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PALLADIUM, PLATINUM, RHODIUM, RUTHENIUM AND IRIDIUM IN PERIDOTITES AND CHROMITITES FROM OPHIOLITE COMPLEXES IN NEWFOUNDLAND

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ABSTRACT

Samples of spinel lherzolite, harzburgite, dunite and chromitite from the Bay of Islands, Lewis Hills, Table Mountain, Advocate, North Arm Mountain, White Hills Peridotite, Point Rousse, Great Bend and Betts Cove ophiolite complexes in Newfoundland were analyzed for the platinum-group elements (PGE) Pd, Pt, Rh, Ru and Ir. The ranges of concentration (in ppb) observed for all rocks are: <0.5 to 77 (Pd), <1 to 120 (Pt), <0.5 to 20 (Rh), <100 to 250 (Ru) and <20 to 83 (Ir). Chondrite-normalized PGE ratios suggest differences between rock types and between complexes. Samples of chromitite and dunite show relative enrichment in Ru and Ir and relative depletion in Pt and Pd. These trends are similar to those from ophiolite complexes in Turkey, Iran, Oman, southwestern Oregon, northern California, New Caledonia, Greece, and the Polar Urals, USSR. Partial melting of mantle material, either by a single-stage or multistage process, and either in sulfur-saturated or unsaturated conditions, which produces a residue and melt with different PGE concentrations, coupled with the crystallization of the melt to form the upper portions of the ophiolite, is invoked to explain the distribution of the PGE in the rocks.

Keywords: ophiolite complexes, Newfoundland, platinum-group elements, platinum, palladium, rhodium, ruthenium, iridium, peridotite, chromitite.

SOMMAIRE

Nous avons dosé les éléments du groupe du platine (EGP) Pd, Pt, Rh, Ru et Ir dans des échantillons de lherzolite à spinelle, harzburgite, dunite et chromitite des massifs ophiolitiques de Terre-Neuve, situés à Bay of Islands, Lewis Hills, Table Mountain, Advocate, North Arm Mountain, White Hill, Point Rousse, Great Bend et Betts Cove. Les domaines de concentration observés sont les suivants [concentration exprimée en milliardièmes (ppb)]: pour Pd, <0.5 à 77, pour Pt, <1 à 120, pour Rh, <0.5 à 20, pour Ru, <100 à 250 et pour Ir, <20 à 83. Les concentrations des EGP, normalisées par rapport à la chondrite, montrent des différences entre types de roches et entre complexes. Les échantillons de chromitite et de dunite montrent un enrichissement relatif en Ru et Ir et un appauvrissement en Pt et Pd. Ces tendances sont semblables à celles qu'on observe dans les complexes ophiolitiques de Turquie, de l'Iran, de l'Oman, du Sud-Ouest de l'Orégon, de Californie septentrionale, de Nouvelle-Calédonie, de Grèce et de l'Oural polaire, URSS. Une fusion partielle du manteau en un ou plusieurs stades, dans des conditions de saturation ou de sous-saturation en soufre, qui produirait un résidu et un liquide ayant différentes répartitions des EGP et, d'autre part, une cristallisation de la phase liquide pour donner les parties supérieures de l'ophiolite, expliqueraient la distribution des EGP dans ces roches.

(Traduit par la Rédaction)

Mots-clés: complexes ophiolitiques, Terre-Neuve, éléments du groupe du platine, platine, palladium, ruthénium, iridium, péridotite, chromitite.

INTRODUCTION

Previous studies of the distribution of the platinum-group elements (PGE) in ophiolite assemblages from Cyprus, Oman, New Caledonia, the Polar Urals and southwestern Oregon (Agiorgitis & Wolf 1977, 1978, Page *et al.* 1979b, 1982, 1983, Oshin & Crocket 1982) and summaries of other available data on PGE in ophiolite assemblages (Naldrett & Cabri 1976, Crocket 1979) suggest that Os–Ir–Ru-enriched patterns of chondrite-normalized ratios of PGE in rocks, particularly chromitites, are characteristic of ophiolite assemblages and distinctive from other mafic and ultramafic environments. Mineralogical studies of placer deposits associated with known ophiolitic assemblages, such as those in Tasmania (Cabri & Harris 1975, Ford 1981) and in Papua - New Guinea (Harris & Cabri 1973), and investigations of platinum-group minerals in chromitites from ophiolites such as in Cyprus (Constantinides *et al.* 1980), Shetland Islands (Prichard *et al.* 1981), Canada (Talkington *et al.* 1982a, b), southwestern Oregon (H. Stockman, pers. comm. 1980) and New Caledonia (Z. Johan, written comm. 1980), show the predominance of Os–Ir–Ru minerals and the scarcity of Pt–Pd minerals, thus supporting the distinction in PGE distributions. In addition, comparison of the PGE distribution in ultramafic xenoliths (Jagoutz *et al.* 1979, Morgan & Wandless 1979, Morgan *et al.* 1980, Mitchell & Keays 1981) with those from ophiolite sequences seems to indicate or suggest hypotheses for processes that affect the PGE distributions in different parts of the ophiolite assemblage.

The purposes of this report are (1) to review the geological setting of the ophiolite complexes in Newfoundland and to focus on the necessary geological and petrological details of the complexes sampled and analyzed, (2) to present the results of PGE analyses and to examine their chondrite-normalized patterns in relation to the petrology of the samples, in order to characterize the distribution of PGE from well-documented ophiolites of late Precambrian and Paleozoic age, (3) to compare their PGE distribution with ophiolites elsewhere, and (4) to explore various hypotheses that might account for the distribution of PGE in ophiolite assemblages.

This report has not been reviewed for conformity with standards of stratigraphic nomenclature and classification adopted by the U.S. Geological Survey.

Geological Settings

The geology of Newfoundland has been summarized by Williams (1979), who divided the island into four geological zones based on contrasts between Middle Ordovician and older rocks. These zones are, from west to east, Humber, Dunnage, Gander and Avalon, as shown in Figure 1. Only ophiolites from the Humber and Dunnage zones are discussed in this paper.

