

CHAPTER 4

GRANITOIDS AND INTERMEDIATE - SILICIC VOLCANICS

A number of tectonically disrupted tonalitic intrusives (Pola Fogal Hornblendite-Tonalite Suite, new name) and a partly disrupted pile of intermediate-silicic volcanics (Pitch Creek Volcanics, Mayer, 1972) display a relatively close spatial relationship with the PBOC. The nature of this spatial association might suggest that the PBOC constitutes the mafic and ultramafic parts of an island arc-type ophiolite, perhaps in some respects analogous to the Smartville Ophiolite (Menzies *et al.*, 1980), the Canyon Mountain Ophiolite (Gerlach *et al.*, 1981) and the Pindos and Vourinos ophiolites (Miyashiro, 1975, 1977; Capedri *et al.*, 1980). On the basis of the limited field and geochemical data available, a close genetic relationship between the PBOC and these more silicic intrusives and extrusives is considered probably unlikely. However, it is not inconceivable that the PBOC, the Pola Fogal Hornblendite-Tonalite Suite and the Pitch Creek Volcanics share a common volcanic arc-related tectonic setting (see Chapter 7), although they may not be genetically interrelated.

4.1 Pre-Permian Intrusives and Extrusives

The Pitch Creek Volcanics are a pile of quartz keratophyres, keratophyres, keratophyric breccias, and altered andesitic extrusives and intrusives (dykes and ? sills ~1m to several tens of metres in width/thickness). These rocks lie adjacent to, and in part straddle, the Peel Fault System in the southeastern part of the Pigna Barney-Curricabark area (Map 1). For the most part they crop out only poorly. Internal and marginal field relationships are rarely exposed and remain somewhat conjectural.

Mayer (1972) tentatively considered that the Pitch Creek Volcanics are Lower Devonian in age and probably underlie the Glen Ward beds. He noted that the "(?) top of the sequence is generally faulted against the Glen Ward beds" (Mayer, 1972, p.42). Although this contact is poorly exposed, between GR 720,808 and GR 734,815 the Glen Ward beds are uncharacteristically cleaved, sheared, mesoscopically faulted, and locally

warped and mesoscopically folded. Highly sheared (?) Pitch Creek Volcanics (shear foliation is sub-vertical and trends ~005) crop out in the bed of the Pigna Barney River at GR 7325,8132. Although these observations reinforce Mayer's (1972) conclusion that the Pitch Creek-Glen Ward contact is largely faulted, Rigby (1980) suggested that the Glen Ward beds are in depositional contact with the Pitch Creek Volcanics. On the other hand, exposures of Glen Ward argillites, epiclastics and doleritic rocks along the valley floor of the Pigna Barney River between GR 714,810 and GR 723,808 (see Map 1) strongly suggest that, at least in part, the Pitch Creek Volcanics overlie the Glen Ward beds. This relationship is best exposed at GR 7144,8095 where a keratophyric member of the Pitch Creek Volcanics overlies the Glen Ward beds with variable angular unconformity.

Topographic benches (? flow terraces) and sub-horizontal flow banding (e.g. GR 692,798) within the Pitch Creek Volcanics suggest that they are largely flat-lying, in contrast with the steeply-dipping Glen Ward beds. Furthermore, intermediate dykes apparently originating from the Pitch Creek Volcanics intrude the upper parts of the Glen Ward beds [Rigby, 1980; *cf.* Chapter 3, Section 3.5.4(3)(iv)] suggesting that, at least in part, the Pitch Creek Volcanics are somewhat younger than the Glen Ward beds. However, because the Pitch Creek Volcanics and the Glen Ward beds appear to have experienced similar (prehnite-pumpellyite facies) burial metamorphic histories, it may well be that their respective ages are not markedly dissimilar.

Field relationships between the Pitch Creek Volcanics and lithologies other than the Glen Ward beds are complex (Map 1) and, once again, are somewhat equivocal due to poor exposure. Although actual contacts are nowhere exposed, the Pitch Creek Volcanics appear to be: (i) intruded by tonalitic and dioritic members of the Pola Fogal Hornblendite-Tonalite Suite (see below); (ii) in fault contact with the PBOC, the Myra beds and the Manning Group, and (iii) possibly in fault contact with a block consisting of weathered argillites, volcanogenic epiclastics and doleritic rocks here tentatively correlated with the Glen Ward beds.

The Pola Fogal Hornblendite-Tonalite Suite, named after the property on which the most hornblende-rich variants occur, is a group of tectonically disrupted, highly altered intrusives displaying a close spatial association with the PBOC (Map 1). All well-exposed contacts with

the Myra beds and the PBOC are tectonic (sheared and faulted), and adjacent serpentinite does not display petrographic or other evidence of hornfelsing (e.g. development of antigorite). In fact, serpentinite may be posthumously emplaced along faults within members of the Fogal Suite (GR 6905,8155), and discrete blocks of the latter have also been incorporated in the PBOC serpentinite-matrix melange (Map 1). Although members of the Pola Fogal Suite appear to intrude the Pitch Creek Volcanics (Map 1), in the vicinity of the former the Pitch Creek Volcanics are either too weathered or too altered (e.g. replaced by carbonate ~GR 726,832; e.g. 359, 360) to recognise any evidence of hornfelsing.

Overall, the Pola Fogal Suite display extreme variation in modal abundances of their three principal components *viz.* primary green hornblende, plagioclase and quartz. Lithologies range from sheared cumulate hornblendite (e.g. 340) containing in excess of 90% coarse-grained (up to 1cm) green hornblende + albitized plagioclase + minor Ca-rich pyroxene, to relatively quartz-rich tonalities. The latter generally contain 40%-50% quartz as large (up to 1cm) ragged phenocrysts and irregular intergranular patches in association with albitized plagioclase (10%-40%) and prismatic green hornblende (5%-20%). Some intermediate variants contain several percent altered biotite and/or up to perhaps 10%-15% highly kaolinized K-feldspar (e.g. 342, 343). Fe-Ti oxides are present only in accessory amounts.

In all variants plagioclase is almost entirely albitized, and significantly kaolinized and sericitized. Chlorite and/or epidote partially replace hornblende in most examples and intense epidotization is common.

The pervasive and often intense alteration of major primary phases in the Pola Fogal Suite must discourage any attempts to evaluate pristine major and minor element abundances and their possible significance. These comments are equally applicable to the more silicic (highly albitized) representatives of the Pitch Creek Volcanics (see below).

For the most part, the Pitch Creek Volcanics are also pervasively altered and, apart from some quartz, relict primary phases are rare in all but some andesitic types. The relatively silicic variants typically contain quartz and/or albitized plagioclase microphenocrysts in a

devitrified groundmass consisting largely of these phases plus chlorite.

Textures in the andesitic variants are usually pilotaxitic (e.g. 350) or fine-grained intergranular (e.g. 352) with microphenocrysts of albitized plagioclase, Ca-rich pyroxene (or its alteration products) and Fe-Ti oxides. Some of the plagioclase-phyric types contain abundant prismatic and acicular brown-green amphibole in the groundmass (e.g. 354) but, in general, relict amphiboles are rare.

All silicic-andesitic variants contain prehnite-pumpellyite facies alteration assemblages which may include abundant chlorite, carbonate and quartz plus lesser amounts of epidote, sericite, pumpellyite and prehnite. The more silicic variants are almost invariably highly altered and many contain abundant quartz and/or carbonate veins. Fe-Ti oxides are commonly hydrated and many outcrops display pervasive limonite staining. By comparison, the andesitic types are often relatively fresh and four of these have been analysed to obtain a general indication of the pristine magmatic characteristics of the Pitch Creek Volcanics as a whole.

The analysed samples include: (i) two pilotaxitic types with relatively abundant microphenocrysts of fresh or slightly chloritized Ca-rich pyroxene, and albitized plagioclase which may be slightly altered to sericite \pm chlorite (analyses 1 and 2, Table 4.1); and (ii) two intergranular types with abundant fresh to completely chloritized Ca-rich pyroxene intergranular to prismatic plagioclase (analyses 3 and 4, Table 4.1). The pilotaxitic and intergranular types both contain abundant groundmass Fe-Ti oxides and minor amounts of pumpellyite and carbonate.

Bearing in mind the interpretation constraints imposed by variable degrees of alteration, the chemical data (Table 4.1, analyses 1-4) collectively indicate the calc-alkaline affinities of the more mafic members of the Pitch Creek Volcanics. These include relatively low TiO_2 contents (appropriate for orogenic calc-alkaline andesites and related types *cf.* Gill, 1981; but significantly greater than the TiO_2 contents of the PBOC low-Ti basalts and doleritic rocks; Tables 5.5a and 5.6a), high Al_2O_3 (> 16%), and relatively low total Fe which decreases with increasing SiO_2 . Their somewhat irregular but nevertheless high K_2O and P_2O_5 contents (0.9%-1.8% K_2O ; (0.17%-0.38% P_2O_5) and their correspondingly high abundances of several incompatible trace elements (Rb,

TABLE 4.1

Major and Trace Element Analyses of Andesitic
Members of the Pitch Creek Volcanics

ANALYSIS	No.	1	2	3	4
SAMPLE		350	351	352	353
SiO ₂		54.77	55.52	58.93	60.09
TiO ₂		1.06	1.09	1.17	1.16
Al ₂ O ₃		16.95	16.99	16.88	17.45
Fe ₂ O ₃		4.48	2.10	3.00	3.28
FeO		5.06	4.82	3.49	3.08
MnO		0.18	0.16	0.12	0.09
MgO		3.45	5.47	2.64	2.60
CaO		5.98	4.00	2.88	1.01
Na ₂ O		4.50	4.73	6.67	7.41
K ₂ O		1.79	0.93	1.50	1.00
P ₂ O ₅		0.38	0.17	0.36	0.28
Vol ¹		1.59	3.83	2.09	2.44
TOTAL		100.19	99.81	99.73	99.89
<i>mg</i>		41.1	59.7	44.0	44.3

TRACE ELEMENTS (ug/g)

Rb	17	10	17	15
Ba	485	744	497	294
Sr	926	515	695	262
Li	8.8	15.4	5.5	2.8
Zr	118	136	133	133
Y	30	30	33	32
Nb	8	5	5	8
Cu	475	33	13	5
Zn	108	98	90	85
Ni	8	54	3	3
Co	43	54	40	27
V	320	156	159	105
Cr	n.d.	n.d.	6	n.d.
La	25	13	18	12
Ce	44	33	39	28
Nd	29	18	25	20
Pb	n.d.	n.d.	3	n.d.

¹ see Appendix G. n.d. = not determined

$$mg = 100Mg / (Mg + Fe^{2+} + Fe^{3+})$$

Ba, Zr, Y, LREE) relative to the low-Ti basalts ($K_2O < 0.4\%$, $P_2O_5 < 0.05\%$ Table 5.6a), reinforces the interpretation that these Pitch Creek Volcanics and the PBOC low-Ti basalts are genetically unrelated by fractional crystallization or partial melting controls.

Attempts to date representatives of the Pitch Creek Volcanics and the Pola Fogal Suite by the U/Pb isotopic compositions of zircons met with only limited success. Amounts of zircon recovered from two Pitch Creek andesites and a keratophyre were insufficient for isotopic dating, and grains were too fractured and too cloudy for fission-track dating. Attempts to recover zircons from the three larger Pola Fogal intrusives closely associated with the Pitch Creek Volcanics (Map 1) were completely unsuccessful. However, sufficient zircons for isotopic analysis were recovered from a hornblende-rich Pola Fogal Suite inclusion in schistose serpentinite at GR 6325,8213, and a tonalitic variant at GR 6205,8276. These zircons produced discordant results* and isotopic ages (see Appendix H) range from 434 m.y. (Early Silurian) to 331 m.y. (Early Carboniferous). Attempts to further constrain the ages of these rocks *via* U/Pb isotopic analyses of coexisting sphene and apatite are still in progress.

