Petrology and geochemistry of the mantle-sequence peridotite of the Darvel Bay Ophiolite, Sabah, Malaysia

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Abstract: The mantle-sequence peridotites of the Darvel Bay Ophiolite are represented predominantly by depleted harzburgites. These rocks are characterised by mineral chemistry of spinel X_{Cr} = 39, X_{Mg} = 61; olivine Fo = 90 and orthopyroxene (Opx) En = 88–90, Al_2O_3 - 3.4 wt.%, CaO = 1.8 wt.%), suggesting a mantle residue which has undergone a moderate to high degree of a previously depleted source (oceanic upper mantle). Composition of spinel X_{Cr}-Opx (Al_2O_3) and bulk-chemistry indicate ~ 20% partial melting of this source. The Darvel Bay harzburgites are less depleted (refractory) mantle than the harzburgites of Oman, Papuan and Halmahera Ophiolites. The Darvel Bay harzburgites represent a supra-subduction zone (SSZ)-ophiolite type, supported by bulk-rock chemistry of TiO_2 contents. The tectonic evolution model of the Darvel bay Ophiolite is much easier to explain using a model of supra-subduction zone (SSZ) ophiolite accreting new material in a forearc region.

INTRODUCTION

Beneath the Crustal Sequence (which comprises the Cumulate Sequence, the High Level Intrusives, the Sheeted Dyke Complex and the Extrusive Sequence) of the igneous stratigraphy of a complete ophiolite lies the Mantle Sequence, consisting of variable proportions of harzburgite, lherzolite and pods of dunite (e.g. Moores, 1982; Browning, 1984). This sequence usually has a tectonite fabric (e.g. Allen, 1975; Anonymous, 1972; Coleman, 1977; Gass, 1980), and is separated from the overlying crustal sequence by a 'Petrological Moho' (e.g. Malpas, 1978). No 'Moho' can be mapped in the Darvel Bay region, this is because of poor exposure. However, Hutchison (1978) interpreted that the boundary should occur in the area of Pulau Sakar and Pulau Tabauwan. The mantle sequence in Darvel Bay area (Fig. 1) is predominantly harzburgite and the rocks record a particularly high degree of mantle partial melting, more than that required to create a mid-oceanic ridge basaltic (MORB) magma (e.g. Green et al., 1979; Gass, 1980; Boudier and Coleman, 1981). These rocks also widely interpreted as mantle residuals after (or depleted by) the extraction of MORB-magma generated by upper mantle partial melting.

FIELD DESCRIPTIONS

The harzburgite has the largest outcrop of the area occupied by the Darvel Bay Complex,

particularly on the mainland (Shariff, 1993). No lherzolite has been observed in the study area. The harzburgite forms an east-west elongated body about 20 miles long and up to 4 miles wide (Fig. 1). Harzburgite has been observed in the Silam Quarry (sample SQ), in the southern part of Pulau Sakar (sample PS8) and in the northern part of Pulau Tabauwan (sample TI2). Most of the harzburgite rocks are serpentinized to varying degrees, especially at the margin of the body. These rocks were observed along the Jalan Danum at km 15 (Localities JD1, JD4; Shariff, 1993), along Jalan Silam at km 133, north of Silam Timber Camp Check Point (Localities JS4, JS5, JS10; Shariff, 1993), along the coastline near Silam Timber Camp and Tanjung Silam (Localities JSL, TS; Sariff, 1993), near the Silam Dam (Locality ES; Shariff, 1993) and around Sungai Tingkayu (Locality TK; Shariff, 1993). The rocks are dark blue in colour, sometimes black, with waxy or polished surfaces, brown colour on weathered exposures, and locally sheared and/ or foliated.