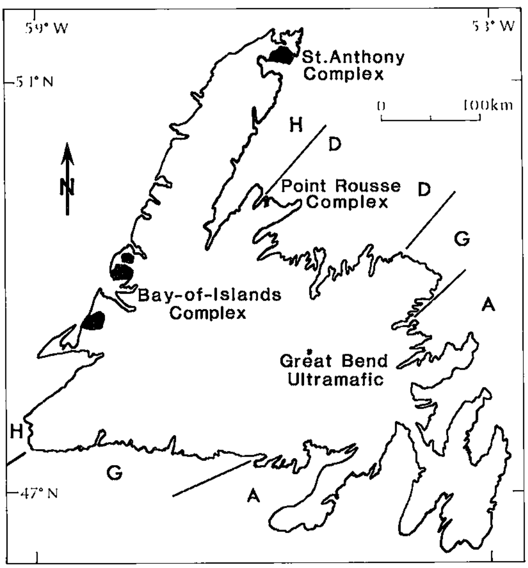

FIG. 1. Tectonic, lithostratigraphic zones of Newfoundland (after Williams 1979) and location of complexes sampled. H Humber Zone, D Dunnage Zone, G Gander Zone, A Avalon Zone.

In the Humber Zone, which contains the Bay of Islands, Advocate and St. Anthony ophiolitic complexes, the Middle Ordovician and older rocks are separated into three elements on the basis of tectonic similarities and lithology: (1) Precambrian basement, (2) Cambro-Ordovician autochthonous and neoautochthonous sequences of predominant carbonates, with minor clastic and volcanic rocks, and 3) Cambro-Ordovician allochthonous sequences of clastic material, carbonates and ophiolite sequences. These tectonolithologic elements are believed to record the development and destruction of an Atlantic-type continental margin (Stevens 1970, Church & Stevens 1971, Williams & Stevens 1974).

The Dunnage Zone represents vestiges of the Paleozoic Iapetus Ocean (Williams 1979, Hibbard & Williams 1979), where arc-basin rocks rest on oceanic crust (Hibbard & Williams 1979). Ophiolitic rocks occur at the western and eastern margins of the zone. At the western margin, the Advocate and Point Rousse ophiolite complexes occur at the Baie Verte - Brompton Line, which defines a zone of intense deformation and is the boundary between continental material to the west and oceanic material to the east (St-Julien *et al.* 1976, Williams & Talkington 1977). The Betts Cove ophiolite occurs near the western margin. At the eastern margin of the Dunnage Zone, mafic-ultramafic rocks of the Gander River Belt, especially the Pipestone Pond and Great Bend bodies, have been interpreted as ophiolitic fragments and mantle diapirs, respectively (Kean 1974, Stevens *et al.* 1974). However, recent mapping by Colman-Sadd (1981) suggests that these and other mafic-ultramafic bodies along the eastern margin of the Dunnage Zone are ophiolites.

Ophiolites of the Humber Zone

The Bay of Islands Complex

The ophiolite suites making up the Bay of Islands Complex have received considerable study (Smith 1958, Irvine & Findlay 1972, Williams *et al.* 1972, Malpas 1976, Karson 1977) that has identified the major lithological components, geochemistry, petrogenesis and tectonic evolution of these late Precambrian - early Paleozoic remnants of oceanic material (Fig. 2). Three of the four ophiolites in the Bay of Islands Complex have been sampled for this study: Lewis Hills, North Arm Mountain and Table Mountain. Sample locations are shown on Figure 2, and petrological details of individual samples are presented in the appendix.

Lewis Hills: The geology of the Lewis Hills has been discussed by Karson (1977) and Karson & Dewey (1978). The stratigraphic relations of this ophiolite are more complex than those of the other three Bay-of-Islands ophiolites. Nevertheless, most of the

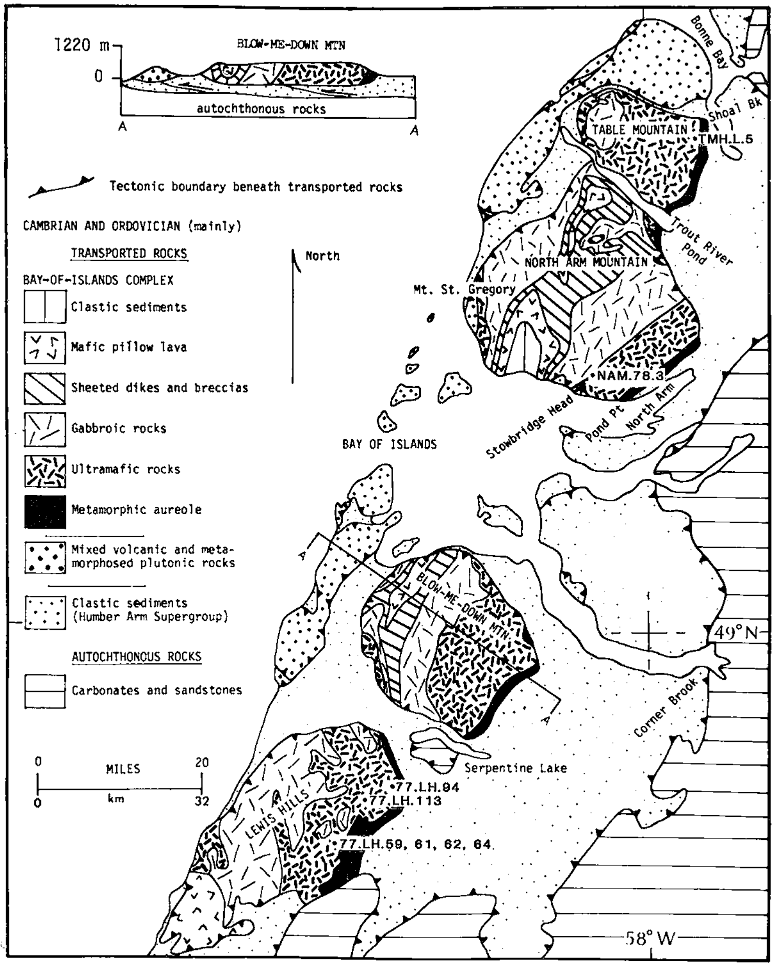

FIG. 2. Geological map of the Bay of Islands Complex (after Williams & Smyth 1973), showing location of analyzed samples.

lithological components that occur in other Bay-of-Islands ophiolites are present here.

Podiform deposits of chromite appear to be situated in a zone approximately 600 m below the 'critical zone' (Smith 1958, Malpas 1976) in a region of interlayered dunite and peridotite (harzburgite). Pyroxenite veins parallel to layering are locally abundant. The lithologies analyzed include harzburgite from the tectonized peridotite, cumulus dunite stratigraphically above the tectonized peridodite, and chromitites (see Table 1 and the appendix for details of individual samples). Samples were selected from the Springer's Hill deposit that crops out in a zone that strikes east–west and is approximately 300 m x 20 m (Snelgrove 1934, Berger 1962). Extensive trenching and small-scale mining operations of many chromite pods have left only the enclosing dunite sheath.