Unfortunately, the available isotopic data do not place any meaningful constraints on the age of the Pitch Creek Volcanics. However, it should be noted that the $^{206}\text{Pb}/^{238}\text{U}$ ages measured (339 m.y. and 331 m.y.; Table H-1) indicate the minimum possible crystallization ages for these zircons. Consequently, these Pola Fogal intrusives are at least the oldest known granitoids in Zone B, and perhaps the oldest known granitoids in the NEO (see Table 0.2). Although it is not inconceivable that the $^{207}\text{Pb}/^{206}\text{Pb}$ ages (434 m.y. and 409 m.y.; Table H-1) might represent actual crystallization ages for the particular Pola Fogal variants sampled, because both appear to be in fault (shear) contact with the surrounding lithologies the implications of these ages must remain uncertain. If all members of the Pola Fogal Suite are similar in age, and if some do in fact intrude the Pitch Creek Volcanics (see above), then perhaps their ages fall somewhere in the range Early Carboniferous-

* These zircons display no evidence of 'inherited' cores.

Early Devonian.

Tonalitic intrusives similar to those in the Pola Fogal Suite occur in the Woolomin beds to the northwest of the Pigna Barney-Curricabark area (Bayly, 1974; my personal observations, 1977). If these are essentially equivalent to those closely associated with the Pitch Creek Volcanics (Map 1), their apparent displacement might suggest that possible post-Early Carboniferous strike-slip movements on the Peel Fault System were sinistral (*cf.* Corbett, 1976) and of relatively small magnitude (? < 40 km)*

4.2 Permian Intrusives

The Barrington Tops and Mount Ephraim intrusives (see Maps 1 and 2) are hornblende-biotite (\pm augite) granodiorites (380, 384) which appear to include some tonalitic variants (see analysis 13 of Shaw and Flood, 1981). They are essentially unstressed I-type granitoids and form the most southerly, and perhaps oldest (see below) members of the New England Batholith (*s.l.*; Fig. 0.1). Zircons were separated from these two intrusives to investigate the possibility that their U/Pb isotopic characteristics might record the ages of their respective source rocks (*cf.* Krogh and Davis, 1973; Bickford *et al.*, 1980; Chen and Moore, 1981) and thus give some indication whether the basement to the Tamworth Belt might possess oceanic characteristics (e.g. Crook and Felton, 1975; Crook, 1980a) or perhaps by depressed Pre-Cambrian or Lower Palaeozoic continental crust (e.g. Rutland, 1973). These zircons did not display any inherited U/Pb isotopic characteristics. Although this result is consistent with derivation of the Barrington Tops and Mount Ephraim granodiorites from a relatively Zr-poor, perhaps oceanic-type source, it certainly does not preclude other source types. In fact the relatively high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of these granodiorites (0.705 ± 0.005 ; Table H-2) might suggest some crustal contamination.

The U/Pb isotopic ages of these zircons are discordant and fall

* N.B. Trondhjemitic and tonalitic intrusives in the Woolomin beds in the Barry area (see Figs 0.2 and 1.1) appear to be Early Permian in age (265 m.y., Hensel *et al.*, 1982; Hensel pers. comm., 1982) and thus unrelated to the Pola Fogal Suite.

in the range 281 m.y.-251 m.y. for the Barrington Tops Granodiorite, and in the range 270 m.y.-211 m.y. for the Mount Ephraim Granodiorite (Table H-1). Biotite from the Barrington Tops Granodiorite yielded a Rb/Sr age of 262 m.y. (Table H-2). This suggests that the $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages might represent maximum crystallization ages for these intrusives and the younger isotopic ages (Table H-1) could record (?) later-stage lead-loss events.

Sericitized leucocratic dykes and sills are locally abundant in the vicinity of the Barrington Tops and Mount Ephraim Granodiorites (Maps 1 and 2). A genetic relationship between these granodiorites and the former appears likely, but has not been definitely established. Although leucocratic dykes are widespread in the Glen Ward beds, almost all of these are too small to be depicted on Map 1. They do not appear to intrude the PBOC or the Myra beds but this observation places few tangible constraints on the tectonic emplacement ages of the Myra beds and the PBOC.

PART II

THE PIGNA BARNEY OPHIOLITIC COMPLEX

Introduction and General Description

The Pigna Barney Ophiolitic Complex (PBOC) is a lithologically distinctive ophiolitic melange which is largely confined to major fault zones in the Pigna Barney-Curricabark area. Highly sheared serpentinitized harzburgite is the dominant lithology. This material typically forms the matrix of the melange and it may surround or abut locally abundant blocks of disrupted cumulate* and non-cumulate mafic and ultramafic intrusives and basaltic extrusives (ophiolitic members). Also occurring within this serpentinite-matrix melange are scattered blocks of low- to medium-grade metamorphic lithologies, fragments of the adjacent Myra beds and Glen Ward beds, and fragments of the Pola Fogal hornblendite-tonalite suite (exotic members). The type area for the PBOC is outlined in Figure B-1 (Appendix B) and the overall distribution of the PBOC is shown in Figure 1.1.

Ophiolitic Members (see Chapter 5)

Throughout much of the Pigna Barney-Curricabark area the PBOC is represented almost entirely by highly serpentinitized and often highly sheared ultramafic rocks. However, within the ophiolitic assemblage as a whole, seven major lithological groups have been recognized. In order of general structural position and inferred original stratigraphic position (Fig. 5.1) these groups are:

* In this thesis the term 'cumulate' is applied to igneous intrusives which may or may not display igneous lamination but which possess interlocking textures closely resembling those conventionally interpreted to reflect a mode of origin involving significant crystal settling and accumulation (see Wager *et al.*, 1960; Wager and Brown, 1968; Jackson, 1971). However, this genetic interpretation of cumulate textures is currently undergoing critical reappraisal (e.g. Campbell, 1978; McBirney and Noyes, 1979; Casey and Karson, 1981; Irvine, 1982). In particular, rocks possessing adcumulus textures, and this includes almost all PBOC cumulates, most probably crystallized entirely (or almost entirely) *in situ* on the bounding surfaces of their magma "chambers". Consequently, I use the textural terminology of Wager *et al.* (1960) and Jackson (1971) only in a descriptive, non-genetic sense in accord with redefinitions of terms proposed by Irvine (1982).

1. Tectonized harzburgite.
2. Cumulate harzburgite (not found in the type area).
3. Miscellaneous ultramafic lithologies.
4. Cumulate olivine norites*.
5. Cumulate gabbros.
6. Doleritic intrusives.
7. Basaltic extrusives and fine-grained basaltic intrusives (?).

With the exception of group 2, representatives of all of these lithological groups are present in the type area (Fig. B-1) where, apart from the lack of a sheeted dyke complex, they conform in general sequence and rock type (Fig. 5.1) to the 1972 Penrose Conference definition of ophiolite (Conference Participants, 1972). Contacts between the various lithologies are almost invariably faulted and substantial portions of each lithological group, especially groups 1-5, are highly sheared. Thus, although a relatively normal ophiolitic succession is developed in the type area, there, and within the PBOC as a whole, the initial intrusive-extrusive relations and the initial relative abundances of rock types are poorly preserved. Where observed, contacts with the Myra beds, Glen Ward beds and Manning Group are also faulted, but the internal pseudo-stratigraphy of the PBOC (Fig. 5.1) would suggest that it was initially conformably or unconformably overlain by the Glen Ward beds (see Chapter 1).

In view of the marked internal fragmentation of the PBOC and the relatively incoherent tectonic mixing of its various component lithologies, this study mainly attempts to reconstruct the essential characters of the Complex from a petrological viewpoint.

All ophiolitic members of the PBOC are altered to some degree. Much of this alteration would appear to be related to sea-floor or

* Throughout this thesis the term olivine norite is used in its broadest sense and refers to ol + opx + plag + cpx + spinel assemblages with normative (see Appendix A) or modal ol > 10%, opx > 10%, plag > 10% and cpx < 10%. In the terminology of Streckeisen (1976) the majority of these rocks are olivine mela-norites (plag < 35%). Olivine norites with > 35% plagioclase are not uncommon in the PBOC but these are usually saussuritized and amphibolitized (see Section 5.4.2) and few have been examined in detail.

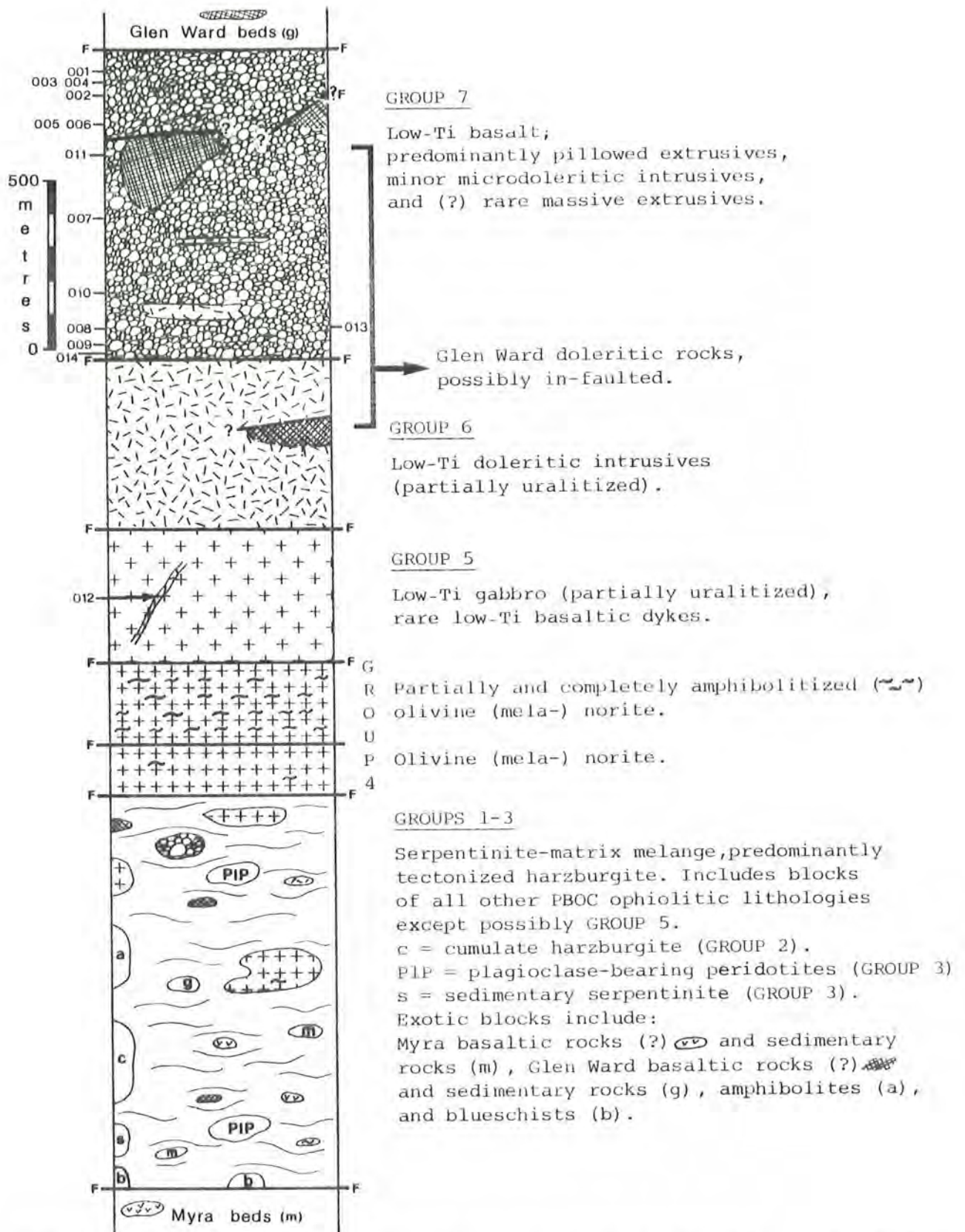


Fig. 5.1: Schematic composite section of the PBOC predominantly constructed from field relations in the type area (see Fig. B-1). Some lithologies included from outside the type area are drawn against the left side of the column. Stratigraphic thicknesses are approximate. Minor intrusives (?) and tectonic inclusions are not drawn to scale. Sample numbers 001-014 indicate approximate stratigraphic positions of analysed low-Ti basalts (see Table 5.6a). Contacts between all major lithological groups are faulted (F - F); numerous other faults are not shown.

subsea-floor secondary processes, especially in the basaltic extrusives, and this obviously imposes some constraints on conclusions based on the bulk chemistry of these rocks (see Chapter 3, Section 3.5.1). Chemical adjustments which accompanied serpentinization, saussuritization and amphibolitization of the intrusives are examined semiquantitatively in Appendix A. Those results, and the presence of relatively fresh spherulitically devitrified sideromelane in some basaltic extrusives, enable specific generalizations on the intrinsic chemistry of many ophiolitic members of the PBOC to be made with some confidence.

