magmatic Ni content.

Recent models for the Voisey's Bay deposit (Li and Naldrett, 1999) suggest that a low R-factor, low-grade sulphide liquid formed at early stages, and was then progressively upgraded by continued interaction with fresh magma that had not previously encountered sulphides. A similar process has been envisaged at Noril'sk in Russia (Lightfoot *et al.*, 1994). This is essentially equivalent to increasing the R-factor through a multistage process. The less depleted and undepleted troctolites that now dominate the Voisey's Bay intrusion provide evidence for this continued magmatic flux. The early formed sulphide liquid at Voisey's Bay would have had metal contents akin to those observed in and predicted for the PLI, based on the Ni contents of olivines in the most depleted rocks (Li and Naldrett, 1999). If a model of this type is to be applied to the PLI, the general absence of less-depleted mafic rocks in the PLI may suggest that later pulses of fresh magma were less abundant, and that sulphide liquids were not upgraded to the same extent. However, it is possible that such less-depleted magmas remain undocumented, particularly within the South intrusion, which remains relatively unexplored.

CONCLUSIONS

1. The PLI is a relatively primitive, MgO-rich, mafic igneous suite. Previously noted petrological similarities between the PLI and the troctolitic rocks of the Voisey's

Bay and Mushuau intrusions (Kerr, 1999) are endorsed by similarities in both major- and trace-element geochemistry.

2. The main petrological units within the PLI have similar compositions, and mostly fall upon common geochemical variation trends, but the PLI includes two discrete magma types. The South intrusion has higher TiO_2, K_2O and incompatible-element contents, and provides the closest match to the Voisey's Bay intrusion. The North intrusion more closely resembles the Mushuau intrusion, although it is not an exact match. Other PLI bodies mostly appear to have similar affinities to the North intrusion. The three main units within the North intrusion appear to have formed from discrete, but closely related, batches of magma. Contrasting olivine fractionation trends (MacDonald, 1999) indicate that the South and North intrusions respectively approach contrasting closed-system and open-system magmatic environments.

3. Diabase units from South and North intrusions share their respective geochemical traits, but have more evolved compositions than spatially associated gabbros. Although they probably do not represent *true* parental magma compositions for the bulk of the PLI, diabase compositions do provide some general constraints on the character of such magmas, which were certainly more primitive than the diabases.

4. Mineralized melagabbro and peridotite in the South intrusion are geochemically similar to spatially related unmineralized gabbro, and thus probably represent mafic cumulates. Similarly, the Mineralized sequence of the North intrusion has the same geochemical characteristics as the spatially associated unmineralized rocks, implying a close genetic link between the two.

5. PLI gabbros have low Ni contents and low Cu/Zr ratios suggesting that the magmas were depleted strongly in chalcophile elements as a result of sulphide liquid segregation. Preliminary calculations suggest that at least 15 million tonnes of Ni metal, several times more than is presently known to be contained at Voisey's Bay, remains largely unaccounted for.

6. The generally low Ni contents of PLI magmas imply that associated sulphide liquids would contain 1.5% to 3% Ni, which is in general agreement with observed sulphide Ni contents. The strong and widespread depletion of Ni in PLI gabbros implies that R-factors were lower than at Voisey's Bay, and perhaps also that sulphide liquids were not as effectively upgraded. Thus, although large amounts of sulphides may remain undiscovered, there may also be inherent limitations upon their grades.

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