North Arm Mountain: The geology and stratigraphy of North Arm Mountain have been discussed by Williams *et al.* (1972) and Malpas (1976). North Arm Mountain preserves a nearly complete ophiolitic section, except for a lack of lherzolitic material at the base of the tectonite peridotite.

A sample has been selected from the Stowbridge chromite deposit, which is located approximately 400 m stratigraphically below the 'critical zone'. The chromite is found in seams, patches and small pods (20 cm in diameter) within dunite (Snelgrove 1934), but is also closely associated with pyroxenite layers and lenses. The analyzed material is a sample of a chromite seam enclosed by dunite in pyroxenite (see appendix).

Table Mountain: The stratigraphy of Table Mountain has been discussed by Williams *et al.* (1972) and Malpas (1976). The stratigraphic sequence for the

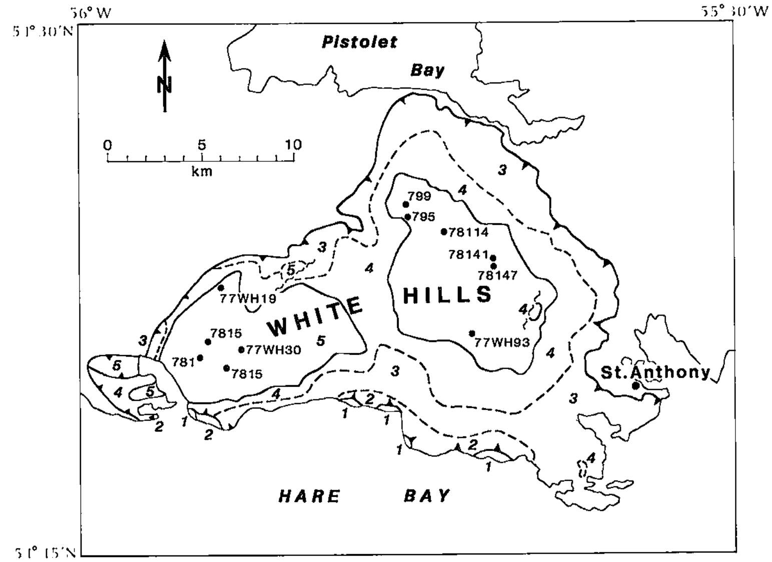

FIG. 3. Simplified geological map of the southern part of the St. Anthony Complex (after Jamieson 1979, Talkington 1981), showing location of analyzed samples. Key: 1 Maiden Point Formation, 2 Ireland Point Volcanic Suite, 3 Goose Cove Schist, 4 Green Ridge Amphibolite, 5 White Hills Peridotite.

ophiolitic rocks from base to top consists of spinel lherzolite (~200 m), harzburgite (~3,000 m), dunite (~300 m), 'critical zone' (~200 m) and gabbro (~1,000 m) (Malpas 1976). The spinel lherzolite, which is representative of partially depleted upper mantle, in the opinion of Malpas (1976), was sampled in the Winterhouse Brook area.

St. Anthony Complex

The ophiolite, which is part of the St. Anthony Complex, has been described by Cooper (1937), Smyth (1971), Riccio (1976), Jamieson (1979, 1981), Talkington (1979, 1981), Talkington & Jamieson (1978), Jamieson & Talkington (1980), Talkington & Malpas (1980a,b) and Williams & Smyth (1983). These studies have shown that the St. Anthony Complex, and specifically the White Hills Peridotite (Fig. 3), has features that distinguish it from the general (reconstructed) appearance of most ophiolites of the world, and more specifically from the Bay of Islands Complex. These differences are: (1) only the ultramafic section of the ophiolite is preserved; (2) harzburgite interlayered with spinel lherzolite forms approximately 85% of the peridotite outcrop; (3) dunite occurs as layers, lenses and dykes throughout the peridotite; (4) gabbro veins are found only in the eastern peridotite massif, and (5) alkali pyroxenites are found between the peridotite and a well-developed metamorphic aureole. However, owing to the lack of cryptic layering of minerals and bulk-rock variations and to structural complexities, stratigraphic relations cannot be determined for the White Hills Peridotite (Talkington 1981).

White Hills Peridotite: This late Precambrian – early Paleozoic ophiolite segment is composed of two large ultramafic massifs and one small dissected body that crops out in a belt trending approximately east–west on the northern tip of the Great Northern Peninsula (Fig. 3). Eleven samples of the various lithologies were selected from previously collected samples (Table 1 and appendix) and include spinel lherzolite, harzburgite, dunite and chromite-bearing orthopyroxenite. These lithologies are interpreted to be petrogenetically related as source material (spinel lherzolite), refractory residue (harzburgite), crystal cumulates from a first-stage partial melt (dunite), and crystal cumulates from a second-stage partial melt (chromite-bearing orthopyroxenite) (Talkington 1981).

Advocate Complex

The Advocate Complex (Fig. 1) lies along the northeastern part of the Baie Verte lineament and consists of ultramafic rocks, massive and foliated gabbros, sheeted dykes, pillow lavas and slates (Williams & Talkington 1977, Williams *et al.* 1977, Bursnall 1975). The complex is cut by steep northeast-trending shear zones and contains a steep northeast-trending foliation. The large ultramafic body on the northwestern margin contains the Advocate asbestos deposit, from which a serpentinized peridotite and chromite-bearing dunite were collected from dump materials (appendix). Another sample was collected from a mélange block of metaperidotite in garnet schists of the Fleur de Lys Supergroup (Williams 1977).

Ophiolites of the Dunnage Zone

Point Rousse Complex

The Point Rousse Complex, of Early Ordovician age or older, described by Norman & Strong (1975) and Williams *et al.* (1977), is composed of several structural blocks that contain sections of ophiolite stratigraphy (Fig. 4). Three samples were collected from the complex and include drill core of dunite and harzburgite from Grassy Island and dunite from Ming's Bight (Table 1 and appendix).

Great Bend ultramafic body

The roughly circular Great Bend ultramafic body, described by Kean (1974), is composed of a core of dunite and peridotite with an outer zone of anorthosite and gabbro (Fig. 5). Along the western side, the body is in contact with hornfelsed sediments, which prompted Kean (1974) to suggest that the body may have intruded the sediments. One dunite sample, selected from previously collected samples, comes from a pit on the east side of the Bay d'Espoir Highway. Stratigraphic relations of the dunite to other units of the complex are not known.