To a greater or lesser extent all ophiolitic members of the PBOC are characterized by exceptionally low incompatible element abundances and relatively high normative orthopyroxene contents. The overwhelming predominance of rock types with these characteristics in the PBOC distinguishes it from most other ophiolitic complexes (*cf.* Coleman, 1977) and from possibly all other mafic-ultramafic assemblages in the NEO (*cf.* Wilkinson, 1969; Leitch, 1979). Indeed, in most ophiolites (and in other mafic-ultramafic complexes in the NEO) plagioclase-bearing intrusive assemblages are characterized by $\text{cpx} \gg \text{opx}$, and where present, markedly incompatible element-depleted mafic rocks are typically subordinate to other more "normal" basaltic types (e.g. Sun and Nesbitt, 1978; Duncan and Green, 1980). Basaltic rocks of the latter type are abundant in the Glen Ward beds adjacent to the PBOC, but these do not constitute part of a typical ophiolitic association (see Chapter 3).

Exotic Members (see Chapter 6).

These include all tectonic blocks incorporated in the serpentinite-matrix melange of the PBOC which are lithologically dissimilar to, and distinct from, fragments of disrupted ophiolitic members. Most of the tectonic blocks appear to have been derived from the Myra beds or the Glen Ward beds but additional exotic metamorphic and metasomatic types are also present. The exotic members of the PBOC are described briefly in Chapter 6.

CHAPTER 5OPHIOLITIC MEMBERS OF THE PBOC5.1 TECTONIZED HARZBURGITES5.1.1 Field Relations

Serpentinized harzburgite is the dominant and most widespread lithology in the PBOC. For the most part it occurs as highly sheared elongate and irregularly-shaped masses constituting disaggregated and slightly dispersed serpentinite-matrix melange zones along or adjacent to the Peel and Curricabark fault systems (Map 1). Wherever observed, contacts with surrounding lithologies are invariably faulted, although such faults are often difficult to trace beyond the outcrop limits of these serpentinite masses. This is particularly true in the Myra beds where shearing is often more prevalent in the vicinity of serpentinite masses, and individual faults blend into more diffuse shear structures.

Although blocks of other lithologies are locally abundant in the PBOC serpentinite-matrix melange, much of it is autoclastic, having been derived largely by the tectonic disruption of serpentinized harzburgite (Plate 5.1A,B; see below). Textural evidence (see Section 5.1.2) suggests that these harzburgites were deformed and recrystallized prior to serpentinization, although much shearing has occurred subsequently. Williams (1979) has described a similar sequence of events in equivalent serpentinized harzburgites in the Glenrock Station area.

Terminology

To distinguish them from cumulate harzburgites in the PBOC (Section 5.2), in this thesis the deformed and recrystallized harzburgites (Group 1) are referred to as tectonized harzburgites. When compared with other ophiolitic assemblages, the PBOC tectonized harzburgites correspond to the metamorphic peridotites of Coleman (1977) and the harzburgite tectonites of many other workers (e.g. Jackson *et al.*, 1975; George, 1978; Himmelberg and Loney, 1980; Ross *et al.*, 1980). For the PBOC examples, however, the term tectonized harzburgite is preferred because 'harzburgite tectonite' implies that the rocks concerned possess fabric elements which may be systematically related to some form of coherent deformation (e.g. Turner and Weiss, 1963). Whereas most metamorphic harzburgites in ophiolite complexes display well-developed

tectonite fabrics such as macroscopic and megascopic folds (e.g. Moores, 1969; Ross, 1977; Ross *et al.*, 1980; Boudier and Coleman, 1981; *cf.* Nicolas and Boudier, 1975) and metamorphic layering (e.g. Menzies and Allen, 1974; Sinton, 1977; George, 1978; Thayer, 1980), and the term harzburgite tectonite is usually appropriate, these features are not evident in the PBOC harzburgites.

On occasion, however, relatively unsheared blocks of PBOC harzburgite possess a crude sub-mesoscopic lineation defined by the crude alignment of partially serpentized orthopyroxene-rich porphyroclastic augen and neoblastic aggregates in an almost entirely serpentized, originally olivine-rich matrix (Plate 5.1F). This lineation constitutes the only pre-serpentinite-matrix melange fabric recognizable in outcrop. It occurs in tectonic blocks and slabs of all sizes, but any larger-scale structures to which it might be related have been completely obliterated by the melange-forming event(s). Consequently, although these blocks of PBOC harzburgite display tectonite fabrics on a sub-macroscopic scale, the overwhelmingly predominant fabric is that of a melange, and it would be misleading to apply the term 'tectonite' in the same context as it is used by other workers. The more general term 'tectonized' is preferred, and where it is necessary to refer to the PBOC tectonized harzburgites plus harzburgite tectonites as a general class of peridotites, these are collectively termed tectonized harzburgites.

Melange Fabric

Within the PBOC serpentinites, schistosity and cleavage typically dip steeply and strike sub-parallel to the general trend of the host serpentinite masses. In many outcrops, schistosity and cleavage are warped around sub-horizontal axes (Plate 5.1C) so that their dips vary within the range 90 ± 20 degrees. Locally, however, these fabric elements may wrap around more massive blocks, may be randomly rotated by late-stage small-scale faults, and are often chaotically deformed (Plate 5.1D). Thus, the internal fabrics of these serpentized harzburgites are often exceedingly complex or incoherent, and their relationships to the deformation in the surrounding rocks are uncertain.

The proportion of sheared and highly cleaved serpentinite matrix varies considerably from outcrop to outcrop. Matrix-poor and matrix-rich

examples are illustrated in Plate 5.1A,C,D. The matrix-poor examples are almost invariably autoclastic tectonized harzburgite, massive blocks of which are randomly oriented throughout the subordinate matrix. Tectonic blocks of other lithologies are not found in melange of this type.

The matrix-rich melange also consists almost entirely of tectonized harzburgite, although blocks of ophiolitic and exotic lithologies are locally abundant. Most of the smaller of these blocks are lensoidal, partially disaggregated, and are elongate sub-parallel to the strike of the predominant foliation in the surrounding sheared matrix (Plate 5.1E). Larger blocks are typically less attenuated, although most are disaggregated to some extent.

Tectonized harzburgites in the PBOC are devoid of demonstrably intrusive dunites and discrete mafic partial melt segregations such as those in some other harzburgite tectonites (e.g. Himmelberg and Loney 1973,1980; Menzies and Allen, 1974; Capedri *et al.*, 1977; Dick, 1977; Sinton, 1977; Harkins *et al.*, 1980) and the Ronda alpine peridotite, Spain (Dickey, 1970; Dickey *et al.*, 1977). However, rare tectonic blocks of serpentized cumulate dunite (e.g. 473), metacumulate (recrystallized) dunite (e.g. 499, 528), interlayered cumulate dunite and orthopyroxenite (e.g. 489) and cumulate plagioclase-bearing harzburgite (e.g. 472, 500) do occur in the more highly sheared PBOC tectonized harzburgites. Although these might represent fragments of units originally intruding the tectonized harzburgites, field and other data critical to an evaluation of this interpretation are few (see Sections 5.2 and 5.3). In fact, contacts between tectonized harzburgite and all other ophiolitic and exotic members of the PBOC are invariably sheared, and consequently original relations are not preserved

5.1.2 Petrography

The PBOC tectonized harzburgites are almost invariably highly serpentized (see Appendix A). Relict mineral fragments and porphyroclastic textures (Mercier and Nicolas, 1975) are preserved in the more massive blocks, but in the sheared matrix these petrographic characteristics are almost entirely obliterated.

Relict porphyroclasts of orthopyroxene and bastite pseudomorphs

after orthopyroxene^{*} may range up to 1 cm in maximum dimensions, but grain size of 3-5 mm predominate. These orthopyroxenes typically form: (i) discrete abraded blocky crystals (Plate 5.1G) displaying weakly developed-pronounced strain extinction, kink bands and glide planes, or (ii) augen-shaped multicrystal aggregates (Plate 5.1F). They occur in a matrix largely consisting of slightly finer-grained, highly serpentinized olivine, and minor neoblastic aggregates of orthopyroxene±clinopyroxene±spinel±olivine. In this matrix, some secondary magnetite trails surrounding optically continuous mesh-textured serpentine pseudomorphs after olivine appear to delineate original grain boundaries. These are distinct from magnetite trails which formed during serpentinization along fractures in the original olivine grains, as the latter cross-cut the mesh texture. Those apparently delineating original grain boundaries suggest that the pre-serpentinization textures of the olivine-rich matrix were largely coarse neoblastic or sub-equigranular. No unequivocal evidence for the presence of former coarse-grained olivine porphyroclasts has been observed in the PBOC tectonized harzburgites, although it must be acknowledged that these might be difficult to identify, given the advanced degree of serpentinization (see Appendix A).

Compared with other ophiolitic analogues, the PBOC tectonized harzburgites are characterized by abnormally high orthopyroxene contents. From outcrops, sawn hand-specimens, and thin sections, qualitative and semi-quantitative estimations of the proportion of orthopyroxene+bastite pseudomorphs to olivine+mesh-textured serpentine indicate that prior to serpentinization the modes of PBOC tectonized harzburgites consisted of approximately 60%-70% olivine, 30%-40% orthopyroxene, <1% clinopyroxene and ~1% spinel. The normative compositions of these rocks indicate a similar range of olivine:orthopyroxene ratios (see Table B-1), with CATION normative OPX^{**} averaging 36% (Table 5.1). In comparison,

* No partial bastite-like pseudomorphs after clinopyroxene or features typical of complete pseudomorphism of clinopyroxene by bastite-like serpentine morphologies (see Wicks and Whittaker, 1977; Dungan, 1979a) were observed in any of the ultramafic rocks examined in this study.

** Mineral components of the CATION norm described in Appendix A are capitalized to distinguish them from CIPW normative minerals (lower case italics). Note that this cation norm is used exclusively for rocks described in Sections 5.1 to 5.4 of this thesis.

most harzburgite tectonites described from ophiolites contain less than 30% modal orthopyroxene (Fig. 5.2; Coleman, 1977, p.25) although England and Davies (1973) have reported 40% orthopyroxene in harzburgite tectonites from the Papuan Ultramafic Belt.

Nicolas *et al.* (1980) recognize systematic textural variations in ophiolite harzburgite tectonites, and they relate these to various stress regimes operating during the formation and emplacement of the ophiolites. They constructed a generalized ophiolite harzburgite tectonite stratigraphy (Fig. 2 of Nicolas *et al.*, 1980) based largely on the microfabrics of these rocks. Thus, many ophiolitic peridotites may be seen to consist of a basal zone (~2 km thick) of extremely deformed mylonitic harzburgite or lherzolite which is progressively overlain by a zone of moderately deformed depleted harzburgite (~5-7 km thick) and an upper transition zone of plastically deformed, often magmatically impregnated, depleted harzburgite (several km thick).

After examination of thin sections of PBOC tectonized harzburgites, A. Nicolas (pers. comm., 1981) believes that these rocks are too highly serpentized to permit confident conclusions from petrofabric studies, especially as the preservation of olivine neoblasts is important for such studies, (Nicolas, 1978). In addition any pristine tectonite stratigraphy in the PBOC is likely to have been almost entirely obliterated by post-serpentinization shearing, tectonic attrition, and mixing during emplacement. Accordingly it is not surprising that discrete blocks of tectonized harzburgite in close spatial association (tens of metres) at locality 3 (Fig. B-1) display spinel habits indicative of different deformational and recrystallization histories. With increasing deformation and recrystallization these spinel habits range from: (i) vermicular "intergrowths" with orthopyroxene porphyroclasts (Plate 5.1F,H) to; (ii) intergranular, coexisting with relatively fine-grained neoblastic silicates (Plate 5.1I) to; (iii) trails of sub-equidimensional grains (Plate 5.1J) in the olivine-rich matrix aligned sub-parallel to the porphyroclast lineation (see Section 5.1.1). The latter spinels presumably are recrystallized holly-leaf types (see Mercier and Nicolas, 1975) and they may represent a textural transition from porphyroclastic to equigranular types.

