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GEOLOGY AND DISTRIBUTION OF PLATINUM-GROUP ELEMENTS, BUCKO LAKE INTRUSION, THOMPSON BELT, MANITOBA

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ABSTRACT

The Bucko Lake Ni–Cu sulfide deposit is hosted by the Bucko Lake intrusion (BLI), one of several ultramafic bodies of komatiitic affinity of Early Proterozoic age in the Thompson belt, Manitoba. The BLI cuts presumably Archean gneissic country-rock. The intrusion is composed predominantly of harzburgite, dunite, and olivine orthopyroxenite. Metasomatic alteration of the intrusion occurred in at least two stages. The first stage involved the pervasive serpentinization of the intrusion, with good preservation of relict textures. During the second stage of alteration, next to granitic pegmatite dikes, original textures were destroyed, and a new growth-oriented fabric was generated. Primary disseminated Ni sulfide mineralization at Bucko Lake is typical of that in komatiitic dunite-associated deposits. Mobilized sulfides occur in amphibolite xenoliths, sheared granitic pegmatite dikes and sheared peridotite, and are subdivided, on the basis of their relative timing of emplacement, into two types: early xenolith-hosted sulfides and later stringer sulfides. The abundance of platinum-group elements, Au, Cu and Ni in primary sulfides was apparently unaffected by serpentinization and amphibolite-grade metamorphism, but Cu and Au were lost during the metasomatic alteration adjacent to granitic pegmatite dikes. The composition of xenolith-hosted mobilized sulfides is similar to that of the primary sulfides, but stringer sulfides are relatively enriched in Cu and depleted in Ni and Ir. The composition of sulfides in the southern part of the Thompson belt is similar to that of Archean deposits, but is more primitive than that of komatiite-hosted deposits in the Cape Smith belt. This is significant, since the Thompson belt and Cape Smith belt are segments of the Early Proterozoic Circum-Superior belt.

Keywords: Thompson belt, platinum-group elements, element mobility, dunite-associated deposit, Bucko Lake Ni–Cu deposit, Manitoba.

SOMMAIRE

Le gisement de sulfures à Ni–Cu de Bucko Lake a, comme encaissant, les roches du massif intrusif ultramafique de Bucko Lake, à affinité komatiitique et d'âge protérozoïque, dans la ceinture de Thompson, au Manitoba. Ce complexe recoupe des gneiss supposés archéens; il contient surtout harzburgite, dunite et orthopyroxénite à olivine. Deux stades d'altération métasomatique ont affecté le massif. Le premier a causé la serpentinisation répandue de ces roches, sans toutefois oblitérer les textures primaires. Au cours du second, une altération près de filons de pegmatite granitique a détruit les textures primaires et a imposé une texture nouvelle selon l'orientation des minéraux néoformés. La minéralisation primaire, impliquant sulfures nickelifères disséminés, est typique des gisements associés aux dunites komatiitiques. Des sulfures remobilisés se trouvent maintenant dans des xénolithes d'amphibolite, dans des filons de pegmatite granitique et dans la péridotite, les deux derniers étant cisaillés. D'après leur mise en place, ces sulfures sont soit précoces, inclus dans les xénolithes, soit tardifs, présents en fissures. La teneur en éléments du groupe du platine, Au, Cu et Ni dans les sulfures primaires n'a vraisemblablement pas changé au cours de la serpentinisation et d'un épisode de métamorphisme au facies amphibolite. Par contre, Cu et Au ont été lessivés suite à la métasomatose près des filons pegmatitiques. La composition des sulfures piégés dans les xénolithes ressemble à celle des sulfures primaires, mais les sulfures tardifs font preuve d'un enrichissement relatif en Cu et d'un appauvrissement en Ni et Ir. La composition des sulfures dans la partie méridionale de la ceinture de Thompson ressemble à celle des sulfures des gisements d'âge archéen, mais serait plus primitive que la composition des sulfures des gisements à affinité komatiitique dans la ceinture du Cap Smith. Cette observation semble importante, parce que les ceintures de Thompson et du Cap Smith feraient partie de la ceinture Circum-Supérieure, d'âge protérozoïque précoce.

(Traduit par la Rédaction)

Mots-clés: ceinture de Thompson, éléments du groupe du platine, mobilité des éléments, gisement à Ni–Cu, association dunitique, gisement de Bucko Lake, Manitoba.

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INTRODUCTION

The Bucko Lake Ni–Cu sulfide deposit, hosted by the Bucko Lake intrusion (BLI), is located approximately 55 km southwest of Thompson, Manitoba, near the southern end of the exposed Thompson belt (Fig. 1). It is one of several ultramafic bodies of komatiitic affinity of Early Proterozoic age in the Thompson belt. Previous studies of the ultramafic bodies have focussed on either the petrology and major-element geochemistry (Coats 1966, Coats & Brummer 1971, Peredery 1979, Peredery *et al.* 1982) or the sulfides (Coats *et al.* 1976, Naldrett *et al.* 1979, Peredery *et al.* 1982). The main goal of this study is to describe specific aspects of distribution of platinum-group elements (PGE) in relation to the petrology and geochemistry of the host ultramafic body.

Alteration of the Bucko Lake intrusion occurred in at least two unrelated periods of metasomatism. The first period involved pervasive serpentinization of the intrusion, with good preservation of relict textures, and the second period involved intense alteration adjacent to cross-cutting dikes of granitic pegmatite. Despite the alteration, primary minerals have been preserved locally, and document a nearly complete section of the intrusion. The close proximity of serpentinized rocks containing abundant relict minerals and intensely altered rocks provides an opportunity to examine the effects of metasomatism on the distribution of PGE.

The dominant Ni sulfide ore at Bucko Lake is disseminated to net-textured and is typical of the komatiitic dunite-associated deposits described by Lesher & Groves (1984). At least two types of mobilized sulfides occur in close proximity to the zones of primary sulfide ore. Comparisons of the PGE concentrations between

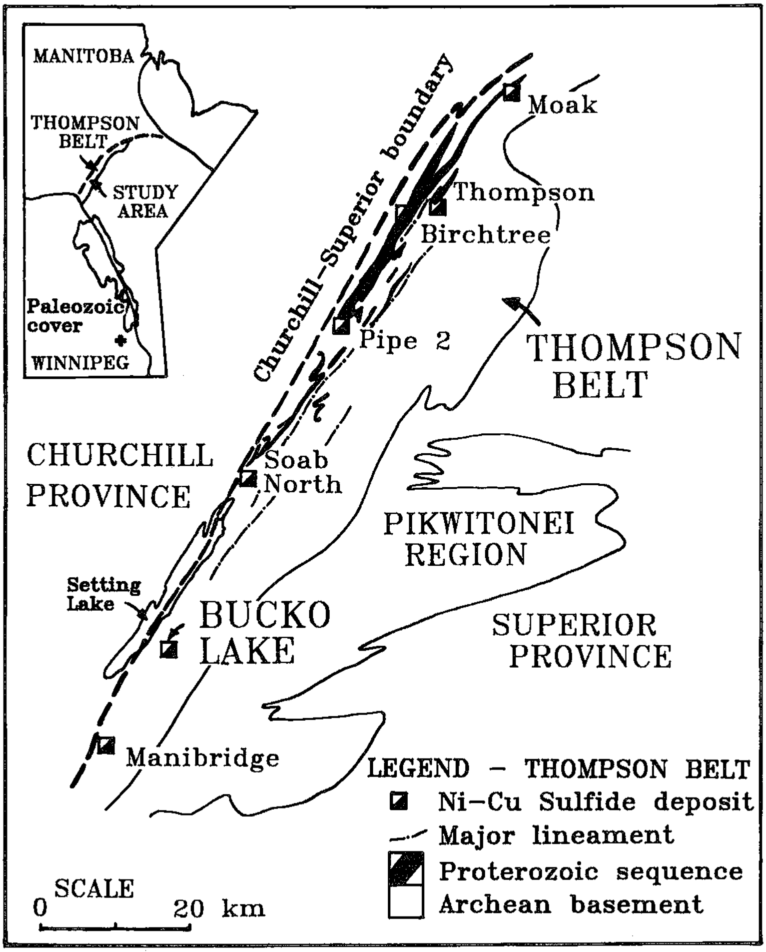

FIG. 1. Location map of the Thompson belt and the Bucko Lake deposit (after Peredery 1979).

the mobilized and primary sulfides provide information related to the behavior or fractionation of the PGE during mobilization. Other studies of this type are typically hampered by the difficulty to obtain the composition of the magmatic sulfides from which the mobilized sulfides were derived (*e.g.*, Lesher & Keays 1984, Rowell & Edgar 1986).