Serpentinization of harzburgite is prevalent and can be very extensive, so that the primary phases (olivine, orthopyroxene) are partly and/or completely replaced by serpentine minerals and spinel is the only preserved primary phase. No igneous layering and/or banding was seen in the harzburgites, probably due to the extensive serpentinisation of the rocks. Sometimes the rocks have a blocky, rectilinear, jointing pattern in outcrop and are dominantly olive green in colour, with lesser dark

porphyroblast orthopyroxene and occasionally with shiny, dark blue chromite crystals. In the exposures along the coast south of Pulau Sakar the serpentinized harzburgite has been cut by several shear zones with a sinistral sense of movement and trending nearly E-W (Plates 3-2A and B; Shariff, 1993). In several localities such as KS11, JS5, JS10–11 and ES the harzburgite body has been cut by gabbro pegmatite dykes (Shariff, 1993). On an outcrop scale the dykes show a variation in colour from pale brown to darker brown and vary in width from 40 cm to 1.2 m. These dykes are very coarse-grained with minerals between 1.0 to 4.0 cm. No chilled margins are associated with these dykes. This indicates that the dykes were intruded into the peridotite harzburgite while the latter was still hot. The dykes generally trend E-W with dips always steeply and/or nearly vertical to the south, sometimes to the north.
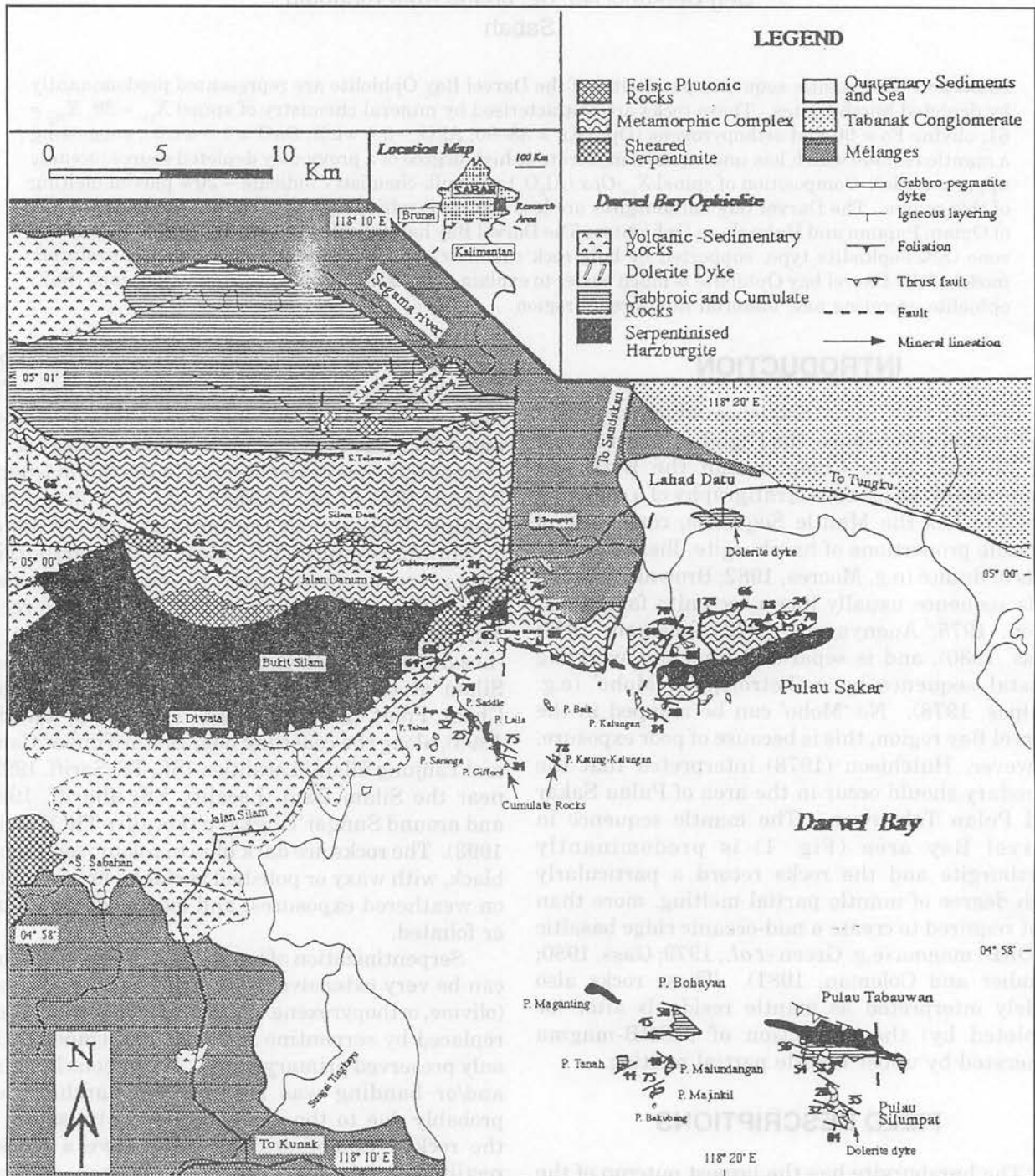