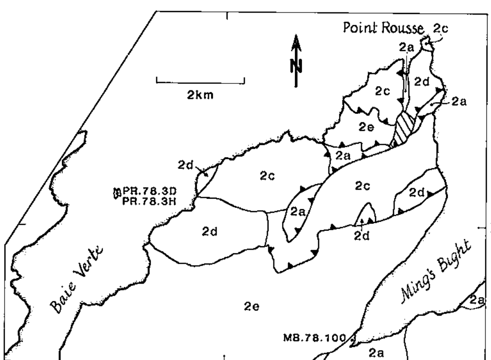

FIG. 4. Generalized geological map of the Point Rousse Complex (after Hibbard 1978), showing location of analyzed samples. Key: 2a ultramafic rocks, 2b cumulate ultramafic rocks and gabbro, 2c gabbro, 2d sheeted dykes, 2e mafic volcanic rocks.

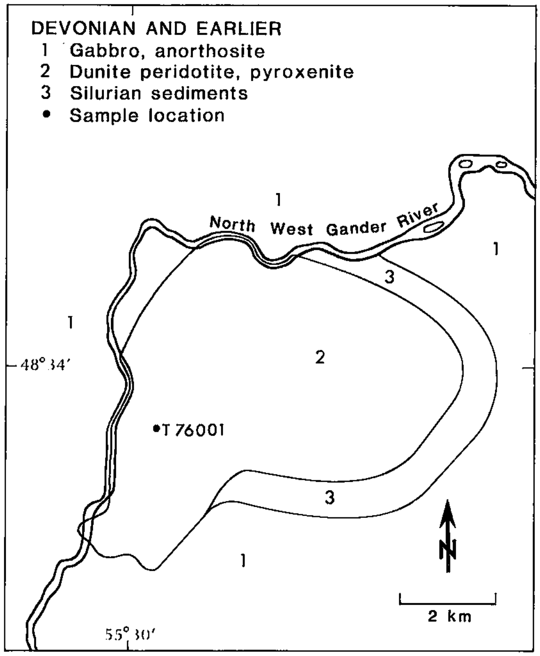

FIG. 5. Generalized geological map of the Great Bend ultramafic body (after Kean 1974).

Betts Cove Complex

The Betts Cove Complex (Fig. 1) consists of a basal ultramafic unit overlain by poorly developed gabbroic unit (Upadhyay *et al.* 1971). A sheeted dyke complex that locally grades upward into mafic volcanic rocks overlies the gabbroic unit. A metaperidotite and metapyroxenite were collected from near Kitty Lake in the complex (appendix).

Analytical Techniques and Results

Analytical information for palladium, platinum, rhodium, iridium and ruthenium, along with brief sample descriptions, is given in Table 1. Platinum, palladium and rhodium analyses were performed by a fire-assay atomic-absorption method described by Page *et al.* (1980) and Simon *et al.* (1978). The technique has detection limits of 1, 0.5 and 0.5 ppb (parts per billion) for Pt, Pd and Rh, respectively, as defined by sample size and limitations of the method. The analyses for iridium and ruthenium were done by the method of Haffty *et al.* (1980), with detection limits of 100 and 20 ppb for Ru and Ir, respectively. Both methods involve a fire-assay preconcentration step similar to that described by Haffty *et al.* (1977). Precision of the analytical techniques is discussed by Simon *et al.* (1978) and Haffty *et al.*

TABLE 1. PALLADIUM, PLATINUM, RHODIUM, RUTHENIUM AND IRIDIUM CONCENTRATIONS IN REPRESENTATIVE SAMPLES FROM OPHIOLITIC COMPLEX IN NEWFOUNDLAND

Sample number	Pd	Pt	Rh	Ru	Ir	Sample Description
BAY-OF-ISLANDS COMPLEX						
Lewis Hills						
77LH59	1.1	1.5	1.9	<100	<20	Contact of chromite pod and dunite sheath (Trench 9), Springer's Hill
77LH61	1.5	1.5	4.5	240	40	Chromitite (Trench 9), Springer's Hill
77LH62	1.7	<1	2.1	100	25	Chromitite (Trench 9), Springer's Hill
77LH64	1.1	3.2	3.7	180	33	Eighty percent massive chromite + dunite, near margin of Trench 9, Springer's Hill
77LH94	1.1	3.0	0.6	<100	<20	Harzburgite (tectonite peridotite), northeast of Hines Pond
77LH113	<0.5	<1	<0.5	<100	<20	Dunite (cumulate), east of Fox Island River
North Arm Mountain						
NAM.78.3	24	14.0	5.2	<100	<20	Chromite seam in dunite. Seam + dunite is enclosed by orthopyroxene-clinopyroxene-olivine cumulate. Critical zone approximately 2 km northeast of Stowbridge Head
Table Mountain						
TMH.L.5	5.2	12.0	0.6	<100	<20	Spinel lherzolite, Winterhouse Brook area
ST. ANTHONY COMPLEX						
White Hills Peridotite						
77WH19	1.9	120	20.0	tr	tr	Chromitite seam in orthopyroxenite. Western peridotite massif, north of Long Pond
77WH30	4.6	38	5.2	250	83	Fifty percent massive chromite seam in orthopyroxenite. Western peridotite massif, east of Long Pond
7815	4.8	2.7	2.0	<100	<20	Spinel lherzolite, western peridotite massif, west of Long Pond
795	3.7	<1	2.4	<100	<20	Spinel lherzolite, eastern peridotite massif, west of Stock Pond
7818	6.7	2.9	4.0	<100	<20	Harzburgite, western peridotite massif, northeast of Brimstone Pond
781	7.6	2.7	2.2	<100	<20	Harzburgite, western peridotite massif, northwest of Brimstone Pond
78114	<0.5	<1	3.3	<100	<20	Dunite, eastern peridotite massif, west of Eastern Long Pond
799	6.6	4.2	2.6	<100	<20	Dunite, eastern peridotite massif west of Stock Pond
78141	<0.5	<1	3.5	<100	<20	Dunite, eastern peridotite massif, west of Eastern Long Pond
77WH93	5.0	2.4	4.5	<100	<20	Dunite, eastern peridotite massif, west of Western Long Pond
78147	3.3	1.2	4.5	<100	<20	Dunite, eastern peridotite massif, west of Eastern Long Pond
POINTE ROUSSE COMPLEX						
PR78.3D	<0.5	3.3	<0.5	<100	<20	Dunite, Grassy Island
PR78.3H	<0.5	1.2	<0.5	<100	<20	Harzburgite, Grassy Island
MB78.100	<0.5	<1	3.9	<100	<20	Dunite, road cut in Ming's Bight
GREAT BEND COMPLEX						
T-76001	3.1	4.5	2.8	<100	25	Dunite, east side of Bay d'Espoir Highway
ADVOCATE COMPLEX						
5FDL77	8	11	6	<100	<30	Metaperidotite
FDL77	5	tr	5	<100	<30	Harzburgite, Advocate asbestos deposit
7FDL77	77	36	5	<100	<30	Dunite, Advocate asbestos deposit
BETTS COVE COMPLEX						
2BD77	23	31	<5	<100	<30	Harzburgite, Kitty Lake area
3BC77	4	tr	<5	<100	<30	Metapyroxenite, Kitty Lake area

Analysts for Pd, Pt, and Rh: M. Doughten, L. Mei, and P. West.
Analysts for Ir and Ru: J. Haffty and A. Haubert. tr=trace

(1980). Samples with "less than" values or trace values are not used in the calculations.