GEOLOGICAL SETTING OF THE THOMPSON BELT

The Thompson belt forms an integral part of the boundary between the Churchill Province to the northwest and the Pikwitonei Region of the Superior Province to the southeast (Fig. 1). The Thompson belt is largely composed of Archean granulite-facies gneisses that were retrograded to the amphibolite facies (Rance 1966, Cranstone & Turek 1976, Weber & Scoates 1978), and realigned to a northeasterly trend when the Superior Province collided with the Churchill Province during the Hudsonian Orogeny (Bell 1971, Green *et al.* 1985, Fueten & Robin 1989, Bleeker 1990). Along the western edge of the northern half of the belt are remnants of a pile of Early Proterozoic metasedimentary–metavolcanic supracrustal rocks (Scoates *et al.* 1977, Brooks &

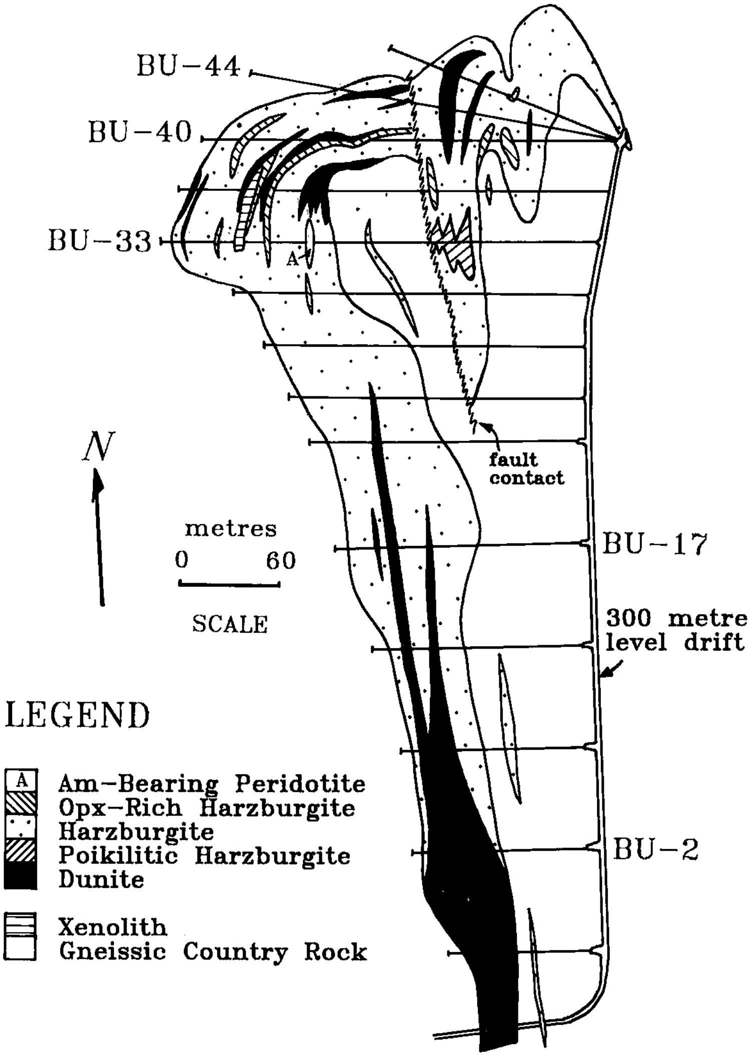

FIG. 2. Geological plan of the Bucko Lake intrusion at the 300 m level. "BU–2" symbol refers to borehole.

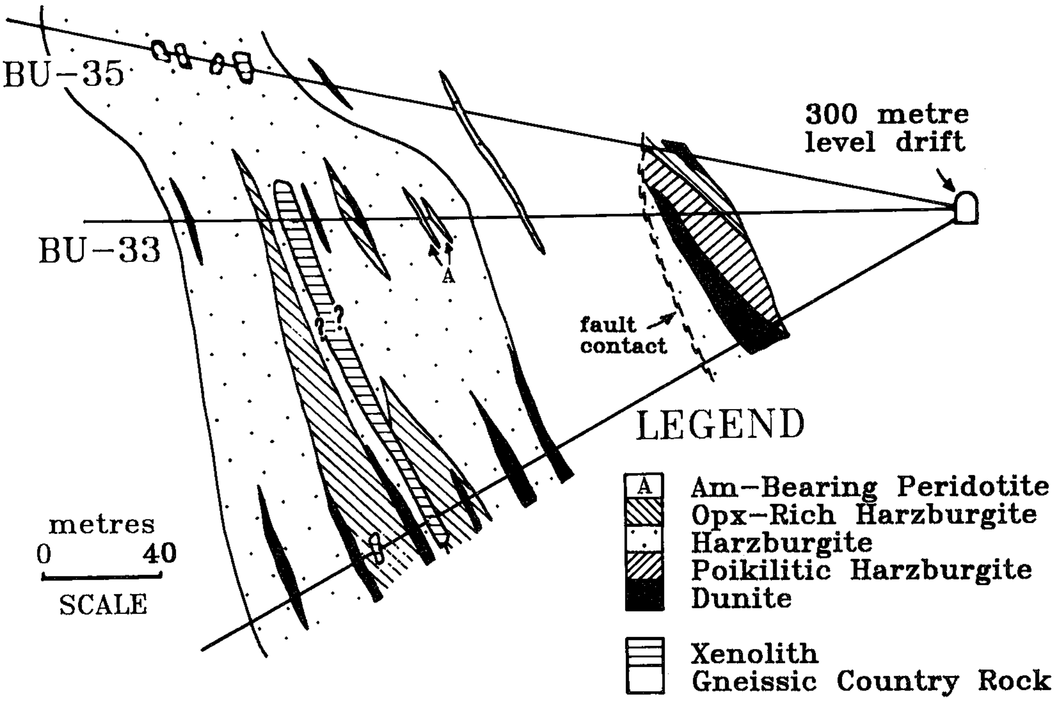

FIG. 3. Geological cross-section along borehole BU–33 of Fig. 2.

Theyer 1981, Bleeker 1990). The ultramafic bodies with associated nickel deposits were emplaced into the Archean gneissic basement and the pile of supracrustal rocks. The ultramafic intrusions and the supracrustal metavolcanic flows were postulated to have been consanguineous by Stephenson (1974). Peredery (1979) demonstrated their komatiitic affinity.

PETROLOGY OF THE BUCKO LAKE INTRUSION

The Bucko Lake intrusion strikes approximately north for greater than 800 meters, and dips steeply east (Figs. 2, 3). The intrusion has the shape of a synform with a fold axis that plunges steeply to the south. However, based on trends of decreasing forsterite content of olivine (described below), both limbs face east. The uniform facing directions of the limbs indicate that the west limb was duplicated by faulting, and that the original east limb was displaced. Alternatively, the limbs could represent two separate, parallel intrusions. Despite the latter possibility, faulting must have been involved, since stratigraphy in the east limb is truncated by the contacts.