Figure 1. Simplified geological map of the Darvel Bay Complex, Sabah, Malaysia.

PETROGRAPHY

Rock Texture

The harzburgites are strongly serpentinized, with serpentine minerals showing typical net, honeycomb or mesh texture (Plate 3-5A; Shariff, 1993) and bladed mat-textures (Plates 3-5B and 3-6; Shariff, 1993) commonly making up as much as 90% of the rock (e.g. samples JS4, JS4b, JD5, ES, ES1, ES2, JS10; Shariff, 1993). However, some of the samples are still fresh, confirming these rocks as being dominantly harzburgite (Plates 3-7 and 3-8; Shariff, 1993). The fresh harzburgite generally shows an idiomorphic granular and/or neoblast to porphyroblastic textures (Plate 3-8; Shariff, 1993). However, relics of flow fabrics (? tectonite foliation) were observed in harzburgite which is exposed in the northern part of Pulau Tabauwan. These fabrics are defined by the alignment of chromites and/or magnetites (Plate 3-9A; Shariff, 1993). Sometimes, cataclastic textures, due to tectonism, are present in the serpentinites (Plates 3-9B and 3-10; Shariff, 1993).

Mineral Assemblages

The Darvel Bay harzburgite consists of between 75 and 85% modal olivine, with olivine grains averaging 1 to 3 mm in size, but rarely reaching 10 mm (Shariff, 1993). The olivine grains are usually subhedral. In most rocks, the olivine is partly or completely altered to serpentine. In some grains alteration is accompanied by sub-rounded patches of magnetite and chromite. Olivine and/or its alteration product may form up to 75–85% of the rock. Sometimes, porphyroblastic olivines with undulose extinction are common in the rocks in which serpentinisation is not complete.

Orthopyroxenes display a subhedral and prismatic shape. Orthopyroxene may constitute up to 10% of the rock ranging up to 7 mm in size. Orthopyroxenes commonly occur as porphyroblasts, and contain deformed cleavage planes and exsolution lamellae and often show undulose extinction.

Harzburgites are mostly free of clinopyroxene, although some samples contain up to 2 modal % with grains up to 1 mm across. Individual clinopyroxene are sometimes clustered around the boundaries of larger orthopyroxene grains. This is thought to be largely a result of a sub-solidus granule exsolution process (Hodges and Papike, 1976; Lindsley and Anderson, 1983).

Chrome-spinel ranges up to 4 mm and up to 2 modal %. Spinels from the mantle sequence samples in the present study have a dark-brownish colour (Shariff, 1993). They occur as small anhedral grains, parallel, or slightly oblique (10–20°) to the tectonite fabrics. In sample SX, the spinel grains have been altered and replaced by a dark-brownish opaque mineral, may be ferritchromit (Fe^{3+}-rich secondary product), which is strongly depleted in Mg and Al, and relatively enriched in Cr (e.g. Miller, 1953; Engin and Aucott, 1971; Ahmed and Hall, 1984). Sometimes, these spinels were seen associated with pale-green chlorites. Kitahara et al. (1966) suggested that the occurrence of altered spinel (ferritchromit) which is associated with chlorite indicate that it was formed above the upper stability limit of serpentine, above 570°C at 10 kbar water pressure. Major elements Al_2O_3 and MgO which are released from the alteration of spinel result in: (1) the alteration of serpentine to tremolitic amphibole (Engin and Aucott, 1971), (2) the formation of interleaved serpentine and chlorite (Shen et al., 1988), and (3) the alteration of serpentine to bluish-grey chlorite (Ahmed and Hall, 1984).