Table 1 demonstrates that the analytical technique for Ru and Ir is not sufficiently sensitive for most samples from ophiolites in Newfoundland. There are only five determinations of Ru and six determinations of Ir above the detection limit, and only one analysis for Ir pertains to a rock that is not chromite-rich. Based on analytical results presented by Oshin & Crocket (1982) for ophiolitic rocks from the Thetford area (Quebec), one can suggest that the Ir content of the samples from Newfoundland might be in the range of 1/100 to ½ the limit of detection of the method used by Haffy *et al.* (1980). Therefore, calculations of chondrite-normalized ratios for Ir and Ru represent maximum ratios.

Analytical results for the ophiolite complexes and rock types from Newfoundland are summarized in Table 2. These averages and ranges are similar to the data for the ophiolites in New Caledonia (Page *et al.* 1982), Turkey and Iran (Page *et al.* (1979a), Pakistan (Page *et al.* 1980a), Greece (Agiorgitis & Wolf 1977, 1978), Oman (Page *et al.* 1979b), southwestern Oregon (Page *et al.* 1975, Page 1969), and elsewhere in the world (Crocket 1979). The averages and standard deviations (Table 2) should be viewed with caution, considering the number of samples representing each complex and rock type. Nevertheless, differences in content of Pd, Pt and Rh between different ophiolite complexes in Newfoundland appear to be small, *i.e.*, within a factor of 10. When the samples are grouped by rock type, dunite, harzburgite and spinel lherzolite tend to have similar contents and ranges of Pd, Pt and Rh; however, samples of chromitite have the widest range in PGE content and higher contents of Ru and Ir compared to the other rock types. The higher Ir and Ru contents are due to sulfide and alloy inclusions containing Ir, Ru and Os; these phases occur enclosed in the chromite (Talkington *et al.* 1982b) (see appendix). No Pt- or Pd-bearing phases were identified. Similar PGE minerals have been identified in chromitite from other ophiolite complexes (Constantinides *et al.* 1980, Prichard *et al.* 1981, Z. Johan written comm. 1980, H. Stockman, pers. comm. 1980). These inclusions are also dominated by Os, Ir and Ru minerals.

Another way to examine the PGE data summarized in Table 2 or for individual samples is to normalize the concentrations with respect to average concentrations in chondrites and to plot the ratios on diagrams similar in appearance to those used for rare-earth elements. A similar plot has been used by Naldrett *et al.* (1979) for nickel sulfide deposits of the Sudbury district and for those associated with komatiites. Chondrite concentrations used in normalizing the data are Pd 1,200 ppb, Pt 1,500 ppb, Rh 200 ppb, Ru 1,000 ppb and Ir 500 ppb, which are the average values given by McBryde (1972). Although other estimates of average values for chon-

TABLE 2. RANGE, AVERAGE, AND STANDARD DEVIATION OF PGE IN COMPLEXES AND ROCKS FROM NEWFOUNDLAND

	Range (parts per billion)					Average and standard deviation (parts per billion)				
	Pd	Pt	Rh	Ru	Ir	Pd	Pt	Rh	Ru	Ir
Lewis Hills	<0.5-1.7	<1-3.2	<0.5-4.5	<100-240	<20-40	1.3±0.3	2.3±0.9	2.6±1.6	179.3±70.2	32.7±7.5
North Arm Mountain	--	--	--	--	--	24.0	14.0	5.2	<100	<20
Table Mountain	--	--	--	--	--	5.2	12.0	0.6	<100	<20
Bay-of-Islands Complex	<0.5-24	<1-14	<0.5-5.2	<100-240	<20-40	5.1±8.5	5.9±5.6	2.7±1.8	173.3±70.2	32.7±7.5
White Hills Peridotite	<0.5-7.6	<1-120	2.0-20	<100-250	<20-83	5.0±1.8	[1]7.7±13.4	4.9±5.1	250	83
Advocate Complex	5-77	tr-36	5-6	<100	<30	30±41	23.5±17.7	5.3±.6	<100	<30
Point Rousse Complex	<0.5	<1-3.3	<0.5-3.9	<100	<20	<0.5	2.3±1.5	3.9	<100	<20
Great Bend Complex	--	--	--	--	--	3.1	4.5	2.8	<100	25
Betts Cove Complex	4-23[1]	tr-31	<5	<100	<30	13.5±13.4	31	<5	<100	<30
Spinel lherzolite	3.7-5.2	<1-12	0.6-2.4	<100	<20	4.6±0.8	7.4±6.7	2.3±1.7	<100	<20
Harzburgite	<0.5-7.6	<1-30	<0.5-5.0	<100	<20	8.7±8.4	8.2±12.8	3.0±1.9	<100	<20
Dunite[2]	<0.5-6.6	<1-4.5	<0.5-4.5	<100	<20-25	4.5±1.6	3.1±1.4	3.6±0.8	<100	25
Chromitite	1.1-24	<1-120	1.9-20	<100-250	<20-83	5.8±9.0	35.0±49.8	6.5±6.8	173.3±70.2	49.3±30.1

[1]Does not include high value for 77WH19. [2]Does not include sample 7FDL77 with chromite clots.

drite abundances are available, the usage of McBryde's data is retained in this paper because previous data used for the comparison were normalized to chondrite using those data. The absolute values adopted for average chondrite abundances are not important; they only give a way of comparing PGE data in a graphical manner. The chondrite-normalized ratios for the average spinel lherzolite, harzburgite, dunite and chromitite are compared on Figure 6A, B, C and D; the boundaries of the fields are based on the chondrite-normalized standard deviations. In general, normalized patterns for dunite, harzburgite, spinel lherzolite and chromitite appear similar. Because of the lack of sensitivity for the analytical method for Ir and Ru, chondrite-normalized patterns for the spinel lherzolite (Fig. 6A) and harzburgite (Fig. 6B) samples do not necessarily show overall negatively sloping patterns; only the part of the pattern including Pd, Pt and Rh is documented. However, the overall patterns for dunite and chromitite appear to have negative slopes. Examination of absolute concentrations and chondrite-normalized ratios for individual rock-samples from the different complexes suggests differences between rock types and between complexes. Average chondrite-normalized PGE ratios for the individual complexes derived by using all the rock types available from the complexes are compared in Figure 7. Major differences in the patterns produced involve the relative enrichment or depletion of Pt with respect to Pd and Rh and the concentrations of the PGE in the rocks of the individual complexes. For example, the chondrite-normalized ratio derived for the White Hills Peridotite shows relative depletion in Pt with respect to Pd and Rh, whereas that ratio in the sample from Table Mountain shows relative enrichment in Pt with respect to Pd and Rh.