The intrusive contacts of the intrusion are mostly obscured by later granitic pegmatite dikes, alteration or faulting. The actual contact was observed at only one location. At this locality, the following features were observed, from the gneiss into the intrusion. The gneissic texture is folded within 15 cm of the contact. The contact is gradational over approximately 0.5 cm. Next to the contact is a zone, approximately 35 cm thick, of fine-grained granular amphibole with traces of interstitial plagioclase. Next to the granular amphibolite is a 45-cm-thick layer of fibrous amphibolite. The fibrous amphibolite is followed by harzburgite. Minor thin layers of disseminated sulfide occur in the country rock a few cm from the contact, and are parallel to the folded gneissosity.

The Bucko Lake ultramafic intrusion is composed of, in decreasing order of abundance, harzburgite, dunite, olivine orthopyroxenite, poikilitic harzburgite, orthopyroxenite, and hornblende peridotite. The divisions between these rock types are arbitrarily drawn using the classification scheme of Streckeisen (1976). An exception to Streckeisen's scheme is the placement of the boundary for dunite at 85 modal % olivine instead of 90 in order to account for secondary minerals, *e.g.*, magnetite, tremolite and phlogopite.

The degree of alteration of primary minerals in the intrusion ranges from moderate to total. Olivine is invariably serpentinized, but it is common to find up to 5% remnant olivine occurring in thin section. Orthopyroxene is commonly partly altered to tremolite and lesser amounts of serpentine. Despite the alteration, original minerals are recognizable by pseudomorphic textures or can be inferred from assemblages of secondary minerals. Consequently, rock types are referred to on the basis of the inferred primary assemblage. It should be noted that the degree of alteration is not so great as to make the identification of rock types equivocal. In general, olivine pseudomorphs are well preserved, and distinguishing dunite from harzburgite and poikilitic harzburgite is unambiguous. However, differentiating between amphibole-rich units formed by alteration of an orthopyroxene-rich cumulate during the event of pervasive serpentinization and similar units formed by metasomatism during the emplacement of granitic pegmatite dikes is difficult, but can be done by geochemical means (see below).

The primary igneous minerals apparently crystallized in the order olivine ± chromite, orthopyroxene, and finally, hornblende. In general, olivine and chromite are subhedral cumulate grains; orthopyroxene is either poikilitic, enclosing olivine, or anhedral and interstitial to olivine; hornblende is subhedral and interstitial to olivine.

Harzburgite is the dominant rock-type in the intrusion. It consists of olivine, orthopyroxene, hornblende and accessory chromite. Secondary minerals include serpentine, magnetite, tremolite, phlogopite and chlorite. The dominant texture is that of a mesocumulate. Olivine grains are subhedral and equigranular, and range in size from 0.2 to 2.5 mm, with an average size of about 0.6 mm. In hand sample, olivine is black and easily recognized in the lighter-colored matrix.

Dunite is composed of 85 to 90 modal % olivine and minor chromite. Secondary minerals include serpentine, magnetite, phlogopite and tremolite. Olivine forms equant, rounded grains commonly outlined by secondary magnetite. The range in grain size is similar to that in harzburgite. In hand sample, dunite is light green to black. Dunite is gradational into harzburgite as the amount of interstitial orthopyroxene increases.

Harzburgite is gradational into olivine orthopyroxenite and orthopyroxenite. The change is marked by an increase in orthopyroxene and a corresponding decrease in olivine. Olivine typically occurs in rounded clusters of several fine-grained, serpentinized crystals. The orthopyroxene is anhedral and partly to completely altered to tremolite, which gives the rock a ragged or interlocking texture.

Poikilitic harzburgite is found only in the central portion of the eastern limb of the intrusion. It is composed of olivine and 15 to 60% orthopyroxene. Secondary minerals include serpentine and magnetite and lesser amounts of tremolite, phlogopite and chlorite. The orthopyroxene is partly serpentinized and forms stubby oikocrysts up to 1 cm in size, which enclose olivine. The olivine within the orthopyroxene is smaller and more rounded than the olivine outside of the oikocrysts, implying that olivine was resorbed during orthopyroxene growth. The dominant texture is that of an adcumulate. The poikilitic harzburgite layers are a few to several cm thick and are interlayered with dunite. In hand sample, the orthopyroxene is grey-white and easily distinguished from the black olivine.

Hornblende peridotite consists of 70 to 85% subhedral olivine and 15 to 30% interstitial, subhedral hornblende and minor amounts of phlogopite and magnetite. The hornblende is optically positive, has a low $2V$ and is moderately pleochroic, from pale yellow-brown to yellow-green and bluish green. The apparent primary texture of the hornblende and a lack of associated orthopyroxene and tremolite indicate that the hornblende is a primary phase and not a product of alteration.

Several units of amphibolite, up to a few meters thick, occur in the northern part of the intrusion. They consist of variable amounts of medium-grained hornblende and plagioclase and contain abundant (up to 25%) sulfide mineralization. The possibility that the amphibolite units within the intrusion represent the gabbroic end-member derived during the fractionation of the komatiitic magma was investigated by Good (1985). He showed that major- and trace-element abundances and interelement ratios of the amphibolite are inconsistent with an origin by fractionation of olivine, pyroxene or plagioclase from a melt that could have crystallized the ultramafic units. It was concluded that the amphibolite units represent modified slices of the gneissic country-rock. The included sulfides are therefore referred to as xenolith-hosted sulfides.

Granitic pegmatite dikes, ranging in thickness from centimeters to several tens of meters, cross-cut the ultramafic rocks and amphibolites, and make up approximately 20 to 30 volume % of the ultramafic intrusion. The dikes are white to red-orange, coarse grained to pegmatitic, and consist of approximately equal amounts of K-feldspar, plagioclase and quartz, and minor biotite. At the dike contacts, zoned metasomatic alteration is superimposed on the serpentinized ultramafic rocks. The dike-related metasomatic alteration totally destroyed original textures, and generated a new growth-oriented fabric. This alteration occurs in discrete halos that range in thickness from centimeters to several meters and typically consists of three zones. From the dike outward, the zones consist of (1) a thin layer of phlogopite schist, (2) a 1- to 10-cm-thick band of acicular crystals of tremolite oriented perpendicular to the contact, and (3) a unit of medium-grained anthophyllite, tremolite and minor phlogopite. The amphibole crystals in the latter zone are fibrous and, unlike the amphibole in zone (2), are oriented randomly. Magnetite occurs in lenses 1–2 mm thick that are commonly located at the contacts between the zones. Similar zoned halos of metasomatic alteration were noted by Coats *et al.* (1976) at the Manibridge deposit, approximately 25 km to the southwest, and were studied in detail by Coats (1966) at the M11A deposit of Falconbridge, located approximately four km to the northeast.

The spatial relationship of the rock types, excluding the granitic pegmatite dikes and their zoned halos of metasomatic alteration, is shown in the plan and cross section of the intrusion in Figures 2 and 3, respectively.

COMPOSITION OF THE INTRUSION

A detailed chemical profile of borehole BU–33 is shown in Figure 4. Included in Figure 4 is the forsterite content of olivine and the CIPW normative composition of the samples. Only Al_2O_3, TiO_2 and Y are plotted, since these elements are shown below to have been the least mobile during the events of metasomatism associated with serpentinization and the intrusion of granitic pegmatite dikes.

There are two opposing trends exhibited in Figure 4 that suggest that concentrations of incompatible elements are controlled by two processes. The trends exhibited in the section from 155 to 250 m suggest that fractional crystallization was important in controlling variation in trace-element concentrations, whereas in the section from 70 to 100 m, adcumulate growth was apparently more important.

In the section from 155 to 250 m, the trend of decreasing forsterite content in olivine corresponds to decreasing content of normative olivine and increasing trace-element concentrations. This trend is expected during the periodic recharging of a crystallizing magma chamber and implies that fractional crystallization plays an important role in the determination of whole-rock compositions.