Accessory magnetite occurs as intergranular euhedral grains and as inclusions within olivine and pyroxene, and may constitute up to 5% of the rock. Fibrous chrysotile and platy antigorite occur in most harzburgites, as alteration products of olivine and pyroxene, forming intergrowth texture.

Amphibole and chlorite are also seen in the serpentinized harzburgite. Amphibole (tremolite) occurs as fibrous and prismatic grains, sometimes diamond shaped. They are colourless to pale green and may constitute between 5 to 7% of the rocks. Some of the tremolite shows typical 120° cleavage (samples ES, JS10). Chlorite also occurs with fibrous and prismatic habits and may form mineral aggregates with a pale green colour.

ANALYTICAL METHODS

Chemical compositions of mineral phases from the Darvel Bay peridotites were analysed on the electron microprobe (JEOL Superprobe 733) at Birkbeck College, coupled with a Link Analytical Systems model 860 energy dispersive system; correction procedures were carried out using a full ZAF correction program supplied by Link. An accelerating voltage of 10 kV and probe current of 10 nA were used, and minimum beam spot sizes are 1.0 µm. Calibration is against natural mineral standards and during analysis cobalt is used as the primary reference standard. Elements routinely analysed were Si, Ti, Al, Fe, Mg, Mn, Ca, Na, K, Cr and Ni.

Further data processing (recalculated formula) was achieved through the use of a suite of programs developed by Dr. Robert Hall (University College of London). Mineral formula proportions were

calculated on the basis of: 4(O) — Olivine; 16(O) — Spinel; 6(O) — Pyroxenes; 24(O) — Garnets; 23(O) — Amphiboles; 32(O) — Feldspar; 25(O) — Epidote; 9(O) — Serpentine; 22(O) — Mica; 28(O) — Chlorite. Cation ratios are abbreviated as follows: X_{Mg} = Mg/(Mg + Fe^{2+}) and X_{Cr} = Cr/(Cr + Al).

Bulk-rock geochemistry were analysed using a Philips PW1480 XRF spectrometer at Royal Holloway University of London and are presented on a volatile-free basis normalised to 100% totals for major elements (Thirlwall and Marriner, 1986). Approximate errors (2σ counting statistics) are ± 1 ppm for most elements, ± 0.2 ppm for Nb, ± 0.4 ppm for Rb and Y, ± 1.5 ppm for La and Ce, ± 2 ppm for Cu and Zn, ± 3 ppm for Ba, ± 6 ppm for Cr and ± 50 ppm for Cl.

MINERAL CHEMISTRY

Chemical compositions of primary mineral phases of the Darvel Bay harzburgite (samples SX, SQ1) were determined by the electron probe microanalyzer, JEOL SUPERPROBE 733 at Birkbeck College, University of London. Detailed descriptions of analytical techniques were given in Appendix 1-1 (Shariff, 1993).

Cation ratios are abbreviated as follows; X_{Mg} = Mg/(Mg + Fe^{2+}) and X_{Cr} = Cr/(Cr + Al). Chemical compositions of constituent minerals of the studied samples are given in Appendix 3-1 (Shariff, 1993).

Olivine

Olivines are unzoned and have an average Fo content of 90.4 (n = 8) (Table 1). The average X_{Mg} of olivine falls in a relatively narrow range between 0.894–0.908. The NiO content of olivine is always below microprobe detection limit. MnO contents of olivine reach 0.21 wt.% with average of 0.20 (n = 10). MnO shows a weak negative correlation with Fo, reflects the parallel substitution of Mn for Fe in the olivine lattice.