Although some samples are abundantly neoblastic (Plate 5.2A)

PLATE 5.1

- A,B. PBOC serpentinite-matrix autoclastic melange. At this locality (GR6516,8154) all tectonic blocks are partially serpentinitized tectonized harzburgite in a completely serpentinitized, highly sheared matrix. Both photographs are similar in scale (N.B. hammer in B).
- C. Sub-parallel schistosity and spaced reticulate cleavage in PBOC schistose serpentinite. Note gentle warp in cleavage displayed near the left side of the photograph. Field of view approximately 4.5m in width. GR6516,8154.
- D. Chaotic deformation in highly schistose serpentinite. Disrupted white veins are largely talc and commonly occupy minor fault zones. GR6838,8167.
- E. Partially disaggregated lensoidal block of olivine norite (463) in highly schistose serpentinite. Small sub-rounded blocks isolated in the schistose matrix are all fragments of olivine norite similar to that forming the larger block. GR6205,8266.
- F. PBOC tectonized harzburgite (PBOCTH). Orthopyroxene-rich porphyroclastic augen [largely pseudomorphed by bastite (pale)] with associated augen- or irregularly-shaped neoblastic aggregates (examples arrowed) in a highly serpentinitized, originally olivine-rich matrix (dark). Note vermicular spinel intergrown with some bastite 'porphyroclasts' [sample 426, transmitted light].
- G. PBOCTH. Dislocated and abraded enstatite porphyroclast with associated recrystallized Cr-Al spinel (larger black grains). Pale areas with small irregular black grains (magnetite) are serpentinitized olivine [sample 495, mag. = 22x, nicols half-crossed].
- H. PBOCTH. Vermicular Cr-Al spinel intergrown with enstatite porphyroclast [sample 498, mag.= 22x, crossed nicols].
- I,I'. PBOCTH. Composite photomicrograph. Neoblastic aggregates of enstatite + Cr-Al spinel + minor olivine and diopside. Neoblasts pale in I (plane-polarized light) and dark in I' (crossed nicols). The remaining dark (I) and light (I') areas are serpentinitized olivine [sample 498, mag.= 22x].
- J. PBOCTH. Trails of sub-equidimensional Cr-Al spinel grains (black) in a (serpentinitized) olivine-rich matrix [sample 502, mag.= 9x, partially crossed nicols].

PLATE 5-1



A



B



C



D



E



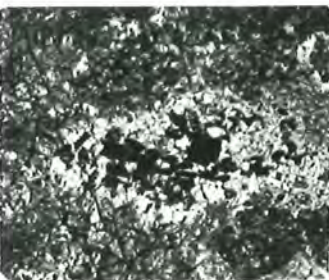
F



G



H



I



I'



J

indicating high strain (Nicolas *et al.*, 1971; Nicolas, 1978), textures which would be indicative of extreme pre-serpentinization deformation (e.g. highly attenuated fine-grained porphyroclastic textures and mylonitic textures) are not preserved in the PBOC harzburgites. Indeed, porphyroclastic textures in most of the PBOC massive tectonized harzburgite blocks reflect only moderate deformation and recrystallization and are most likely derived from the upper parts of the pristine harzburgite section. Some contain occasional delicate, highly cusped intergranular partially- or completely serpentinized orthopyroxene (Plate 5.2B). Where present, these cuspidiform grains have morphologies similar to interstitial pyroxenes in partial melt-textured plagioclase lherzolites from Othris (Menzies, 1973), in Troodos harzburgite tectonites (George, 1978), and typical of post-cumulus phases in the overlying olivine norites (Section 5.4) and cumulate rocks in general (e.g. Wager *et al.* 1960; Jackson, 1971). These textures might suggest that the host harzburgites experienced some crystallization of trapped partial melts or some magmatic impregnation from magmas formed beneath, and thus belong to the ophiolitic 'transition zone' (*cf.* Dick, 1977; Sinton, 1977; Nicolas *et al.* 1979, 1980). Nevertheless, the whole-rock and mineral chemistries of these PBOC tectonized harzburgites do not reinforce such an interpretation (see below), and these textures remain somewhat enigmatic.

5.1.3 Mineral Chemistry

Relict olivines, pyroxenes and Cr-Al spinels were analysed in seven representative samples of PBOC tectonized harzburgite. Irrespective of their habits, all mineral phases within individual samples display negligible intra- and inter-grain compositional variation, and analyses listed in Table C-2 are quite representative. Indeed, exsolution blebs of spinel and (rare) clinopyroxene in orthopyroxene porphyroclasts are essentially identical in composition to those in adjacent and discrete neoblastic aggregates. This is consistent with an origin of these particular aggregates via the attrition and recrystallization of the marginal portions of orthopyroxene grains rich in exsolved spinel and clinopyroxene (see Mercier and Nicolas, 1975). In addition, cuspidiform orthopyroxene relicts in the olivine-rich portions of these rocks have

identical chemical compositions to the accompanying porphyroclasts. Thus, coexisting phases in the PBOC tectonized harzburgites are well-equilibrated, the pyroxenes at temperatures in excess of 800°C, and the olivine and spinel at similar or somewhat lower temperatures in excess of 600°C (see Appendix D).

Olivine

Olivines in the PBOC tectonized harzburgites display a limited range in composition from Fo_{92.3} to Fo_{91.0} (Table C-1) and their NiO contents fall in the range 0.25%-0.39%. In these respects they are comparable to olivines in most ophiolitic harzburgite tectonites (Coleman, 1977), although many such olivines are slightly less forsteritic and (see Table 2 of Dick, 1977) some are depleted in NiO relative to the PBOC examples (e.g. olivines from harzburgite tectonites in the Canyon Mountain Ophiolite contain less than 0.2% NiO; Himmelberg and Loney, 1980). Others may be enriched in NiO (e.g. those in the Red Mountain harzburgite tectonites contain 0.40%-0.48% NiO; Sinton, 1977). In these PBOC olivines, MnO and CaO are below the detection limits of the microprobe (less than 0.09% and 0.07% respectively) and consequently they are depleted in MnO, at least, relative to their counterparts containing ~0.1%-0.2% MnO in other ophiolitic assemblages (see, for example, Sinton, 1977; Dick, 1977; Arai, 1980; Himmelberg and Loney, 1980).

Cr-Al Spinel

Cr-Al spinels in the PBOC tectonized harzburgites possess Cr ($100Cr/(Cr+Al)$) and M ($100Mg/(Mg+Fe^{2+})$) values within the overall ranges displayed by spinels from Alpine-type peridotites (Fig. 5.3d). They are strongly depleted in Ti and V (Table (c-2), and calculated Fe^{3+} (Table C-2), assuming stoichiometry, is lower in these spinels than in many from other Alpine-type peridotites (Fig. 5.3c). Overall, their Cr values range from 32-43 (Fig. 5.3d) and on average they are more aluminous than most spinels in ophiolitic harzburgite tectonites. For example, ranges of Cr values displayed by spinels in some of the latter harzburgites include: (i) 37-55, Burro Mountain (Loney *et al.*, 1971); (ii) 30-63, Red Mountain, N.Z. (Sinton, 1977); (iii) 46-73, Vulcan Peak Peridotite (Himmelberg and Loney, 1973); (iv) 19-75,

Josephine Peridotite (Dick, 1977); (v) 71-77, New Caledonia (Rodgers, 1973; Bevan and Rodgers, 1977), (vi) 40-90, Newfoundland ophiolites (Malpas and Strong, 1975), and ~90, Papuan Ultramafic Belt (Jaques and Chappell 1980).

Many of the harzburgite tectonites cited above contain more than one generation of spinel, and the overall Cr-Al variation in these spinel populations may reflect successive or inhomogeneous melt-extraction or melt-impregnation events (e.g. Dickey, 1970; Menzies, 1975; Dick, 1977). In any event, these processes most probably generate spinels with increased *Cr* values in the host peridotites; either by extraction of Al, Fe and Mg from *in situ* spinels during partial melting (Dickey, 1970; Mysen and Kushiro, 1977; Jaques and Green, 1980) or strong partitioning of Cr into spinels crystallizing from trapped or introduced Cr-rich partial melts (Dickey *et al.*, 1971; Dickey and Yoder, 1972; Burns, 1975). However, where spinels in the host peridotite are open to reaction with migrating aluminous (~basaltic) liquid, they can reequilibrate to more aluminous compositions (Menzies, 1975). Nevertheless, spinel habits (Section 5.2) and the relatively restricted range of Al-rich spinel compositions found in the PBOC tectonized harzburgites would suggest that these rocks have not experienced significant magmatic impregnation or extreme partial melting, and that such melts as might have been produced or introduced did not crystallize spinel within these hosts. Some Al-rich spinel of magmatic origin does occur, however, in the cumulate harzburgites (Section 5.2), and at least one occurrence of chromitite in the PBOC might reflect magmatic accumulation of spinel from highly magnesian melts within the tectonized harzburgites or near the base of the associated cumulate sequence.

Chromite forming a massive, partially recrystallized chromitite block which has weathered out of highly schistose serpentinite at GR 6763, 8194 is more magnesian and substantially more Cr-rich than disseminated spinels in the PBOC harzburgites described above (see Fig. 5.3d). Pristine textures in the chromitite have been obliterated by micro-granulation, and its mode of origin is uncertain. Its chemistry is, however, similar to that of some podiform chromitites of probable cumulate origin (i.e. relatively high *M* and *Cr* values) which are typically associated with dunitic intrusives in harzburgite tectonites (e.g. Dickey, 1975; Greenbaum, 1977; Mussallam *et al.* 1981; see Fig. 5.4). Accessory spinels in PBOC

dunitic blocks are significantly less magnesian than the chromitite, and this reflects the relatively Fe-rich chemistry of their hosts (see Section 5.3), although they do possess more-or-less comparable Cr values (Table C-2). It is conceivable, therefore, that the chromitite is magmatic and has been tectonically displaced from its original igneous association (*cf.* Greenbaum, 1977).

Orthopyroxenes

All orthopyroxenes in the PBOC tectonized harzburgites are enstatites of relatively uniform composition ($En_{92.4-91.5}$). Minor components of these enstatites are restricted to the following ranges: $CaO\% = 0.3-1.1$, average = 0.45; $Al_2O_3\% = 2.2-3.2$, average = 2.5; $Cr_2O_3\% = 0.2-0.6$, average = 0.5. Enstatites with these compositions (see Figs. 5.5, 5.6) are more-or-less typical of tectonized harzburgites which have experienced moderate degrees of partial melting, whereas more magnesian Al-poor enstatites (En_{94} , $Al_2O_3 < 1\%$) are indicative of extreme depletion (Dick, 1977; Hervig *et al.*, 1980; Jaques and Chappell, 1980). On average, however, the PBOC enstatites contain less CaO than those with comparable mg values (and Al_2O_3 contents) in other tectonized harzburgites (Fig. 5.5; Coleman, 1977; Dick, 1977). The uncharacteristic Ca-enrichment in enstatites from sample 496 (Table C-2, page 9) might suggest that the PBOC tectonized harzburgites are not homogeneously depleted on all scales.

Clinopyroxene

In the PBOC tectonized harzburgites, all clinopyroxene neoblasts (and rare exsolution lamellae in enstatites) are calcic diopsides (Fig. 5.5) which display a restricted range in composition from $Ca_{47}Mg_{50}Fe'_3$ to $Ca_{49}Mg_{49}Fe'_2$. They have comparable Cr_2O_3 contents to the coexisting enstatites, but they contain significantly less Al_2O_3 . This Al-depletion might simply reflect competition with spinel for Al during co-exsolution of these phases from pre-existing aluminous enstatite (see Section 5.1.2).

Diopsides in sample 495 are the only pyroxenes in the PBOC tectonized harzburgites to contain detectable Na_2O (Table C-2, page 8). In addition, enstatites in this sample are relatively enriched in Al_2O_3 . These data would suggest that sample 495 is somewhat less-depleted than the other tectonized harzburgites examined.