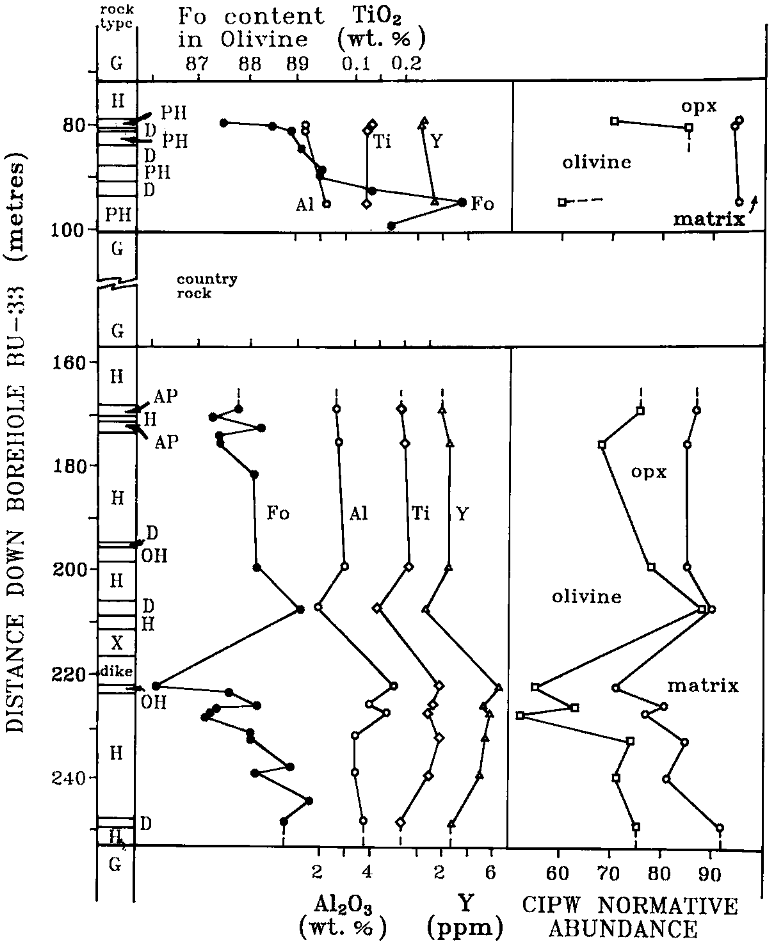

FIG. 4. Detailed chemical section of borehole BU–33 located in Fig. 2. Note the break in the vertical scale. Matrix refers to CIPW norm minerals excluding olivine and orthopyroxene. Abbreviations: G gneissic country-rock, H harzburgite, PH poikilitic harzburgite, D dunite, AP hornblende peridotite, OH orthopyroxene-rich harzburgite.

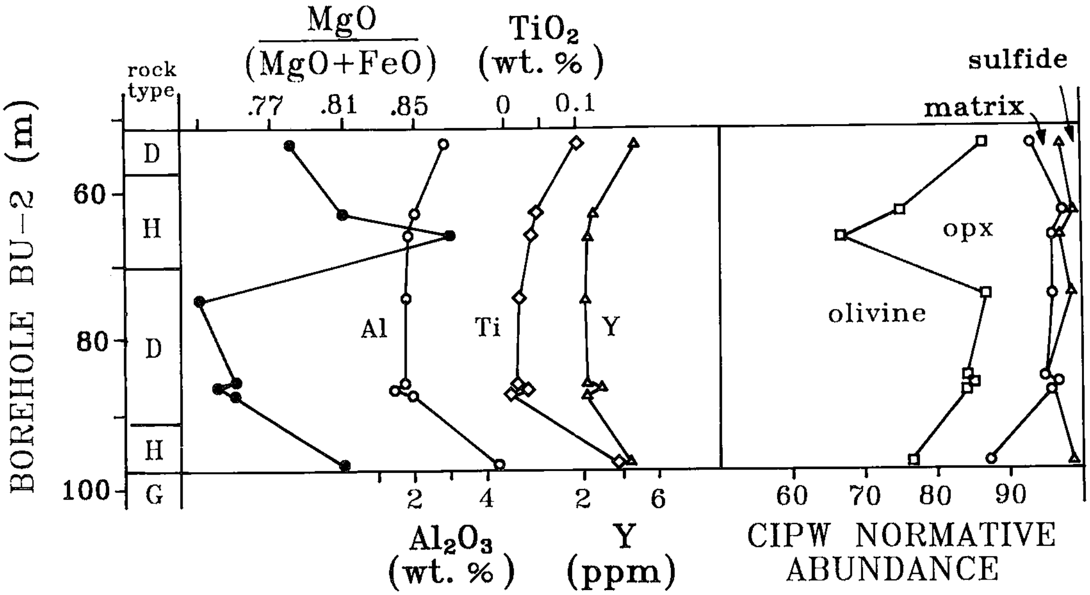

FIG. 5. Detailed chemical section of borehole BU–2, whose location is shown in Figure 2. MgO/(MgO+FeO) is whole-rock value (weight %). Abbreviations as in Figure 4.

In the section from 70 to 100 m, the steep trend of decreasing forsterite content does not correspond to that for the amount of olivine or trace elements. Two samples of poikilitic harzburgite, located at 81 and 96 m, have, respectively, olivine compositions of $Fo_{87.5}$ and $Fo_{92.5}$ and equivalent Y and Al_2O_3 concentrations. These Y and Al_2O_3 values are low and similar to those for dunite in the section from 155 to 250 m. The low values can be explained by hypothetical ejection of interstitial melt during adcumulate growth. It appears, therefore, that the whole-rock concentration of incompatible elements in the section from 70 to 100 m is related to the amount of interstitial melt remaining after crystallization.

A detailed chemical profile of borehole BU–2 is presented in Figure 5. Plotted in Figure 5 are whole-rock data arranged to show MgO/(MgO+FeO), Al_2O_3, TiO_2, Y and CIPW normative compositions. There is no remnant olivine in sections from borehole BU–2, so that olivine compositions are unknown. In general, the abundance of Al_2O_3, TiO_2 and Y decreases inward from both contacts.

ALTERATION

Metasomatic alteration of the Bucko Lake intrusion occurred in at least two stages. The first involved the concurrent serpentinization of olivine, the alteration of orthopyroxene to tremolite, and the formation of ubiquitous phlogopite. The second stage was considerably more intense, but only occurred within halos marginal to granitic pegmatitic dikes. The effects of each stage of alteration are evaluated separately.

To identify elements that were mobile during serpentinization, abundances of major and trace elements (listed in Table 1 and Good 1985), are plotted against MgO plus FeO for samples of harzburgite, dunite and poikilitic harzburgite (Fig. 6). The compositions of olivine and orthopyroxene are indicated on the x axis.

There is a strong to moderate negative correlation for Al_2O_3, TiO_2, CaO, Zr and Y *versus* MgO+FeO (Fig. 6). Elements that show the most scatter are Na, Sr, Rb and K. From these observations, it is inferred that Al_2O_3, TiO_2, CaO, Zr and Y showed the least mobility, and Na, Sr, Rb and K, the greatest mobility during serpentinization.

The trend lines for Al_2O_3, TiO_2, CaO, Zr and Y *versus* MgO plus FeO (Fig. 6) are best-fit regression lines for all of the samples. The trends likely represent mixing lines between the cumulus minerals and the interstitial melt. Since the trends intersect the x axis at about 55%, then it is possible that the cumulus end-member is a mixture of olivine and orthopyroxene, perhaps about 5:1. Alternatively, it is possible that the original trend may have been modified by adcumulate growth. Adcumulate growth of orthopyroxene and resorption of olivine, as is noted in poikilitic harzburgite, will shift data closer to the composition of orthopyroxene. This latter process could account for the slight departure of data downward from the curve at the olivine-rich end.