Comparison with Other Ophiolites and Interpretation

The results of PGE analyses of ophiolites from

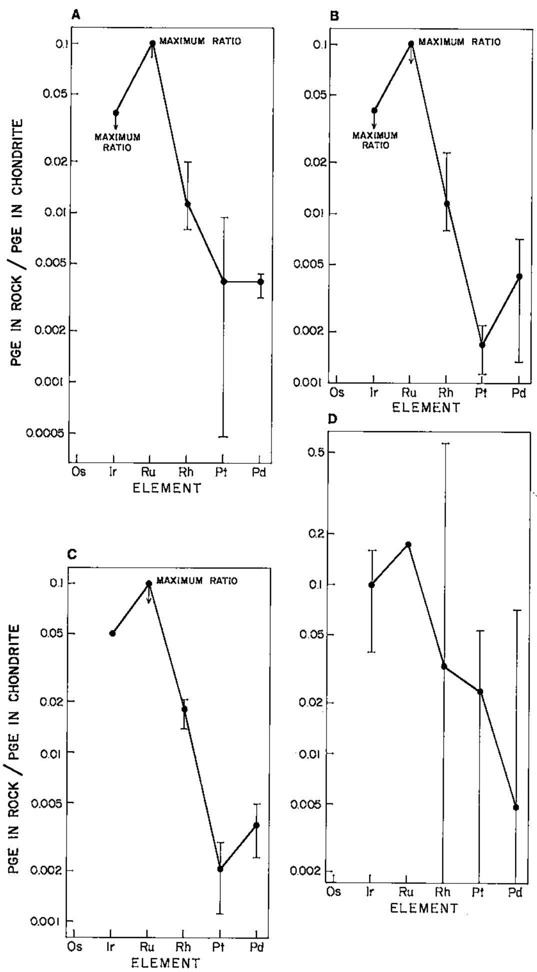

FIG. 6. Average chondrite-normalized PGE ratios by rock type from Newfoundland ophiolites. Bar represents one standard deviation. A. Spinel lherzolite, B. harzburgite, C. dunite, D. chromitite; lower limits of one standard deviation for Rh, Pt, Pd not shown.

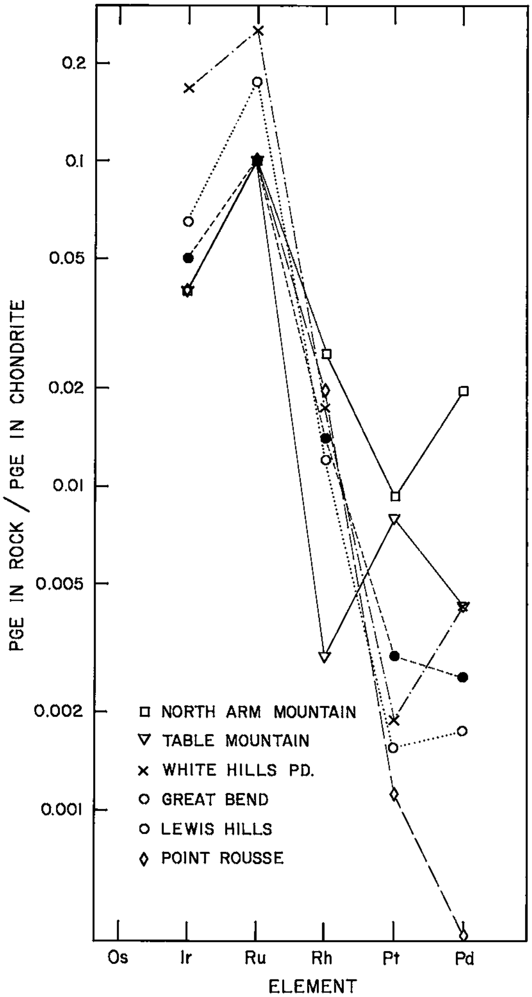

FIG. 7. Chondrite-normalized PGE ratios for averages of all rock types for ophiolite complexes in Newfoundland.

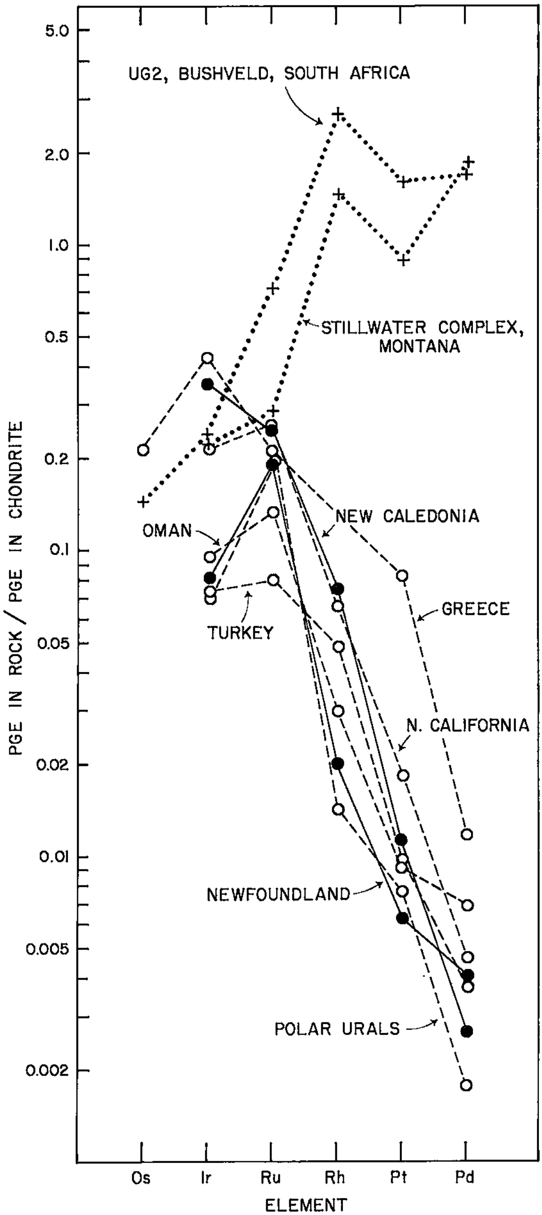

FIG. 8. Average chondrite-normalized PGE ratios for chromitite rocks from various ophiolites compared with the average for all complexes sampled in Newfoundland.