Discussion

In terms of the constraints imposed by partial melting models for the depletion of harzburgite tectonites in 'basaltic' components, the moderate Al_2O_3 contents of the PBOC enstatites are broadly consistent with the relatively aluminous compositions of the coexisting spinels. In other words it is conceivable that C_r values in these PBOC spinels are relatively low because sufficient Al was (and possibly still is) available from coexisting enstatite (\pm diopside) to satisfy most of the host-melt equilibrium requirements during partial melting. It may be fortuitous that spinels in the PBOC tectonized harzburgites have C_r and M values similar to those in the more magnesian PBOC low-Ti basaltic extrusives (Fig. 5.3d) (see Section 5.7.4). To have been in equilibrium with olivine in these harzburgites, the M value of such a melt would be in the range 77-75 (assuming $K_{\text{D}_{\text{Fe-Mg}}^{\text{ol-melt}}} = 0.3$) i.e. somewhat higher than that of the spinel-bearing low-Ti basalts investigated (see Section 5.7). The possibility that these harzburgites might represent refractory residua following the extraction of low-Ti basaltic melts is discussed further in Section 5.1.4.

The physical conditions accompanying partial melting in most depleted harzburgites are not readily accessible from empirical studies of the type reported here. Two-pyroxene and olivine-spinel geothermometers invariably record subsolidus re-equilibration temperatures (see Appendix D). Also, because of the extreme Al-depletion in harzburgites of this type, the Al contents of enstatites typically vary as a function of the bulk composition of their hosts and do not reliably reflect pressures of equilibration (e.g. Dick, 1977; Nicholls, 1977). In fact, for spinel peridotites the reliability of enstatite- Al_2O_3 geobarometers is far from well-established (see Fujii and Takahashi, 1976; Stroh, 1976; Egger, 1979; Lane and Ganguly, 1980), and recently the accuracy of well-established two-pyroxene geothermometers (e.g. Wells, 1977) has also been brought into question. These possibly overstate actual equilibration temperatures by 50-150°C (Fonarev and Graphchikov, 1982). Because pyroxene geobarometers in current use (e.g. Herzberg, 1978) generally rely on accurate estimates of equilibration temperatures, the work of Fonarev and Graphchikov (1982) further reduces the limited accuracy of these techniques. In more general terms, however, the range of $\text{Al}^{\text{IV}}/\text{Al}^{\text{VI}}$ ratios

displayed by pyroxenes in the PBOC tectonized harzburgites would suggest that equilibration pressures were at least comparable to those of other tectonized harzburgites of similar bulk composition (Fig. 5.7).

This does not, however, preclude the possibility that they might have experienced partial melting at substantially higher pressures. For instance, Hervig *et al.* (1980) maintain that Cr-Al spinel harzburgite xenoliths from African kimberlites and alkaline basalts are the residues following partial melting of garnet lherzolites. Orthopyroxenes in the less depleted (fertile) xenoliths from these populations have similar $Al^{IV}:Al^{VI}$ ratios to orthopyroxenes in alpine-type tectonized harzburgites (Fig. 5.7). On the other hand, the $Al^{IV}:Al^{VI}$ ratios of orthopyroxenes in the highly depleted (essentially 'barren') xenoliths are substantially less than those cited above (Fig. 5.7). If indeed the fertile and barren xenoliths were partially melted at similar pressures (the latter at higher temperatures; see Hervig *et al.*, 1980) then Figure 5.7 would suggest that the $Al^{IV}:Al^{VI}$ ratios of orthopyroxenes in rocks of this type might reflect significant compositional controls in addition to possible effects due to pressure.

In all probability, however, pyroxenes in the PBOC tectonized harzburgites last equilibrated under conditions appropriate to the spinel lherzolite stability field, possibly at pressures within the range 10-15 kb (Obata, 1976; Stroh, 1976; Herzberg, 1978), and at subsolidus temperatures at least somewhat in excess of 700°C (*cf.* Fonarev and Graphchikov, 1982; and Appendix D), but well below the temperatures of partial melting.

5.1.4 Whole-rock Chemistry

Major and trace element analyses of 12 PBOC tectonized harzburgites and one harzburgite from the Morrisons Gap area are listed in Table B-1. The mean and standard deviations for 11 of the PBOC harzburgite analyses (analysis 1 from Table B-1 omitted because of low total) appear in Table 5.1.

Because the PBOC tectonized harzburgites are highly serpentinized ($\Sigma Vol. > 11.8\%$, see Table B-1), their bulk chemistry must be interpreted with some caution. However, normative calculations (Appendix A) suggest that, with the possible exception of Ca and alkalis, serpentinization of these harzburgites has not modified the relative proportions of major

elements to any great extent. Similarly, the low standard deviations displayed by most elements (Table 5.1) indicate that such alteration as might have occurred has not produced any marked degree of chemical heterogeneity in these rocks. This is especially true for Fe and Mg, because the Mg^* values (see Appendix A) of the host harzburgites are almost identical to the Mg^* and mg values of their component silicates (see Table C-1).

The PBOC tectonized harzburgites are strongly depleted in incompatible and other 'fusible' components such as Al_2O_3 , CaO and alkalis. On average, they are significantly enriched in SiO_2 and depleted in CaO and MgO relative to typical harzburgite tectonites from ophiolites elsewhere (see Coleman, 1977, for a review), but they compare closely in most other aspects of their chemistry. Massive serpentinite (almost completely recrystallized to antigorite) from the Morrisons Gap area (Table B-1, analysis 13) also displays strongly depleted chemistry. Although it is significantly enriched in Sr relative to the PBOC tectonized harzburgites, the Sr might have been introduced during the mild contact metamorphism (controlling the formation of antigorite) by the nearby Mount Ephraim Granodiorite (Map 2). Apart from these occurrences, the overall distribution of similarly depleted peridotites in the Peel Fault System is largely unknown.

In many PBOC tectonized harzburgites CaO abundances are at least an order of magnitude lower than those typical of ophiolitic harzburgite tectonites (i.e. ~0.5%-1.0% CaO, Coleman, 1977). It is very likely that extreme depletion of CaO in the PBOC examples reflects some loss of Ca during serpentinitization (see Appendix A), the remaining Ca being largely in relict enstatite and a trace of neoblastic diopside.

The SiO_2 contents of typical ophiolitic harzburgite tectonites range from 40% to 45% and probably average ~43%-44% (Coleman, 1977). Their analogues in the PBOC, on the other hand, average 46.5% SiO_2 (Table 5.1). Because of the comparatively high modal orthopyroxene in the PBOC tectonized harzburgites (see Section 5.1.2), their enrichment in SiO_2 and accompanying depletion in MgO relative to other tectonized harzburgites is hardly surprising. If, as appears likely, the PBOC tectonized harzburgites attained their present refractory mineralogical and chemical compositions as a result of partial fusion of a relatively more fertile

peridotite and the extraction of a single or successively primitive basaltic and/or more magnesian melts, then:

- (i) the PBOC pristine undepleted peridotite must have been unusually SiO_2 - and orthopyroxene-rich, and/or impoverished in some basaltophile components e.g. Ti, Al and Ca; or
- (ii) if the PBOC and other tectonized harzburgites are derived from a more-or-less similar mantle precursor, the melt(s) extracted from the PBOC peridotites presumably were significantly depleted in SiO_2 relative to melts derived from most, if not all, other tectonized harzburgites.

Possibility (i) is perhaps the most likely explanation for the unusual (to date) orthopyroxene-rich character of the PBOC tectonized harzburgites. In recent years much evidence to suggest that the upper mantle is both chemically and mineralogically heterogeneous has accumulated from studies of the chemistry of basaltic rocks (see Section 3.5.2) and the diversity of peridotitic inclusions in alkaline hosts (e.g. Hutchison *et al.*, 1975; Maaløe and Aoki, 1977; Carswell, 1980; Hervig *et al.*, 1980). These and other studies of peridotite xenoliths belonging to the Cr-diopside suite demonstrate that at least some portions of the upper mantle contain abundant modal orthopyroxene.

From the average chemical composition of 384 spinel lherzolite xenoliths (average $mg = 89.9$) Maaløe and Aoki (1977) estimate that the average wt% modal composition of the uppermost mantle is olivine 66.70, orthopyroxene 23.74, clinopyroxene 7.83 and spinel 1.73 wt%. Some spinel lherzolite xenoliths ($mg \sim 90$) contain up to 50% more modal orthopyroxene (i.e. 37 vol.%) than the above estimate (see Wilkinson, 1982, page 38). On the other hand, the majority of garnet lherzolite nodules contain between 20 vol.% and 50 vol.% orthopyroxene (possibly averaging ~ 30 vol.%) and consequently a significant proportion of these nodules have relatively high SiO_2 abundances in the range 46.0%-47.5% (see Figs. 5 and 6 of Maaløe and Aoki, 1977). Extremely orthopyroxene-rich garnet lherzolites ($>>60\%$ modal orthopyroxene) are known, and rare spinel lherzolites containing 48%-40% SiO_2 presumably have exceptionally high *en* (see Figs. 1-6 of Maaløe and Aoki, 1977). In addition, some xenolith

populations in South African kimberlites and alkali basalts include harzburgite nodules with modal orthopyroxene ($\text{En}_{95.7-92.3}$) in the range 8%-55% (Hervig *et al.*, 1980), and metamorphic-textured "harzburgite" xenoliths in the Newer Basalts of Victoria contain ~65% orthopyroxene ($\text{En}_{90.7}$, Irving, 1974).

Clearly, the upper mantle does contain a spectrum of orthopyroxene-rich lithologies, and there is no reason to reject the possibility that the PBOC tectonized harzburgites are ultimately derived from such a source. Indeed, there is evidence from among ophiolitic tectonized harzburgites themselves that they are ultimately derived from a considerable range of parent mantle compositions.

Although ophiolitic tectonized harzburgites as a group are quite distinctive in their overall 'depleted' chemistry, their respective chemistries differ significantly in detail. From published analyses of tectonized harzburgites and variably depleted peridotites (in addition to references already cited and references listed in Coleman, 1977, see Ernst and Piccardo, 1979; Sinigoi *et al.*, 1980; Jackson and Ohnenstetter, 1981; Boudier and Coleman, 1981) and associated modal data, it is clear that varying degrees of partial melting of a single fertile (lherzolitic) mantle composition (e.g. Ringwood, 1975) cannot fully account for the chemical diversity of these residua, even allowing for a reasonable disparity in physical conditions accompanying partial melting events in the various peridotites.

During partial melting of peridotite, 'refractory' elements such as Ni, Cr, and to a lesser extent Mg, are strongly partitioned into residual phases (olivine; spinel+pyroxene; olivine+pyroxene+spinel, respectively), whereas 'basaltophile' elements including Si, Ti, Al, Fe, Ca and alkalis are partitioned into the derivative melts (e.g. Reay and Harris, 1964; Mysen, 1975; Mysen and Kushiro, 1977; Leeman and Lindstrom, 1978; Jaques and Green, 1980). Although some partitioning relations may be influenced to some degree by pressure (e.g. $K_D \text{Ni}_{\text{melt}}^{\text{ol}}$ decreases at elevated pressures, Mysen and Kushiro, 1979), varying degrees of partial melting of a model mantle composition would produce simple antipathetic trends between refractory and basaltophile elements in the various residua (*cf.* Maaløe and Aoki, 1977). On the other hand, pairs of refractory elements would vary sympathetically as, to a lesser

extent, should pairs of basaltophile elements. These chemical relations would be unlikely to be substantially modified by any cryptic magmatic impregnation of the residual peridotite because early precipitating phases from peridotite-derived melts are also enriched in refractory elements (e.g. Dickey *et al.*, 1971; Irvine and Findlay, 1972; Takahashi, 1978; Irvine, 1979).

However, the simple chemical relationships outlined above are not particularly well-developed characteristics of the broad spectrum of ophiolitic tectonized harzburgites and partially depleted peridotites. Thus, poor correlations exist between bulk Ni and Cr abundances in various peridotites (see, for example, Fig. 4 of Irvine and Findlay, 1972 and Table 2 of Coleman, 1977) and in samples from some individual tectonized harzburgites (e.g. Mount Albert, Irvine and Findlay, 1972; Samail ophiolite, Boudier and Coleman, 1981) and the correlation between modal (and normative) olivine and bulk Ni is far from ideal (see Table 2 of Coleman, 1977, for a summary). Similarly, poor correlations exist between refractory element abundances and 'basaltophile' element abundances, especially when moderately depleted lherzolites are considered in addition to highly depleted harzburgites. For example, some Ligurian lherzolites considered by Ernst and Piccardo (1979) to be only very slightly depleted in basaltic constituents ($\text{Al}_2\text{O}_3 + \text{CaO} \sim 5 \pm 1 \text{ wt\%}$, TiO_2 0.1%-0.25%, modal diopside 5%-25%) have Ni and/or Cr abundances comparable to depleted harzburgites ($\text{Al}_2\text{O}_3 + \text{CaO} < 1.5\%$, $\text{TiO}_2 \ll 0.1\%$) from other Mediterranean ophiolites such as Troodos, Othris and Vourinos (Moores, 1969; Menzies and Allen, 1974) and, incidentally, comparable to the PBOC tectonized harzburgites. Similar, but less pronounced discrepancies exist when the mineral chemistry of various depleted peridotites is examined in the light of partial melting models involving a single model mantle parent.