The compositional change effected by the alteration

TABLE 1. CHEMICAL COMPOSITION OF ROCKS FROM THE BUCKO LAKE INTRUSION

	2-97	17-86	40-176	33-139	33-240	33-249	33-81	33-82	2-85	33-169	33-243	33-220
rock type	harz	harz	harz	harz	harz	harz	p harz	dun	dun	a per	halo	dike
SiO2 %	44.24	41.52	40.62	44.71	44.66	42.55	44.08	40.88	39.04	42.63	54.53	72.76
TiO2	0.17	0.11	0.22	0.15	0.20	0.12	0.08	0.07	0.02	0.14	0.15	0.05
Al2O3	3.47	1.73	3.83	3.24	3.57	4.32	1.43	1.39	0.77	2.66	3.96	13.24
Fe2O3[1]	10.90	12.75	14.83	11.18	10.28	11.88	15.01	14.86	16.41	11.21	9.26	0.65
MnO	0.05	0.11	0.11	0.14	0.11	0.10	0.08	0.12	0.07	0.10	0.12	0.02
MgO	38.51	41.00	34.13	36.66	38.02	40.39	39.20	39.64	38.17	38.51	227.08	0.28
CaO	0.55	0.30	2.78	1.42	2.10	0.26	0.20	0.05	0.34	1.73	0.76	0.62
Na2O	0.12	0.06	0.44	0.17	0.25	0.06	0.10	0.07	0.05	0.36	0.14	3.22
K2O	1.52	0.46	0.19	1.80	0.74	0.11	0.32	0.66	0.05	0.23	2.53	5.73
P2O5	0.02	0.05	0.05	0.01	0.03	0.04	0.02	0.02	0.00	0.03	0.01	0.03
NiO	0.22	1.41	2.27	0.18	0.87	0.60	0.27	0.27	2.16	0.47	0.81	
TOTAL	99.77	99.50	99.47	99.66	100.83	100.43	100.79	98.03	97.08	98.07	99.35	96.60
Zr ppm	4.9	10	8	3.2	8.5	nd	nd	nd	nd	4.9	6.6	18
Y	2.2	2.2	4.9	3.3	5.0	2.8	0.7	0.4	nd	2	6.7	2.3
Sr	7.7	4.4	29.6	16	9.5	6.4	12	2.2	6.7	6.4	6.8	125
Rb	71	17	5.4	62	32	17	11	28	2.3	14	58	134
Cr	5110	2400	1220	2210	900	2600	3896	4365	3980	2920	900	140

Symbols: harz, harzburgite; dun, dunite; p harz, poikilitic harzburgite; a per, hornblende peridotite; halo, metasomatic alteration halo; nd, not detected. All elements by X-ray fluorescence except Na, by INAA. [1]All samples were analyzed loss free, after treatment with nitric acid and roasting for 12 hours at 1000°C. Hence total iron is expressed as Fe_2O_3 and no value for loss on ignition is quoted.

of serpentinized harzburgite to the fibrous anthophyllite – tremolite – phlogopite rock in a zoned metasomatic alteration halo of a granitic pegmatite dike was investigated by Good (1985) using a mass-balance approach (Appleyard 1980). For this exercise, two samples from the alteration halo (P26 and P29) were compared to three samples of surrounding harzburgite (P25, P27 and P28). The four important results of this study were: 1) the volume of the amphibole–phlogopite rock is approximately 97% that of the serpentinized harzburgite, 2) Al_2O_3, Y, FeO and MnO were apparently unchanged, c) SiO_2 was added, and d) MgO was removed.

The results of the above mass-balance study and the trends for data in Figure 6 are useful in distinguishing between amphibole-rich rock units in the intrusion that were formed by different processes. For example, serpentinized olivine orthopyroxenite resembles altered harzburgite within the fibrous amphibole zone of an alteration halo near granitic pegmatite dikes since both rocks consist predominantly of tremolite. The inability to discriminate visually between these units is one of the major problems in describing the petrography of the intrusion. In this case, the units can be distinguished geochemically because a sample of harzburgite from within an alteration halo adjacent to a dike will have concentrations of Al_2O_3, TiO_2, Zr and Y that are too low relative to the amount of MgO+FeO, and will plot below the trend lines in Figure 6. On the other hand, data for olivine orthopyroxenite will plot along the trend lines of Figure 6.

SULFIDE MINERALIZATION

Ni-sulfide mineralization at Bucko Lake occurs in two prominent settings. The first setting involves primary, disseminated to net-textured sulfides, located within several elongate, lenticular zones in the intrusion. The second setting involves mobilized sulfides, located in close proximity to the zones of primary sulfides.

The primary, disseminated to net-textured sulfides consist of, in order of decreasing abundance, pentlandite, pyrrhotite, chalcopyrite, mackinawite, pyrite, cubanite, and violarite. The pentlandite:pyrrhotite ratio is between three and eight in the net-textured sulfides, but is greater than ten in the disseminated type. The pentlandite:chalcopyrite ratio in both sulfide types varies between 7 and 14. Pentlandite may occur as blocky grains associated with (or as exsolution flames within) pyrrhotite, and in small fractures within serpentinized olivine pseudomorphs. Pentlandite is commonly rimmed or veined by magnetite. Chalcopyrite occurs as rounded disseminated grains that may contain exsolved cubanite. Mackinawite occurs as vermiform veinlets or blades within pentlandite.

The disseminated sulfides in two anthophyllite – tremolite – phlogopite rocks (samples P26 and P29) from alteration halos adjacent to granitic pegmatite dikes consist of pentlandite and accessory chalcopyrite and pyrite. Pyrrhotite was not observed. The pentlandite is Ni-rich (40%) relative to that in the surrounding serpentinites (34–36%) (Good 1985). These sulfides are

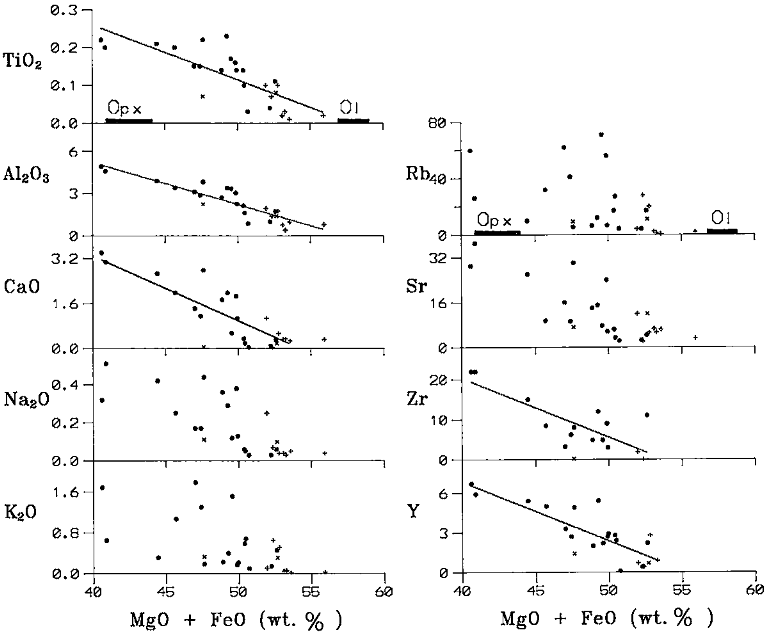

FIG. 6. Stacked variation diagrams for the major and trace elements *versus* MgO+FeO for samples of the Bucko Lake intrusion. The ranges for orthopyroxene and olivine compositions are indicated on the *x* axes at the top of the diagram. The trend lines for Al_2O_3, TiO_2, CaO, Zr and Y are best-fit regression lines for all samples. From these diagrams, it is inferred that Al_2O_3, TiO_2, CaO, Zr and Y showed the least mobility, and Na, Sr, Rb and K, the greatest mobility during serpentinization.

considered to be the remnants of primary disseminated sulfides.

The mobilized sulfides are subdivided into two groups on the basis of host rock, timing of emplacement and composition. The first group of mobilized sulfides are hosted by amphibolite xenoliths located in the northern portion of the intrusion and are termed xenolith-hosted sulfides. The second group of mobilized sulfides are hosted by sheared peridotite and brecciated granitic pegmatite dikes and are termed stringer sulfides.