Orthopyroxene

Orthopyroxene is unzoned. On the standard pyroxene quadrilateral (Fig. 2), orthopyroxenes are between bronzite and enstatite $En_{82-90}Fs_{0-8}Wo_{1-10}$ and are very pale brown in thin section. Orthopyroxene rarely contains small exsolution 'blebs' and thin lamellae of Ca-rich pyroxene along the (100) crystallographic planes. CaO contents are very variable in orthopyroxenes (Fig. 3A). This variation is seen even within individual rocks. This could be in part due to sub-microscopic clinopyroxene exsolution lamellae. From Figure 3A CaO concentrations show a negative correlation with the En composition for the orthopyroxene which have the same features to those of the Oman

and Vourinos Ophiolites. According to Coleman (1977), nearly all the CaO reported in ophiolite mantle sequence orthopyroxenes derive from exsolution lamellae of clinopyroxene. Al_2O_3 contents of the orthopyroxene in the Darvel Bay harzburgite are very high compared with Oman and Vourinos orthopyroxenes (Fig. 3B). This suggests that *the* Darvel bay harzburgite represents less depleted mantle rocks relative to the Oman and Vourinos Ophiolites (Menzies, 1975, 1984).

Orthopyroxene is more magnesian, with an average X_{Mg} of 0.915 (n = 8) compared to 0.903 (n = 8) in the olivine. The difference of X_{Mg} values is due to the temperature-dependant Mg-Fe partitioning between orthopyroxene and olivine (Obata *et al.*, 1974). A strong positive correlation is shown between Al_2O_3 and Cr_2O_3 in the orthopyroxene (Shariff, 1993) suggesting Cr substitution in octahedral sites balancing the presence of Al in tetrahedral pyroxene sites (Deer *et al.*, 1966). Na_2O never occurs at a microprobe-detectable level in harzburgite orthopyroxene. CaO/Al_2O_3 ratios and Al_2O_3 contents of orthopyroxene also show a positive correlation with the X_{Mg} (Shariff, 1993), again suggesting that the charge balance is maintained by a $CaCrAlSiO_6$-type substitution, rather than by one such as $NaAlSi_2O_6$ (Deer *et al.*, 1992).

Clinopyroxene

Clinopyroxene are augite to subcalcic augite, according to Deer *et al.* (1966, 1992) nomenclature, with average composition $En_{69}Fs_3Wo_{28}$ (Fig. 2). They are lower in Cr_2O_3 and Al_2O_3 than their co-existing orthopyroxene but show higher X_{Mg} (average 0.958) (Table 1). TiO_2 is always below microprobe detectable level. Na_2O is about 0.55 wt.% and 0.04 mol%. Compared to the Halmahera harzburgite, the Darvel Bay clinopyroxenes are lower in Cr_2O_3 concentrations, but higher in Al_2O_3. X_{Mg} of Darvel Bay clinopyroxene is almost identical with X_{Mg} of Halmahera clinopyroxene. The X_{Mg} of clinopyroxene harzburgite value is slightly higher than the clinopyroxene of Halmahera lherzolite.

Spinel

Spinels are optically unzoned and have a dark reddish brown colour. Spinel varies in Fe^{3+} from 3.21 to 3.93 wt.%, suggesting that the Darvel Bay spinels probably formed under conditions of low fO_2 (Irvine, 1967). They are rich in Cr_2O_3 (33.4–33.8 wt.%) and the X_{Mg} value ranges from 0.59 to 0.62 [average 0.61 (n = 4)]. The TiO_2 content of the spinel is always below microprobe detectable level. The X_{Cr} average of spinel is approximately 0.4 (Table 1). Values of X_{Cr} in Darvel Bay harzburgite are much lower than in the Halmahera harzburgite

Table 1. Selected mineral chemistry of the primary phases of the Darvel Bay harzburgite. Halmahera peridotites data is for comparison (Ballantyne, 1990). X_{Cr} = Cr/(Cr + Al) and X_{Mg} = Mg/(Mg + Fe^{2+}).