Although these criteria do not necessarily demonstrate that the PBOC tectonized harzburgites (and for that matter, some tectonized harzburgites in the Papuan Ultramafic Belt with modal enstatite ~45% England and Davies, 1973) were actually derived *via* partial melting of an unusually *en*-rich mantle precursor, they do provide evidence of mantle heterogeneity. Nevertheless, to a certain extent the present

levels of SiO_2 -saturation in some refractory tectonized harzburgites might also reflect the influence of H_2O on their partial melting histories (see below).

In general terms, once progressive or successive partial melting has largely eliminated the more readily fusible components (i.e. *ab*, *an* and *di*) from residual peridotites, further partial melting will progressively deplete the residue in *en*. This may occur: (i) *via* the incongruent melting of enstatite to forsterite+liquid under low pressure H_2O -undersaturated conditions (<~5 kb) or under moderate pressure H_2O -saturated conditions, or (ii) *via* the congruent melting of enstatite at pressures in excess of ~5 kb (e.g. Boyd *et al.*, 1964; Kushiro *et al.*, 1968; Kushiro, 1969; Nicholls and Ringwood, 1973; Mysen and Boettcher, 1975; Jaques and Green, 1980). Consequently, at moderate pressures, partial melting of peridotite under H_2O -saturated conditions will produce liquids saturated or oversaturated in SiO_2 (see Jaques and Green, 1980 for a brief review). Relative to partial melting in the same system under essentially anhydrous conditions (i.e. congruent melting of enstatite) the refractory residue from H_2O -saturated partial melting will become more rapidly depleted in *en*, that is, SiO_2 will decrease more rapidly and *mg* will increase more slowly.

To date it has not been demonstrated that any ophiolitic tectonized harzburgites have a history of H_2O -saturated partial melting. However, possible complimentary extrusives (e.g. boninites, high-Mg andesites) do occur in some ophiolites and modern fore-arc settings (see Section 5.7.4) and it may well be that some ophiolitic tectonized harzburgites (e.g. Troodos) have been rapidly depleted in *en* during a H_2O -saturated melting event. The compositions of the PBOC tectonized harzburgites, on the other hand, are possibly more akin to those of a potential source for highly magnesian boninitic or related melts rather than a residuum following the extraction of such melts. Unless their undepleted precursors were exceptionally *en*-rich, the PBOC tectonized harzburgites most probably represent refractory residua following the extraction of more-or less 'normal' picritic (?± basaltic) melts whose *en* contents were lower than envisaged for most primary Ti-poor melts parental to boninites and high-Mg andesites (*cf.* Sun and Nesbitt, 1978; Jenner, 1981; Hickey and Frey, 1982), and 'second stage' magnesian quartz tholeiites (*cf.* Duncan and Green, 1980a,b). Although picrites are presently unrecognized in the PBOC, the presence of rare Mg-rich cumulates (e.g. those containing $\text{Fo} > 90$, see Sections 5.2 and 5.3.1) suggest that picritic liquids did in fact play a role in its evolution. It is conceivable that the melts now represented by the PBOC intrusives and extrusives were ultimately derived from (?as) partial melts of precursors to the associated tectonized harzburgites, but the data available place few tangible constraints on this possibility (see later discussions).

TABLE 5.1

Major and Trace Element Analyses and Normative Mineralogy of Peridotites
from the Pigna Barney Ophiolitic Complex

	Tectonized Harzburgite		Olivine Orthopyroxenites		Cumulate Plagioclase-bearing Peridotites					
	\bar{x} (11)	s	489	509	472	500	499	510	458	501
SiO ₂	46.48	± 0.60	55.05	51.22	43.15	42.92	41.31	43.29	42.64	42.72
TiO ₂	0.01	-	0.02	0.03	0.03	0.02	0.01	0.02	0.03	0.02
Al ₂ O ₃	0.98	± 0.25	0.30	1.23	4.05	2.94	2.53	4.49	3.51	3.02
Cr ₂ O ₃	0.39	± 0.02	0.64	0.66	0.79	0.66	0.44	0.59	0.73	0.62
ΣFeO	7.56	± 0.40	6.56	8.51	10.86	12.22	13.61	11.96	12.96	11.64
NiO	0.33	± 0.02	0.11	0.17	0.19	0.28	0.25	0.21	0.22	0.24
MnO	0.13	± 0.02	0.16	0.21	0.20	0.18	0.17	0.21	0.22	0.26
MgO	43.68	± 0.98	36.62	36.01	37.15	40.79	40.95	36.22	38.33	41.25
CaO	0.14	± 0.12	0.28	1.43	3.38	0.07	0.04	3.05	1.23	0.05
Na ₂ O	0.03	± 0.01	0.04	0.06	0.08	0.04	0.04	0.08	0.08	0.04
K ₂ O	0.01	-	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
P ₂ O ₅	-	-	0.01	-	0.01	0.01	-	0.01	-	-
Total	99.74		99.80	99.54	99.91	100.14	99.32	100.13	100.01	99.87
ΣVol ¹	12.21	0.27	2.76	1.76	8.38	12.06	11.88	10.06	10.14	13.14
FeO ¹	1.24	0.39	5.20	7.49	5.55	2.35	2.75	4.18	5.57	1.66
Mg [†]	91.0	0.5	90.7	88.1	85.7	85.5	84.2	84.2	83.9	86.1
CATION NORM			E		E		E		E	
PL	-	-	-	-	8.8	6 ^C	6 ^C	10	7.4	6.5 ^C
CPX	-	-	0.3	-	6.3	-	-	3	-	-
OPX	35.7	3.9	86.0	71	14.4	15	8	18	18.0	12.5
OL	63.4	4.0	13.1	28	69.2	78	85	68	72.8	79.9
SP	0.8	0.3	0.6	0.7	1.3	1.2	0.8	1.0	1.8	1.1
TRACE ELEMENTS (ug/g)										
Na	218	90	295	453	643	275	229	562	613	328
K	76	27	71	76	163	70	85	104	117	108
Sr	<1	-	<1	<1	<1	<1	<1	4	<1	<1
Ti	100	34	124	203	219	114	81	130	153	109
Ni	2587	150	863	861	1485	2220	1970	1662	1751	1859
Co	117	11	82	89	138	127	180	138	155	156
V	42	13	21	91	72	38	23	51	62	31
Cr	2651	116	4389	4559	5383	4487	3004	4046	4937	4219
Cu	6	6	7	3	20	35	3	9	11	6
Zn	44	5	39	38	49	58	52	59	56	50
Sc	n.d.	n.d.	8	n.d.	21	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. Not determined

1 See Appendix G

 \bar{x} (11) Mean of 11 harzburgites (from Table B-1)

E Mineral chemistry estimated (see Appendix A)

C Norm adjusted to compensate for Ca loss (see Appendix A)

Mg[†] 100(Mg+Ni)/(Mg+Ni+ΣFe+Mn)

Major element analyses are

recalculated to original totals on a volatile-free basis. Trace element values are also recalculated on a volatile-free basis.

5.2 CUMULATE HARZBURGITE

5.2.1 Field Relations

In the northeastern corner of the Watchimbark Serpentinite (especially in the vicinity of GR710,919) rubbly outcrops of plagioclase-free cumulate harzburgite and rare discrete blocks of harzburgite tectonite are interspersed with highly schistose serpentinite. These lithologies are considerably more weathered than schistose serpentinites elsewhere around the margins of the Watchimbark Serpentinite and, by comparison, most other peridotites in the PBOC are relatively fresh. In fact, much of the central and northeastern portions of the Watchimbark Serpentinite are pale rusty-brown due to extensive oxidation and hydration of secondary magnetite. Because of this pervasive oxidation (which is probably the result of a palaeo-weathering event, see Section 5.3.3), primary peridotite textures are very difficult to recognize in outcrop and cumulate harzburgite may well be more widespread in the Watchimbark Serpentinite than is presently recognized. Comparable cumulate harzburgite has not been found elsewhere in the PBOC. However, minor tectonic blocks or pods of rather more Fe-rich plagioclase-bearing cumulate "harzburgites" do occur intermingled with disrupted olivine norites and schistose serpentinites at other localities in the PBOC. These appear to be rather localized in significance and they are described briefly in Section 5.3.2.

5.2.2 Petrography

Although most of the Watchimbark cumulate harzburgites are almost completely serpentinitized, evidence for their origin as magmatic cumulates is preserved as:

- (i) abundant bastites displaying embayed, lobate, cuspidiform and rare poikilitic habits (Plate 5.2C), and
- (ii) intergranular Cr-Al spinel euhedra which are quite distinctive texturally when compared with Cr-Al spinels in the PBOC tectonized harzburgites (Plate 5.2D, *cf.* Section 5.1.2).

The least-serpentinitized examples (e.g. 491, ~80% serpentinitized; 494, ~40% serpentinitized) display well-developed adcumulus textures (Plate 5.2E). Cumulus phases are:

- (i) Olivine; equigranular, $\leq 2\text{mm}$ and largely serpentinized
- (ii) Cr-Al spinel; euhedral to subhedral, 0.05-0.25 mm, pale tan to deep red-brown and often displaying semi-opaque internal patches and/or rims; intergranular and as small inclusions in olivine and orthopyroxene
- (iii) Orthopyroxene; subhedral prisms $\leq 4\text{mm}$ in length which are typically modified by irregular, optically continuous postcumulus overgrowths. Some display occasional blebs or abundant fine exsolution lamellae of Ca-rich pyroxene but the majority of orthopyroxene grains are optically and chemically homogeneous. Most of the larger orthopyroxene crystals display slight strain extinction, possibly in response to relatively late-stage tectonic disruption during final emplacement.

Almost all of the conspicuous cusped adcumulus and postcumulus growths consist of orthopyroxene, although in some samples (e.g. 491, 494) rare clinopyroxene does occur. Estimated pre-serpentinization modes for these rocks fall in the ranges: olivine ~50%-80%, orthopyroxene ~20%-50%, Cr-Al spinel ~0.5%-2%, \pm a trace of clinopyroxene. Olivine-rich types are perhaps the most abundant lithology, but more detailed sampling is necessary to assess this possibility. There is little evidence of mesoscopic or microscopic phase-layering in the samples collected, nor is any layering evident in the outcrops examined.

5.2.3 Mineral Chemistry

Cr-Al Spinel

Although many Cr-Al spinels in Watchimbark cumulate harzburgites display some optical heterogeneity (see Section 5.2.2) all analysed grains are chemically homogeneous. Outer opaque rims on some grains are hematite after secondary magnetite but internal semi-opaque areas are identical in composition to adjacent translucent areas, even in the relatively aluminous types. This is somewhat unusual as relatively aluminous Cr-Al-(Fe) spinels typically are quite transparent (e.g. Heinrich, 1965).

Cr-Al spinels in several Watchimbark cumulate harzburgites are

surprisingly Al-rich (Table C-10). These have Cr values comparable to, or lower than, many spinels in PBOC tectonized harzburgites (Fig. 5.3). On average, however, they do have significantly lower M values and slightly higher calculated Fe^{3+} contents than the latter (Figs 5.3,5.4). Cr-Al spinels in two samples (427 and 436) are significantly more Cr-rich than those cited above. Spinel in sample 427 are almost identical in composition to some Cr-Al spinels in the PBOC olivine norites (Figs 5.3,5.4) whereas those in sample 436 are exceptionally Cr-rich. The Cr values of the latter spinels approach the maximum Cr values displayed by spinels in stratiform intrusions (Fig. 5.3). In the PBOC, spinels with comparable Cr values occur only in tectonic blocks of olivine orthopyroxenite (see Section 5.3.1) and of sedimentary serpentinite (see Section 5.3.3).