The xenolith-hosted sulfides were emplaced prior to stringer sulfides. This is evident by reason of the xenolith-hosted sulfides, which are cut by granitic pegmatite dikes. It follows that xenolith-hosted sulfides were emplaced prior to the deformation event that resulted in the localized shearing of peridotite and granitic pegmatite dikes.

The xenolith-hosted sulfides occur in two forms. The first and most common form is as a matrix (up to 25% sulfide) to amphibole, resulting in a net-textured appearance. The second form is as thin veins, up to tens of cm thick, of massive sulfide that contain rare, angular fragments of peridotite. Both types of the xenolith-hosted sulfides consist of pyrrhotite, pentlandite, chalcopyrite and pyrite in proportions roughly equivalent to those in the primary net-textured sulfides.

The stringer sulfides occur as thin veinlets (up to a few cm thick) interspersed in zones of brecciated granitic pegmatite dikes and sheared ultramafic rocks. The relative proportions of pentlandite, chalcopyrite, pyrrhotite and pyrite in the stringer sulfides are much more variable than in the primary and xenolith-hosted sulfide types. For the samples of stringer sulfide analyzed (n = 6), the ratio pentlandite:pyrrhotite varies from 2 to >20; pentlandite:chalcopyrite varies from and 0.5 to >20.

PLATINUM-GROUP ELEMENTS AND GOLD

Twenty-four samples from the Bucko Lake intrusion were analyzed for the PGE and gold, using the combined fire assay – neutron activation technique of Hoffman *et al.* (1978), and for Ni, Cu, Co and S by X-ray fluorescence. The samples selected are believed to be representative of the primary and mobilized sulfide types. Analytical results are listed in Table 2.

The data on concentrations of Cu, Ni and precious metals are presented diagrammatically in two ways, firstly, as whole-rock abundances (Table 2) normalized

TABLE 2. COMPOSITION OF SULFIDE SAMPLES FROM THE BUCKO LAKE DEPOSIT

sample number	location	rock type	Os ppb	Ir	Ru	Rh	Pt	Pd	Au	S wt.%	Ni	Cu
P7	2-85	dun	56	33	119	36	120	400	13	2.06	1.79	0.13
P8	2-53	dun	16	12	nd	20	73	151	5	1.15	0.97	0.08
P9	17-116	harz	43	28	78	33	184	278	19	1.86	1.28	0.17
P10	17-86	harz	43	26	55	25	75	261	35	1.32	1.11	0.12
P11	40-75	harz	20	11	nd	13	74	108	51	1.04	0.85	0.07
P12	40-176	harz	55	32	98	42	184	412	52	2.48	1.78	0.16
P13	44-59	dike	nd	2	nd	4	93	603	21	2.79	1.29	0.82
P14	29-274	shr	122	80	50	89	538	1214	17	8.21	5.98	0.04
P15	29-275	xen	50	33	81	63	282	2176	19	7.40	5.60	0.10
P16	17-96	dike	nd	1	9	4	82	129	5	0.72	0.53	0.15
P17	53-233	xen	255	132	365	124	179	1179	24	6.34	3.73	0.42
P18	2-55	dike	15	10	20	16	34	75	3	0.48	0.60	0.03
P19	40-147	shr	129	74	224	73	235	905	7	4.53	3.13	0.08
P20	35-236	xen	58	32	99	33	277	509	18	2.19	1.46	0.09
P21	33-219	dike	9	4	16	12	303	353	19	2.68	0.73	1.59
P23	33-223	harz	12	7	19	6	55	66	13	0.42	0.45	0.03
P24	33-226	harz	16	9	49	10	51	78	14	0.38	0.46	0.03
P25	33-228	harz	15	6	28	6	50	58	6	0.24	0.34	0.02
P26	33-229	halo	14	7	24	5	48	52	4	0.14	0.39	0.01
P27	33-233	harz	18	11	39	10	55	77	10	0.44	0.54	0.03
P28	33-240	harz	25	15	51	15	67	85	13	0.65	0.68	0.05
P29	33-243	halo	25	13	46	14	84	120	3	0.30	0.64	0.02
P30	33-249	harz	14	7	28	10	37	61	4	0.44	0.47	0.03

Symbols: harz, harzburgite; dun, dunite; halo, metasomatic alteration halo; xen, xenolith-hosted sulfide; shr, stringer sulfide in sheared peridotite; dike, stringer sulfide in granitic pegmatite dike; nd, not detected. Concentrations of Ni, Cu and S by X-ray-fluorescence analysis (X-Ray Assay Labs, Toronto); concentration of precious metals by fire assay - neutron activation method of Hoffman et al. (1979).

with mantle abundances after Barnes *et al.* (1988), and secondly, as concentrations in 100% sulfides, which have been calculated assuming the ideal composition of the sulfides, and then normalized using mantle abundances.

The proportion of precious metals in the disseminated to net-textured sulfides apparently remained unchanged during metamorphism and serpentinization. The PGE, Ni, Cu and Au curves for individual samples (Fig. 7) are mostly parallel, indicating similar interelement ratios. Therefore, for the Bucko Lake deposit, mobility of the metals during serpentinization must have been minor.

Disseminated sulfides in the alteration halo of a granitic pegmatite dike are depleted in Au and Cu with respect to those in harzburgite. The composition of six samples of serpentinized harzburgite (P23 to 25, P27, P28 and P30) from borehole BU–33 are compared to two intensely altered samples (P26 and P29) in Figure 8. The concentration of all metals except Au and Cu are essentially the same for both groups of samples. Therefore, the alteration of a serpentinized harzburgite to an anthophyllite – tremolite – phlogopite rock has been accompanied by the depletion of Au and Cu, whereas the PGE remained unchanged.

The composition of the two types of mobilized sulfides is related to the range of disseminated to net-textured sulfides in Figure 9. All values are normalized to 100% sulfide. The fields for the three types of sulfide samples partly overlap. The field for the xenolith-hosted sulfides lies almost on top of the range of primary sulfides, and the stringer sulfides are enriched in Cu and depleted in Ni and the Ir group of elements.

The compositional differences between the two groups of mobilized samples are likely related to the conditions under which the sulfides were mobilized. Field relationships indicate that the stringer sulfides formed last, presumably under metamorphic–hydrothermal conditions at lower temperature. On the other hand, the xenolith-hosted sulfides likely formed under higher temperatures, perhaps in response to deformation during peak metamorphism. The approximate maximum temperature attained during metamorphism was estimated by Paktunc (1984) to be 700°C at the Thompson mine. Alternatively, the xenolith-hosted sulfides could have originated by the emplacement of an immiscible sulfide melt into the xenoliths during emplacement of the BLI. This latter hypothesis, however, is considered to be unlikely since the presence of peridotite fragments in xenolith-hosted sulfides suggests that plastic flow of the sulfides may have been a significant mechanism in their formation.

The strong correlation between S and Pd (Fig. 10) for all samples of sulfide does not hold for any of the other PGE or Cu. This would seem to indicate that Pd is not

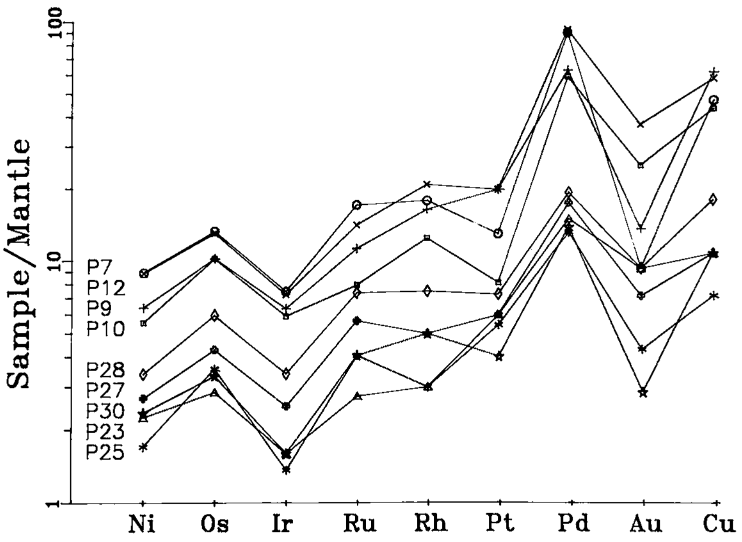

FIG. 7. Mantle-normalized PGE, Au, Cu and Ni for samples of harzburgite with disseminated to net-textured sulfides.

fractionated from S under a wide range of conditions that lead to mobilize sulfides.