Turkey, Iran, Oman, southwestern Oregon, northern California, New Caledonia and Greece, summarized in Page *et al.* (1982), and the Polar Urals, U.S.S.R. (Page *et al.* 1983) suggest that the chondrite-normalized patterns are similar to those obtained from ophiolite complexes in Newfoundland. Chondrite-normalized patterns for chromitite averages from these complexes and for chromitites from two layered complexes are compared in Figure 8. The average chromitite patterns with negative slopes appear to be diagnostic of ophiolitic chromitite. As in the Newfoundland complexes, other rock types, such as harzburgite, dunite, spinel lherzolite, wehrlite and clinopyroxenite, have more complex patterns and relations (Page *et al.* 1983).

The interpretation of chondrite-normalized PGE patterns for rocks from ophiolites involves a number of hypotheses about the origin of these complexes, which are not universally accepted by all investigators, and also involves the identification of which rocks are representative of the hypothesized process. The first problem is the identification of mantle samples that are undepleted in PGE. Results of analyses of ultramafic xenoliths from basalt and kimberlites (Jagoutz *et al.* 1979, Morgan & Wandless 1979, Morgan *et al.* 1980, Mitchell & Keays 1981) suggest that chondrite-normalized PGE patterns of rocks that may be undepleted mantle are relatively flat and have low ratios that reflect the low content of PGE. Flat or approximately flat patterns for lherzolites, harzburgites and dunites observed in other complexes may represent mantle that is undepleted or slightly depleted with respect to PGE. Partial melting of mantle material, either by a single-stage or multistage process under sulfur-saturated or unsaturated conditions would produce a residue and melt with chondrite-normalized PGE ratios that are dependent upon the distribution coefficients for each PGE between the residue and melt. If Pd and Pt are associated with interstitial sulfides in the undepleted mantle, they would probably be removed preferentially from the mantle with the sulfides in the early event of partial melting, thus leaving a residue relatively enriched in Os, Ir and, perhaps, Ru. Some of the spinel lherzolite, harzburgite and dunite from the ophiolite complexes in Newfoundland have been interpreted to represent such a residue. Malpas (1976) postulated approximately 23% partial melting of a spinel lherzolite source for the Bay of Islands Complex, and Talkington (1981) proposed a similar degree of melting of spinel lherzolite for the White Hills Peridotite to produce a harzburgite residuum. Negatively sloping chondrite-normalized PGE patterns, such as in the dunite samples (Fig. 6C), appear consistent with these hypotheses; however, patterns with concentrations of Ir and Ru below detection limits, such as in the spinel lherzolite and harzburgite samples (Fig. 6A,B) are evidence neither for nor against the hypotheses. The melt produced, if sulfur-saturated, could consist of two immiscible phases, a silicate liquid and sulfide liquid, or only a silicate liquid if it is not sulfur-saturated. Such melts could be the parent of other rocks in the immediate ophiolite complex or they could form rocks unrelated spatially to the residuum. Such melts are probably the source of the pyroxenite and gabbro dykes, cumulus ultramafic and mafic rocks deposited on the residuum, and gabbro and mafic rocks that form the rest of ophiolite complexes. If podiform chromitite forms from a magma in a conduit, as postulated by Cassard *et al.* (1981), it is feasible that such a process might be higher in temperature than the accumulation of chromitite in stratiform complexes. Enrichment of the podiform chromitites in Os, Ir and Ru could be due to the entrapment of an immiscible Os–Ir–Ru alloy or sulfide at high temperatures as discrete inclusions in chromite (Talkington and others, in prep). The PGE mineralogy and negatively sloping chondrite-normalized patterns for chromitite from the ophiolites in Newfoundland seem to be consistent with this hypothesis. The major amount of magma produced by the partial melting, which may be relatively depleted in Os, Ir and Ru, is most likely the parent of the cumulates and the volcanic part of an ophiolite. Upon crystallization, such a magma could produce relative enrichment patterns in Pt, Pd and Rh. Data from the upper parts of the Polar Urals ophiolite and in southwestern Oregon (Page *et al.* 1983) support such a hypothesis.

CONCLUSIONS

Samples of spinel lherzolite, harzburgite, dunite and chromitite from the Bay of Islands complex and Lewis Hills, Table Mountain, North Arm Mountain, White Hills Peridotite, Point Rousse, and Great Bend ophiolite complexes contain low concentrations, in the part-per-billion range, of palladium, platinum, rhodium, ruthenium and iridium. Chondrite-normalized ratios for individual samples of rock and different complexes indicate differences in the distribution of PGE between rock types and between complexes. The differences between rock types are considered to be the result of partial melting of mantle material, either by a single-stage or multistage process in sulfur-saturated or -unsaturated conditions, which produced a residue and melt with different PGE distributions, coupled with crystallization of the melt to form the cumulate upper portions of the ophiolite.

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APPENDIX

Lewis Hills

77LH59,61,62,64: All samples are 100% serpentinized olivine. The cumulus chromite is deep red, euhedral to anhedral. Size is approximately 1.5 mm. Pull-apart texture is ubiquitous. Resorption of chromite (embayed contact) is common. Solid inclusions (silicate material, sulfides and native silver) and fluid inclusions are also present in chromite.

77LH94 (harzburgite): This sample consists of olivine, orthopyroxene and spinel and is approximately 70% serpentinized. Only kernels of olivine remain, which produce a mesh texture where not associated with orthopyroxene. The orthopyroxene shows undulatory extinction and is slightly elongate parallel to the dominant foliation. Minor alteration (bastite) is present along fractures and cleavage planes. The spinel is reddish brown, anhedral, and typically has embayed and scalloped grain boundaries. Magnetite-ferritchromite alteration is present along the spinel rim and internal fractures. Size is generally less than 0.3 mm. Spinel is a groundmass phase and associated with olivine, or olivine + orthopyroxene as a reaction product.

77LH113 (dunite): Sample lost.

North Arm Mountain

NAM.78.3 (chromite seam in dunite & pyroxenite): An opaque massive chromite seam approximately 1 cm wide is enclosed by a thin sheath of serpentinized olivine. Trapped intercumulus material in the chromite seam is also serpentinized. The serpentine sheath is bordered by a coarse-grained orthopyroxene–clinopyroxene–olivine–chromite cumulate. These silicates are unaltered except at the serpentine sheath – pyroxenite border and along late-stage fractures.