Relict Silicates

Relicts of olivine and pyroxene occur only in samples 491 and 494. Representative analyses of these phases are listed in page 8 of Table C-2, and salient aspects of their chemistries are summarized below.

Olivine: Fo_{92-91} . NiO abundances (0.23%-0.33%) and Fo contents are within the range displayed by olivines in PBOC tectonized harzburgites (Table C-2).

Orthopyroxene: $En_{91.5-91}$. On average, CaO abundances are slightly higher than those of orthopyroxenes in the PBOC tectonized harzburgites (Fig. 5.5) but their respective Al_2O_3 (2.4%-2.8%) and Cr_2O_3 (0.3%-0.5%) abundances and mg values are comparable (Fig. 5.6).

Clinopyroxene: Cr-diopside. On average, these are slightly more Ca-rich and have slightly lower mg values (~94.2) than diopsides in the PBOC tectonized harzburgites (Fig. 5.5). They do, however, contain significantly more Al_2O_3 (2.7%-3.3%) and Cr_2O_3 (~1%) than diopsides in the tectonized harzburgites (Fig. 5.6).

Discussion

The extensive range of compositions found in these cumulate harzburgite spinels conceivably might reflect either some tectonic mixing of discrete intrusives, or extreme cryptic variation within a single,

subsequently disrupted intrusive. Because Cr is strongly partitioned into early-formed, relatively magnesian spinels (Dickey and Yoder, 1972), the fact that the most Cr-rich spinels in these cumulates have the lowest M values (Table C-10) would tend to favour the former suggestion. However, such cryptic variation is theoretically possible if a single magma chamber, already fractionated, was periodically replenished with relatively unfractionated (Cr-rich) melts (*cf.* O'Hara, 1977; O'Hara and Mathews, 1981). The chemistries of primary silicates coexisting with these Cr-rich spinels could possibly resolve this question, but unfortunately these phases are now completely serpentinized. On the other hand, detrital spinels which are most probably derived from the Watchimbark Serpentinite display extreme compositional variation (see Section 5.3.3) suggesting that this peridotite may have had a complex magmatic and/or metamorphic history.

Spinel in samples 428, 429, 491 and 494 are significantly more Al-rich than might be anticipated by comparison with those in analogous cumulates from layered intrusions (see Fig. 5.3d). Spinel with comparably low Cr values do not appear to crystallize from basaltic melts at elevated pressures (Sigurdsson and Schilling, 1976; Fisk and Bence, 1980). However, detailed experimental data relating spinel compositions and melt compositions at elevated pressures are lacking. Pyroxenes coexisting with these Watchimbark spinels have relatively low Al^{VI} contents (Fig. 5.7) and as such they probably crystallized at relatively low pressures. Also, because late-stage clinopyroxenes are significantly Cr-rich (see above), it is unlikely that the parent melt(s) from which the Watchimbark Al-rich spinels crystallized was significantly depleted in Cr.

Irvine (1977) has shown experimentally that, at low pressures in the system $CaO-MgO-Al_2O_3-Cr_2O_3-SiO_2$, the Cr values of liquidus spinels reflect the proximity of the parent melt to the $MgAl_2O_4$ -spinel liquidus volume. With falling temperature in MORB-like melts (i.e. relatively aluminous melts) the Cr value of crystallizing spinel decreases rapidly (to 37 or less) as the plagioclase liquidus is approached, and then increases as plagioclase begins to crystallize. Although early-crystallized plagioclase (or its alteration products) has not been found in the Watchimbark cumulates, it must be emphasized that these rocks have not been extensively sampled and the possibility that the spinels crystallized

from a relatively aluminous melt ($M \approx 76$) cannot be entirely rejected.

5.2.4 Whole-rock Chemistry

The only Watchimbark cumulate harzburgite chemically analysed is that containing the most Cr-rich spinels (sample 434, Table 5.2, analysis 5). Initially this sample was analysed in conjunction with two less-oxidized samples of schistose Watchimbark Serpentinite for a comparison with nearby sedimentary serpentinites (see Section 5.3.5). For this comparison, sample 434 was chosen to represent the highly altered sections of the Watchimbark Serpentinite. It is highly oxidized ($\text{Fe}^{3+}/\Sigma\text{Fe} = 0.99$) and slightly sheared, and its present chemistry is probably a very poor indication of its pristine composition. In particular, the anomalously low Al_2O_3 and Cr_2O_3 contents of this sample are difficult to explain. Substantial highly weathered portions of this sample were removed prior to crushing for analysis and this might have introduced a significant sampling bias, especially with respect to spinel. Obviously, the petrological significance of this analysis cannot be assessed with any confidence.

5.3 MISCELLANEOUS ULTRAMAFIC LITHOLOGIES

As presently exposed, the rocks described in this section are relatively minor components of the PBOC. They occur only as discrete tectonic blocks which either form inclusions in highly schistose serpentinite, or appear to have weathered out of schistose serpentinite. These blocks are typically lozenge- or prism-shaped and range in length from 1 metre or less (*cf.* Plate 5.1E) to several tens of metres (e.g. plagioclase-bearing peridotites at locality 9). However, the larger blocks are usually disaggregated and may crop out intermittently. Because extreme tectonic disruption has completely obliterated the original field relations of these rocks, their initial origin(s) and volumetric significance in the PBOC are poorly known. Consequently this section is largely descriptive. It is divided into three sub-sections (1-3), the first and second of which deal with plagioclase-free and plagioclase-bearing igneous lithologies respectively, and the third describes sedimentary rocks derived almost entirely from a spectrum of PBOC ultramafic lithologies. These groupings are termed:

1. Cumulate peridotites
2. Cumulate plagioclase-bearing peridotites
3. Sedimentary serpentinite

Of these three groups, only the plagioclase-bearing peridotite inclusions are widely distributed throughout the PBOC serpentinites. A brief discussion of groups 1 and 2 precedes the description of group 3.

5.3.1 Cumulate Peridotites

This group consists of three tectonic blocks of relatively small dimensions (see below). Two of these [(i) and (ii)] are olivine orthopyroxenites (samples 489 and 509 respectively) and the third (iii) is an amphibole-bearing harzburgite (sample 488). These have been examined in varying detail and are described separately below.

(i) Olivine Orthopyroxenite (sample 489, GR 7225,8648)

This forms a bouldery outcrop (5m x 4m x 1.5m) which appears to be residual following the erosion of surrounding schistose serpentinite. Textural and mineralogical evidence (see below) indicate that this

lithology is strictly magmatic and not a variant of the PBOC tectonized harzburgites.

This olivine orthopyroxenite principally consists of extraordinarily large and irregularly-oriented crystals of remarkably fresh enstatite ($\text{En}_{90.9}$) ranging up to at least 16 cm in length (Plate 5.2F). These enstatites display coarse adcumulus textures. They poikilitically enclose abundant small (<0.3 mm) opaque Cr-Al spinel euhedra, and small aggregates (up to several cm) and discrete subhedral to euhedral crystals (up to 5 mm) of partially serpentinized olivine ($\text{Fo}_{90.4}$). Highly serpentinized olivine also forms occasional irregularly-shaped intergranular patches which may contain minor talc and tremolite. Talc-tremolite assemblages also occur intermittently along microshears and cleavage planes in the enstatite crystals. Apart from fine exsolution lamellae in the enstatites, this rock is devoid of Ca-rich pyroxene.

Rare fragmented tabular layers of completely serpentinized dunite occur in parts of the outcrop (Plate 5.2G). These dunite layers range from 5 cm - 10 cm in thickness and their contacts with the enclosing olivine orthopyroxenite are sharp but slightly wavy. The original dunite was much finer-grained (3 mm - 5 mm, sample 534) than the associated olivine orthopyroxenite. No chemical data are available for these dunitic rocks.

Mineral Chemistry

Forsterites ($\text{Fo}_{90.4}$) in the olivine orthopyroxenite are slightly less magnesian and depleted in Ni (average NiO = 0.21 wt%) than those in the PBOC tectonized harzburgites (Table C-2, pages 8 and 9). Enstatites ($\text{En}_{90.9}$) in the olivine orthopyroxenite are also slightly less magnesian than enstatites in the tectonized harzburgites (Table C-2) but, compared with the latter, they contain significantly less Al_2O_3 , Cr_2O_3 and, to a lesser extent, CaO (Figs 5.5,5.6). In fact they contain significantly less Al_2O_3 than orthopyroxenes in all other PBOC mafic and ultramafic rocks (Figs 5.6,5.7) and, indeed, they contain less Al_2O_3 than most other naturally-occurring igneous enstatites (*cf.* Deer *et al.* 1978). Enstatites in this PBOC olivine orthopyroxenite do, however, contain abundant fine exsolution lamellae of Ca-rich pyroxene and, because no other primary Ca-bearing phases are present, the whole-rock CaO abundance

(~0.3 wt %, see Table 5.1) probably reflects the actual CaO contents of these enstatites more closely than the microprobe analyses (0.2% CaO). Nevertheless, they are strongly depleted in CaO relative to orthopyroxenes in all other PBOC cumulates (Fig. 5.5).

Euhedral Cr-Al spinel inclusions in the coexisting enstatites and forsterites are uniform in chemical composition. They are exceedingly Cr-rich (Figs 5.3,5.4) and, considering the relatively high M values of the coexisting silicates, they are surprisingly Mg-poor (Figs 5.3, D-1). These spinels are also slightly enriched in Ti and significantly enriched in calculated Fe^{3+} relative to those in the associated tectonized harzburgites. In these aspects of their chemistry they resemble Cr-Al spinels in most of the more Mg-rich PBOC plagioclase-bearing cumulates (Fig. 5.3).

Whole-rock Chemistry

The chemistry of this olivine orthopyroxenite clearly reflects the high modal orthopyroxene (Table 5.1, sample 489), the small amount of CPX in the CATION norm (0.3%) indicating a Ca-rich pyroxene component (see above). In common with other PBOC cumulate peridotites, this olivine orthopyroxenite contains significantly less NiO and more Cr_2O_3 than the PBOC tectonized harzburgites but, by comparison, it is surprisingly depleted in Al_2O_3 and CaO (considering that some Ca is undoubtedly lost during the serpentinization of many of the other PBOC peridotites and perhaps some of the mafic cumulates; see Appendix A). With the exception of some layered olivine orthopyroxenites from the orthopyroxene-rich Adamsfield Ultramafic Complex, Tasmania (Varne and Brown, 1978) and orthopyroxenite dykes in the Papuan Ultramafic Belt (Jaques and Chappell, 1980), igneous olivine (-bearing) orthopyroxenites of comparable 'depleted' chemical composition are exceedingly rare in ophiolitic assemblages and, for that matter, in layered intrusions (see references listed in Table 3.2).

Assuming olivine and orthopyroxene represent near-liquidus phases, their chemistries suggest that the olivine orthopyroxenite is a cumulate from a relatively Mg-rich melt ($M \sim 75$) which was slightly depleted in Ni and strongly depleted in Al and Ca relative to most naturally-occurring melts with comparable M values. Unfortunately, chemical data are not available for the associated serpentinized dunitic horizons as these might represent fragments of complementary relatively Ni-rich cumulates.

(ii) Olivine Orthopyroxenite (sample 509, CR 6814,8119)

This lithology forms a rubbly outcrop over an area of several tens of square metres and is surrounded by poorly-outcropping schistose serpentinite. It is a slightly serpentinitized, medium-grained orthopyroxene (~70%) + olivine (~30%) + Cr-Al spinel (~1%) adcumulate. Irregularly-shaped orthopyroxene is the principal cumulus phase and these grains typically have dimensions in the range 2 mm - 4 mm. Although the cumulus orthopyroxenes do contain some small (< 0.2 mm) opaque Cr-Al spinel euhedra, the latter typically display an intergranular habit where, on average, they are slightly larger (< 0.3 mm) and are included in intergranular olivine or orthopyroxene. From these textural relations it would appear that the crystallization sequence in this olivine orthopyroxenite was: opx, opx + Cr-Al spinel, opx + Cr-Al spinel + olivine. This unusual crystallization sequence (opx before olivine) might suggest crystallization from an *en*-rich, *di*-poor basaltic melt at elevated pressures, possibly greater than 10 kb (*cf.* Green *et al.*, 1979). However, the Cr-Al spinels in this rock are opaque and hence possibly Al-poor (mineral phases in this rock have not been analysed). The relatively low Al₂O₃ content of the bulk-rock (1.23% Al₂O₃; Table 5.1) also suggests that the orthopyroxenes are relatively Al-poor. These characteristics are possibly inconsistent with crystallization at elevated pressures (e.g. Jaques and Green, 1980) and perhaps a low pressure mode of origin might also be feasible (see discussion below).