The average composition of disseminated to net-textured ore in the Bucko Lake deposit is similar to that of Archean komatiite-associated deposits elsewhere. In Figure 11, the average concentration in ore samples P7 to P12, recalculated to that in 100% sulfide, is compared to the average ore from Kambalda, West Australia

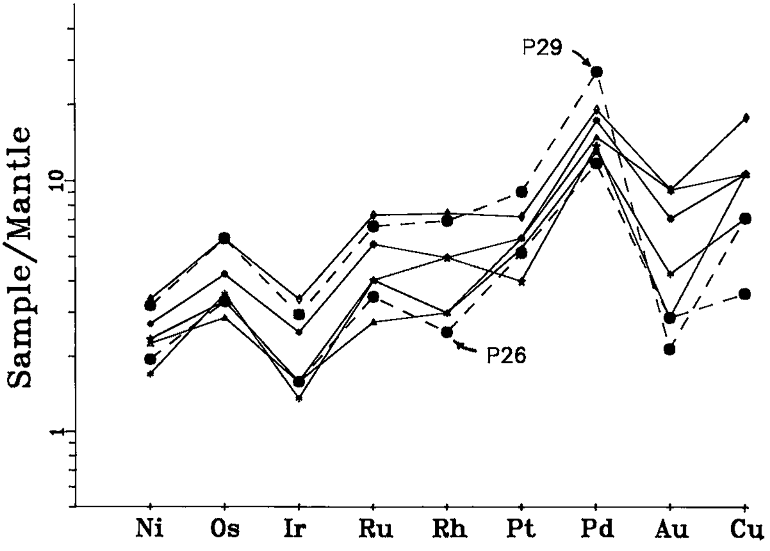

FIG. 8. Mantle-normalized PGE, Au, Cu and Ni for samples P23 to P30 from borehole BU–33, located between 220 and 249 m (symbols as in Figure 7). Samples P26 and P29 (dashed lines) are from zoned halos of metasomatic alteration adjacent to granitic pegmatite dikes, and the rest are harzburgite.

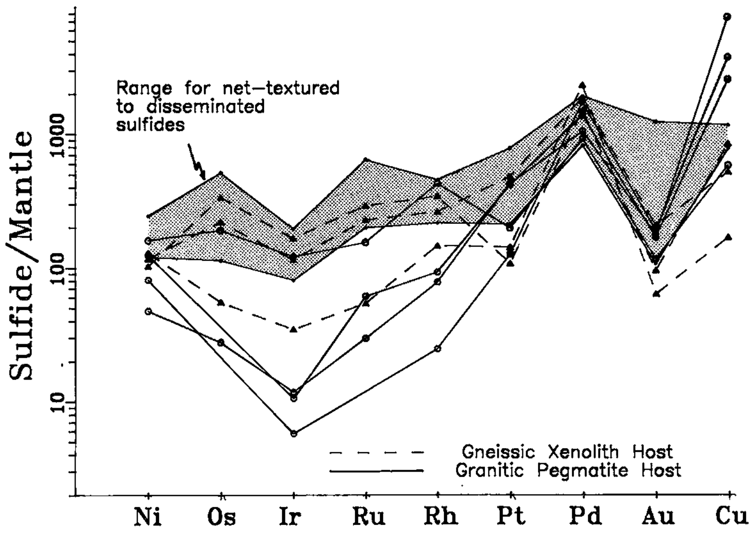

FIG. 9. Comparison of mantle-normalized PGE, Au, Cu and Ni concentrations in xenolith-hosted sulfides (dashed lines), stringer sulfides from granitic pegmatite dikes (solid lines), and the range for primary disseminated sulfide samples. All values are recalculated to represent those in 100% sulfides.

(Cowden *et al.* 1986), the Donaldson West deposit (Dillon-Leitch *et al.* 1986) and Katiniq deposit (Barnes *et al.* 1982) in Quebec, and the Langmuir deposit, Ontario (Naldrett & Duke 1980). The pattern for Bucko is approximately parallel to and slightly higher than that of the Langmuir deposit and the average for the Kambalda deposits. The Proterozoic Donaldson West and Katiniq deposits of the Cape Smith belt are enriched in

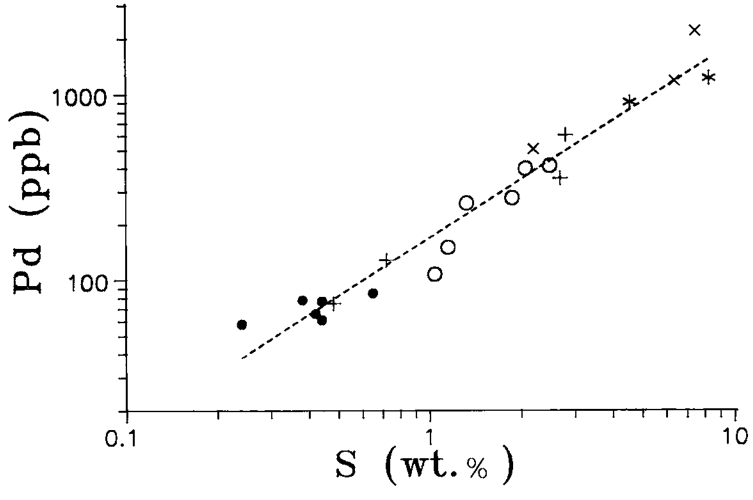

FIG. 10. Concentration of Pd *versus* S for all sulfide samples. Primary disseminated sulfide-bearing samples P23 to P30: closed circles; primary disseminated to net-textured samples P7 to P12: open circles; stringer sulfides in granitic pegmatite dikes: (+) symbols; stringer sulfides in sheared peridotite: (*) symbols, and xenolith-hosted sulfides: (x) symbols.

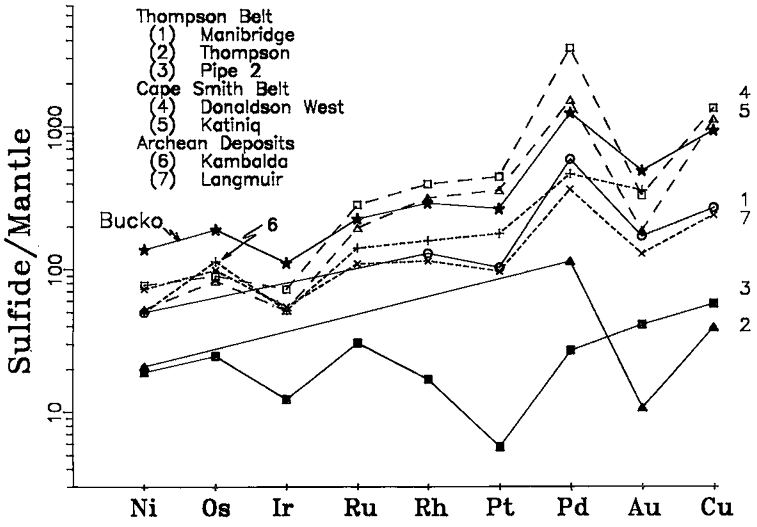

FIG. 11. Mantle-normalized concentrations of PGE, Au, Cu and Ni in 100% sulfides for Bucko Lake and various komatiite-hosted sulfide deposits. Thompson belt deposits: solid lines, Cape Smith belt deposits: long dashed lines, Archean deposits: short dashed lines. Data for Pipe 2 from Naldrett *et al.* (1979), for Manibridge from Naldrett (1981), for Thompson mine from Jonasson *et al.* (1987), for Donaldson West, Katiniq and Langmuir, from Naldrett & Duke (1980), and for Kambalda, from Cowden *et al.* (1986).