Table Mountain

TMH.L.5 (spinel lherzolite): The sample is approximately 40% serpentinized. However, most of the orthopyroxene and clinopyroxene grains are unaltered. These two phases are variably deformed (undulatory extinction, kink-band development in the orthopyroxene). The spinel is reddish brown, anhedral, and has magnetite developed along the boundary with the silicates and along fractures. Spinel is associated predominantly with olivine + orthopyroxene as a wormy or patchy intergrowth, but also with clinopyroxene + olivine and olivine alone.

White Hills Peridotite

7815, 795 (spinel lherzolite): Sample 7815 is approximately 60% serpentinized and sample 795 is approximately 10% serpentinized. Alteration of orthopyroxene to bastite in 7815 is extensive (~ 60%). Clinopyroxene is relatively unaltered in both samples. Spinel is light brown and intergrown with orthopyroxene + olivine or orthopyroxene. Magnetite alteration has developed along the boundary with silicates and along fractures.

781, 7818 (harzburgite): Both samples are approximately 35% serpentinized. Minor incipient alteration of orthopyroxene to bastite is included in this total. Undulatory extinction is present in olivine kernels and orthopyroxene porphyroclasts. In addition, elongation along cleavage planes and minor kink-banding of orthopyroxene are locally developed. Spinel is light reddish brown to reddish brown, anhedral to subhedral, and has irregular grain boundaries with neighboring silicates. Spinel preserves a vermicular texture with olivine and orthopyroxene and interstitial texture with, in some cases, occluded olivine and orthopyroxene. In sample 7818, spinel forms a linear chain with completely or partly occluded silicates.

77WH93, 78114, 78141, 78147, 799 (dunite): These samples have been variably serpentinized (*e.g.*, 77WH93 50%, 78114 40%, 78141 50%; 78147 80%, 799 30%). In addition, these dunites crop out interlayered with spinel lherzolite (77WH93), wehrlite and clinopyroxenite (78141) and harzburgite (78147), as a dunite lens in peridotite (78114), and as a dunite dyke (799). The spinel of each sample is optically and chemically similar to spinel of the adjoining lithology, except for 78114, which has a distinctive chemical composition. All samples contain approximately 2 modal % spinel.

77WH19, 30 (chromite seam in orthopyroxenite): Both samples are orthopyroxenite with chromite concentrations. In 77WH19, orthopyroxene is euhedral to anhedral and ranges in size, depending upon the intensity of shearing, from 1.5 mm to less than 0.1 mm. Undulatory extinction is common, and alteration to bastite and serpentine generally restricted to shear zones and fractures. Olivine is intercumulus (~ 3%) and is variably altered to serpentine in shear zones. Chromite is deep reddish brown, euhedral to dominantly anhedral, and varies in size depending upon shearing. Grain-boundary alteration to ferritchromite is restricted to fractures and shear planes. Laurite, native Ag, (Ni,Fe) arsenide and (Ni,Fe) alloy occur interstitial to silicates and chromite or as inclusions in chromite. In 77WH30, orthopyroxene is euhedral to anhedral and has an average grain-size of 2 mm. Incipient alteration to bastite is minor, although locally intense where olivine is present and at the chromite seam. Olivine is intercumulus (~ 1%) and is approximately 30% altered to serpentine. Chromite is deep reddish brown and euhedral to anhedral. Grain size is variable. Alteration to ferritchromite is developed along fractures. Ni sulfide and (Ni,Fe) alloy occur as inclusions in chromite.

Advocate Complex

5FDL77 (peridotite): The sample, a metaperidotite, occurs as a small body of ultramafic rock in contact with garnet-mica schist. The rock consists of antigorite, carbonate minerals and magnetite.

6FDL77 (harzburgite): The sample is a peridotite from the dump of the Advocate Asbestos open pit. Rock is 80% serpentinized. Relict olivine and orthopyroxene with exsolution lamellae of clinopyroxene show deformation features (kinked orthopyroxene and undulatory extinction in the olivine). Anhedral spinel grains contain a core of reddish brown, translucent spinel (presumably chromite) rimmed and veined by opaque spinel (probably magnetite or ferritchromite). Secondary magnetite associated with serpentinization is abundant.

7FDL77 (dunite): The sample is dunite with spinel clots from the dump of the Advocate Asbestos open pit. The rock is 100% serpentinized; the anhedral spinel grains contain a reddish brown, translucent core (chromite) and are rimmed and veined by opaque spinel (magnetite); these grains occur in clots in the serpentinite matrix.

Point Rousse Complex

PR78.3D (dunite): This sample is approximately 20% serpentinized, with serpentinization locally intense. Olivine is approximately 3 mm across, shows undulatory extinction and minor kink-banding. Grains have an ameboid shape, with embayed grain-boundaries. Spinel is red to reddish brown and subhedral to anhedral. Ferritchromite–magnetite is developed on spinel–silicate boundaries and internal fractures. Embayed grain-boundaries with olivine are common as are serpentine inclusions.

MB78.100 (dunite): This sample is totally serpentinized. The spinel is approximately 95% altered to magnetite. However, in the core of some grains, a deep, reddish brown spinel is preserved.

PR78.3H (harzburgite): This sample is approximately 20% serpentinized. Grain size of olivine and orthopyroxene is 3 mm. Undulatory extinction and ameboid grain-shapes are dominant. Spinel is reddish brown and anhedral, with scalloped and embayed grain-boundaries with silicates. Exsolved spinel is associated orthopyroxene and spinel. Ferritchromite–magnetite alteration is present along spinel–silicate boundaries and internal fractures.

Great Bend

T76001 (dunite): This sample is approximately 95% serpentinized; only kernels of olivine remain. Spinel is deep reddish brown and euhedral to subhedral. Bimodal grain-size is present: 2 mm and 0.4 mm. The larger grains occur in a 0.5-cm-wide seam and contain hydrous silicate inclusions. The smaller grains are disseminated throughout the dunite and are devoid of inclusions.

Betts Cove

2BC77: The sample is a metaperidotite; the rock now consists totally of secondary assemblages of 1) talc, actinolite, serpentine and magnetite pseudomorphs after subhedral to euhedral orthopyroxene, 2) talc, serpentine and magnetite pseudomorphs after subhedral to euhedral olivine, 3) tremolite–actinolite after interstitial clinopyroxene, 4) epidote perhaps after interstitial plagioclase, and 5) clots and veinlets of secondary magnetite and serpentine. The rock probably was an olivine–orthopyroxene cumulate.

3BC77 (pyroxenite): The sample is a metapyroxenite. The rock consists of tremolite–actinolite, carbonate minerals, minor epidote and magnetite.