Whole-rock Chemistry

Compared with olivine orthopyroxenite (i) described above, this example (ii) is significantly enriched in Fe ($Mg^* = 88.1$), Al, Ca and V, and depleted in Si (Table 5.1). The two orthopyroxenites are similar to most other aspects of their chemistry but their textural differences are sufficiently marked to suggest somewhat different genetic histories.

(iii) Amphibole-bearing Harzburgite (sample 488, GR 7218,8690)

This is the only ophiolitic member of the PBOC found to contain primary amphibole. It crops out poorly amongst schistose serpentinite, possibly over an area of several tens of square metres. An approximate mode is 50% olivine, 30% orthopyroxene, 20% amphibole and a trace of Cr-Al spinel. Orthopyroxene grains are relatively large (up to 1 cm),

$$Mg^* = (Mg+Ni)/(Mg+Ni+Fe^{2+}+Fe^{3+}+Mn); \text{ see Appendix A.}$$

irregularly-shaped, and contain abundant olivine inclusions. Occasional deep brown Cr-Al spinels are also included in these poikilitic orthopyroxenes. The finer-grained (< 2 mm) matrix consists of euhedral to anhedral olivine (largely serpentized), orthopyroxene, amphibole and Cr-Al spinel. The amphiboles, in particular, are commonly euhedral (Plate 5.2H) and appear to be magmatic.

Mineral Chemistry

All primary phases are chemically homogeneous and display negligible grain-to-grain variation. Olivine is relatively Mg-rich ($\text{Fo}_{89.2}$), and it is unusually Ni-rich (0.44% NiO) by comparison with other PBOC olivines (Table C-2). Also, relative to other PBOC peridotite cumulates, orthopyroxenes ($\text{En}_{89.3}$) in this amphibole-bearing peridotite are depleted in Ca and Cr (Figs 5.5, 5.6) and the spinels are also relatively Cr-poor (Fig. 5.3d). The amphiboles are Cr-rich tschermakitic hornblendes (analysis 1, Table C-6) with similar *mg* values to the coexisting silicates. Although highly aluminous, the amphibole contains only moderate Al^{VI} and, if the $\text{Al}^{\text{VI}}:\text{Si}$ diagram of Raase (1974) is applicable to magmatic hornblendes, they might have crystallized at relatively low pressures (< 5 kb, Fig. 5.8). However, pargasitic to tschermakitic hornblendes can also crystallize from hydrous, mantle-derived melts at pressures up to 25 kbar (Mysen and Boettcher, 1975) and their tschermakitic component may be more strongly influenced by temperature and bulk compositional controls than by pressure alone (Mysen and Boettcher, 1976).

The bulk chemistry of this amphibole-bearing peridotite has not been determined but the chemistry of its constituent amphiboles indicates that it is enriched in Al, Ca and Na relative to PBOC peridotites derived from similarly Mg-rich melts ($M \sim 71$). The presence of significant primary amphibole indicates that the parent melt was anomalously hydrous compared with all other envisaged PBOC parental melts. This presumably depressed the plagioclase liquidus (e.g. Hamilton *et al.*, 1964) and led to the entry of *ab* and *an* components into relatively sodic (1.5% Na_2O ; Table C-6) tschermakitic hornblende formed relatively early in the overall crystallization history of the melt, possibly by reaction between olivine and the melt (e.g. Anderson, 1980). From the available data it is not possible to assess whether this rock was ultimately derived by

partial melting under hydrous conditions of a relatively fertile mantle source. For the present, this lithology is tentatively included as an ophiolitic member of the PBOC, and is believed to be a rare hydrous variant of the PBOC igneous peridotite assemblage.

5.3.2 Cumulate Plagioclase-bearing Peridotites

Dunitic and harzburgite blocks containing conspicuous white hydrogarnet \pm prehnite and/or cryptocrystalline aluminous phases, all pseudomorphing plagioclase, occur in schistose serpentinite at numerous localities in the PBOC (e.g. 3,4,5,6,8,9,11,12 see Fig. B-1). For the most part these rocks are highly serpentinized but relict textures and bulk chemistry indicate that they were originally relatively olivine-rich (see CATION norms, Table 5.1). Some localized variants (melatroctolites) contain up to 25% "plagioclase" and samples 478 and 482, for example, contain approximately 20% PL (Table B-5). In all of these plagioclase-bearing peridotites "plagioclase" occurs as irregularly-shaped or elongate grains which commonly display embayed, lobate and cuspid margins (Plate 5.2I,J). These morphologies suggest that much of the plagioclase is late-stage or postcumulus. Most of the harzburgitic types and some of the dunitic types also contain a trace of late-crystallizing Ca-rich pyroxene.

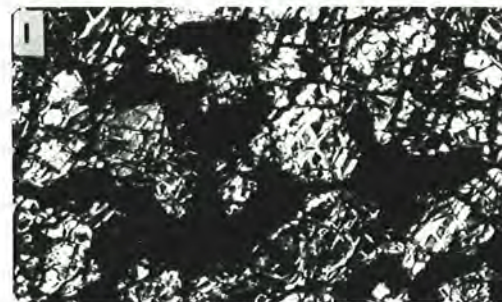
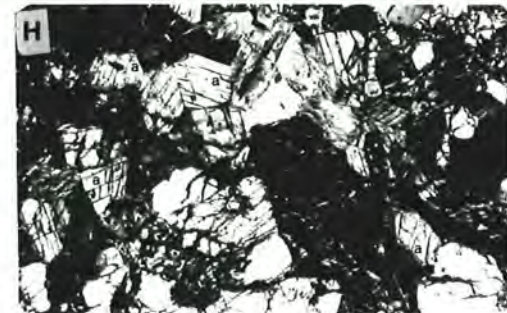
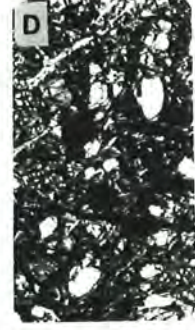
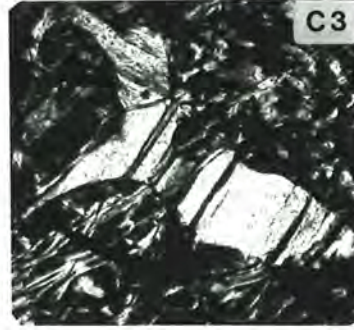
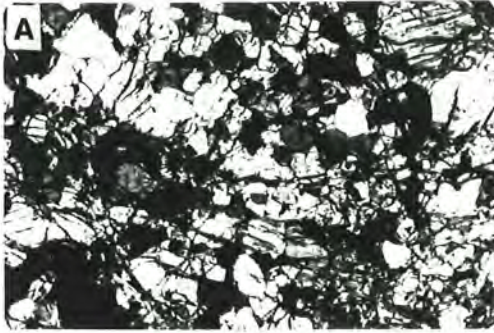
Mineral Chemistry

Olivines in the PBOC plagioclase-bearing peridotites range in composition from Fo₈₈ - Fo₈₄. NiO abundances in these olivines range from 0.33% to less than 1% (samples 464 and 458 respectively) and correlate poorly with Fo (see Table C-2). With some exceptions (e.g. 468, 484) the overall chemistries of Cr-Al spinels in these peridotites are comparable to spinels with similar *M* values in the PBOC olivine norites (Fig. 5.3). Clinopyroxenes in these peridotites are commonly depleted in Ca relative to analogous phases in the olivine norites (Fig. 5.5), but pyroxenes in both rock-types are similar in other aspects of their chemistries (Figs 5.6,5.7). Si:Al^{VI} relations in secondary amphiboles in one of the plagioclase-bearing peridotites (485, Fig. 5.8) suggest that at least some of the plagioclase-bearing peridotites might have experienced secondary alteration at slightly higher pressures than prevailed during analogous alteration in the olivine norites. This

PLATE 5.2

- A. PBOC tectonized harzburgite (PBOCTH). Well-developed neoblastic texture in relatively fresh tectonized harzburgite (sample 490). White grains are predominantly orthopyroxene + minor clinopyroxene, olivine is largely serpentinized (e.g. in lower right quadrant), spinel is black [mag. = 35x , crossed nicols].
- B. PBOCTH. Bastite (pale) pseudomorphing highly cusped intergranular orthopyroxene in olivine-rich (serpentinized) patches. [sample 493, mag. = 90x , crossed nicols].
- C1-3. Bastites (pale) displaying embayed, lobate, cuspidiform and sub-poikilitic habits in PBOC cumulate harzburgites. Note deformation twin in C-1 bastite. [sample 427 (C1,C3) and sample 429 (C2) , mag. = 22x , crossed nicols].
- D. Euhedral Cr-Al spinel (black, centre) in PBOC cumulate harzburgite. Remainder of field of view is partially serpentinized olivine [sample 494, mag. = 35x , crossed nicols].
- E. Adcumulus growths (and ? postcumulus 'outgrowths', see footnote page 206) on enstatites (pale) in PBOC cumulate harzburgite. Predominantly dark areas are partially serpentinized olivine [sample 494, mag.= 35x , crossed nicols].
- F. Large irregularly-oriented enstatite crystals in PBOC olivine orthopyroxenite. Prominent cleavages delineate individual grains (two outlined). Pen is 14.5cm in length [GR7225,8648].
- G. Completely serpentinized dunite layer (d) in PBOC olivine orthopyroxenite (largely covered by moss) [GR7225,8648].
- H. Euhedral - subhedral (?cumulus) magnesiohornblende (a) in PBOC amphibole-bearing harzburgite. Pale grains are orthopyroxene, darker areas are partially serpentinized olivine. [sample 488, mag. = 22x , crossed nicols].
- I. Highly cusped intergranular hydrogarnet (black) pseudomorphing plagioclase in PBOC plagioclase-bearing peridotite. Remainder of field of view is partially serpentinized cumulus olivine [sample 472, mag. = 22x , crossed nicols].
- J. As above [sample 486, mag. = 22x , crossed nicols].

PLATE 5·2



interpretation is broadly consistent with the present occurrences of most olivine norites at relatively higher structural levels than the plagioclase-bearing peridotites (Fig. 5.1). Most pyroxenes in both rock-types have similar Al^{IV}/Al^{VI} ratios and Al^{VI} contents (Fig. 5.7) although these parameters are possibly less sensitive to relatively small pressure variations than are amphibole Al-distributions (see Sections 3.4.1.3, 5.1.3).

Whole-rock Chemistry

Chemical analyses of five PBOC plagioclase-bearing peridotites are listed in Table 5.1 and analyses of four other examples are listed in Appendix B (Table B-1, analyses 4 and 5; Table B-5, analyses 1 and 8). The more highly serpentinized, originally olivine-rich examples (e.g. 499, 500 and 501, Table 5.1) obviously have lost Ca during alteration. Although olivine-rich rocks such as the PBOC plagioclase-bearing peridotites are susceptible to Mg and/or Si mobility during serpentinization (see Appendix A), at least some of the PBOC examples display close correlations between host-olivine Mg^* values and have low $Fe':Mg'$, $Fe':Si$ and $Mg':Si$ alteration factors (e.g. samples 458, 473, 474, 482; Tables A-1 and C-1). Sample 486 does, however, appear to have been depleted in Si during serpentinization (Table A-1).

With decreasing Fo contents of their olivines, (i.e. decreasing M values of the liquids from which they crystallized) the least-altered PBOC plagioclase-bearing peridotites (458, 472, 473, 482, 510) display overall "trends" of decreasing Al_2O_3 and CaO and increasing Ni, Cr and possibly MgO. These trends are not easily reconciled with simple progressive fractional crystallization trends displayed by a single magma or a series of more-or-less identical magmas and thus they suggest that the PBOC plagioclase-bearing peridotite blocks were derived from a variety of originally discrete intrusives. For the most part, however, the chemistries of samples 472 and 473 (analyses 3 and 4, Table B-4) as displayed in Figure 5.9 suggest that they might be genetically related to olivine norites at localities 3 and 11 (see discussion in Section 5.4.4), or at least members of a cumulate series closely related to these olivine norites.