Pd and Cu, and depleted in Ni and Ir, compared to the Bucko Lake deposit.

The abundance of all metals in sulfides of the Bucko deposit is higher than in that of the Pipe 2 and Thompson deposits, located in the Thompson belt. Sulfide-normalized concentrations of metals at the Pipe 2 mine (Naldrett *et al.* 1979) and the Thompson deposit (Jonasson *et al.* 1987) are depleted, particularly in the case of Pt, relative to Bucko and the other komatiite-associated deposits (Fig. 11). Naldrett *et al.* (1979) attributed the depletion at the Pipe 2 mine to a dramatic decrease in the ratio of silicate melt to sulfide melt as a result of the assimilation of crustal sulfur from the Early Proterozoic supracrustal sequence. Independent evidence for the assimilation of crustal sulfur is found in Se/S ratios of the Thompson belt nickel ores (Eckstrand *et al.* 1989). If much of the sulfur in the deposits is derived by contamination, then deposits in the northern part of the belt (from Soab northward), which are hosted in Early Proterozoic supracrustal rocks, may be different from those in the southern part of the belt, which are hosted in presumably Archean gneisses. The nature and composition of contamination could well be different in these two lithologic settings.

The average Pt/(Pt+Pd) and Cu/(Cu+Ni) ratios for several deposits in the Thompson belt and Cape Smith belt are compared in Figure 12. The spread for Cu/(Cu+Ni) and Pt/(Pt+Pd) ratios in the Thompson belt data is likely a function of heterogeneous concentrations of metals in the sulfides, and, therefore, indicates the difficulty in obtaining representative compositions of sulfides for deposits. The Cu/(Cu+Ni) and Pt(Pt+Pd) values for the Manibridge and Bucko Lake deposits are believed to be representative of sulfides in the southern part of the Thompson belt. These values fall within the range of Archean komatiites described by Naldrett (1981), but are separate from those of the Cape Smith belt. Deposits of the Cape Smith belt exhibit more fractionated Pd/Ir, Pt/(Pt+Pd) and Cu/(Cu+Ni) ratios than those in the Thompson belt. This is an important distinction, since both areas occur within the Early Proterozoic Circum-Superior Belt (Baragar & Scoates 1981). The more primitive composition of sulfides in the southern part of the Thompson belt could have been generated by either a higher degree of partial melting in the mantle or by the relatively early saturation of the melt in sulfide during the crystallization of olivine. The mechanisms for this fractionation of metals were described by Naldrett & Barnes (1986) and Barnes *et al.* (1985), who explained the fractionation in terms of the apparent compatible behavior of the Ir group of elements and the incompatible behavior of the Pd group during the partial melting in the mantle, to produce a komatiitic magma, and the subsequent crystallization of this magma.

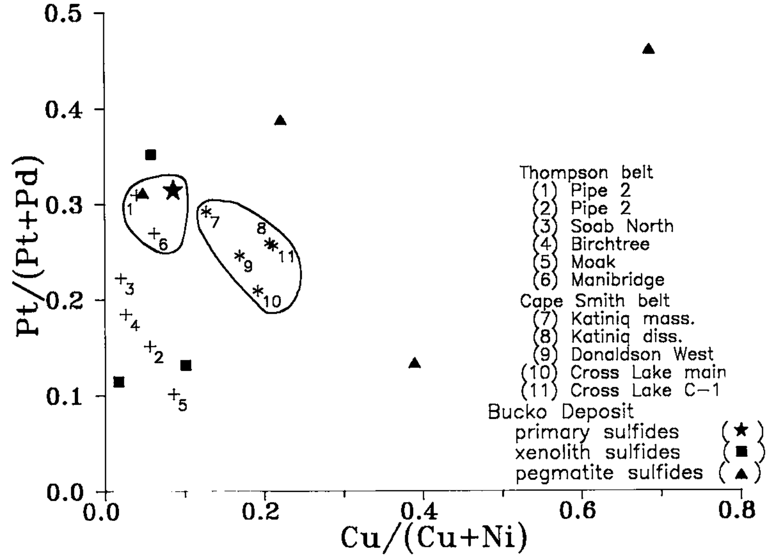

FIG. 12. Pt/(Pt+Pd) *versus* Cu/(Cu+Ni) for Bucko Lake samples compared to those in nickel sulfide deposits in the Thompson belt and Cape Smith belt. Data for Bucko include the average of primary sulfide samples (P7–P12): star, stringer sulfides in granitic pegmatite dikes: triangles, and xenolith-hosted sulfides: squares. Data for Pipe 2 (point 1) from Naldrett *et al.* (1979), for Manibridge from Naldrett (1981), for Soab North, Birchtree, Moak Lake and Pipe 2 (point 2) deposits from Jonasson *et al.* (1987), for Katiniq massive sulfides from Barnes *et al.* (1982), for Katiniq disseminated sulfides, Donaldson West disseminated sulfides, and Cross Lake sulfides from Barnes & Giovenazzo (1990) and references cited.

DISCUSSION AND CONCLUSIONS

The northern portion of the Bucko Lake intrusion is compositionally distinct from the southern portion. The former consists predominantly of harzburgite, with minor interlayered dunite. The correlation of the recurrence of dunite with a decrease in trace-element concentrations and an increase in forsterite contents in olivine is consistent with an origin by crystallization in a magma chamber that was periodically recharged. On the other hand, the southern portion of the BLI consists predominantly of dunite with lesser harzburgite. The abundant dunite and generally low concentrations of trace elements suggest that this section formed part of a magma conduit rather than a magma chamber. In this setting, dunite presumably formed by the accumulation of olivine phenocrysts, which lagged behind as the magma flowed through the conduit.

The majority of sulfides in the BLI are disseminated to net-textured and occur in several stratabound lenticular zones within peridotite. The composition of the sulfides is approximately homogeneous and was apparently unaffected by serpentinization. During intense metasomatic alteration adjacent to granitic pegmatite dikes, the concentrations of S, Cu and Au in the sulfides decreased, and those of the PGE were unchanged. The composition of the Bucko Lake sulfides is considered here to be representative of deposits in the southern part of the Thompson belt.

There are two types of mobilized sulfides: xenolith-hosted sulfides and stringer sulfides. The emplacement of the xenolith-hosted sulfides, presumably by a process such as plastic flow, probably occurred during the culmination of the Hudsonian Orogeny, and has led to little further fractionation of metals. The stringer sulfides postdate the xenolith-hosted sulfides and are hosted by brecciated granitic dikes and sheared serpentinite. As is the case with other intermediate temperature (200–700°C; Nyman *et al.* 1990) hydrothermal PGE deposits (*e.g.*, McCallum *et al.* 1976, Rowell & Edgar 1986, Good 1989), the stringer sulfides at Bucko Lake are enriched in Cu, and depleted in Ni and Ir relative to primary sulfides. Although quartz or calcite is common in vein-type deposits, they are rare in the Bucko Lake stringer sulfides; nevertheless, the similarities in composition and setting imply that the Bucko Lake stringer sulfides are hydrothermal in origin.

Interestingly, there is a strong linear correlation between S and Pd for all of the Bucko sulfide samples. This relationship indicates that Pd is not fractionated from S by the processes that have mobilized the sulfides at Bucko Lake. The correlation with S does not hold for

Pt as well as it does for Pd. A similar relationship to that shown between Pd and S at Bucko Lake was obtained by Dillon-Leitch *et al.* (1986) at the Donaldson West deposit. The reason for this relationship is, as yet, not clear.

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