Darvel Bay Harzburgite

	Olivine			Spinel		Clinopyroxene			
	Fo	MnO	X_{Mg}	X_{Cr}	X_{Mg}	X_{Mg}	Al_2O_3	CaO	Cr_2O_3
n	8	10	8	4	4	2	2	2	2
Range	89.90–90.8	0.19–0.21	0.89–0.91	0.38–0.39	0.59–0.62	0.955–0.961	1.75–2.04	12.68–13.11	0.46–0.60
Average	90.35	0.2	0.903	0.385	0.61	0.958	1.895	12.89	0.53

	Orthopyroxene							
	En	Wo	X_{Mg}	Al_2O_3	CaO	MnO	Cr_2O_3	CaO/Al_2O_3
n	8	8	8	8	8	2	8	8
Range	82–90	0.01–0.1	0.91–0.92	3.13–3.75	0.53–5.20	0.21–0.23	0.71–1.08	0.17–1.39
Average	88	0.03	0.915	3.41	1.79	0.22	0.896	0.78

Halmahera Harzburgite

	Olivine		Spinel	Clinopyroxene			
	Fo	MnO	X_{Cr}	X_{Mg}	Al_2O_3		Cr_2O_3
n	29	29	55	5	5		5
Range	90.1–92.1	0–0.22	0.45–0.76	0.94–0.96	0.63–2.18		0.68–1.18
Average	91.4	0.13	0.62	0.95	1.65		0.93

	Orthopyroxene							
	En	Wo	X_{Mg}	Al_2O_3	CaO	MnO	Cr_2O_3	CaO/Al_2O_3
n	–	–	32	32	32	27	32	32
Range	87.9–91.3	0.8–3.2	0.91–0.93	0.41–2.31	0.39–1.68	0.04–0.24	0.19–0.93	0.73–0.95
Average	–	–	0.92	1.04	0.95	0.12	0.55	0.84

Halmahera Lherzolite

	Olivine		Spinel	Clinopyroxene			
	Fo	MnO	X_{Cr}	X_{Mg}	Al_2O_3		Cr_2O_3
n	9	8	15	11	11		11
Range	90.1–91.0	0–0.19	0.15–0.24	0.91–0.93	4.89–6.36		0.95–1.51
Average	90.4	0.11	0.17	0.92	5.61		1.27

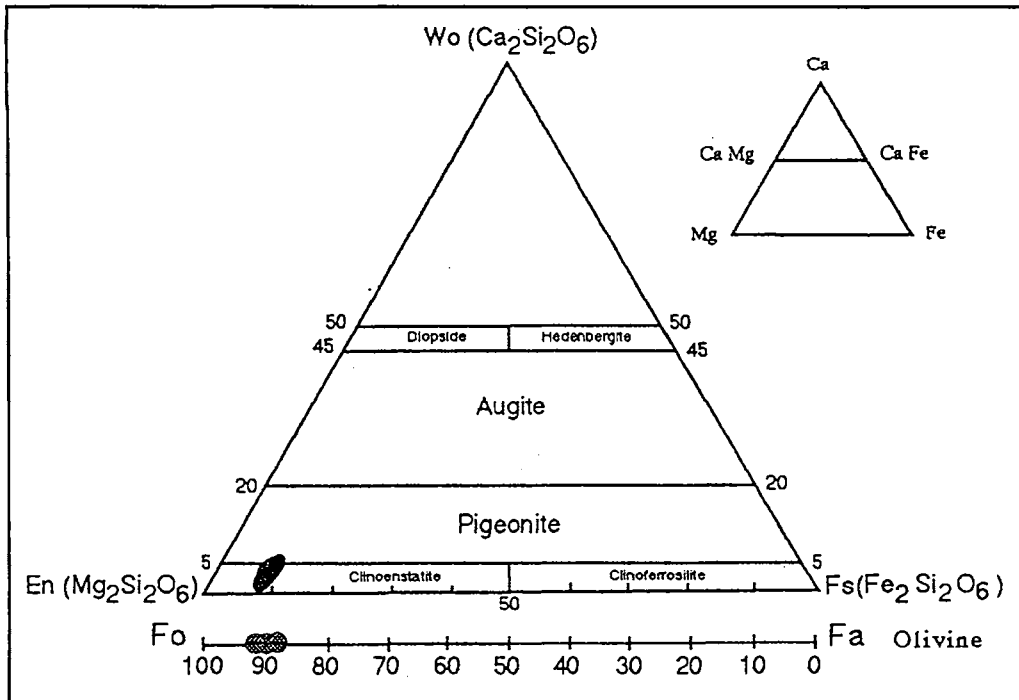|	Orthopyroxene							
	En	Wo	X_{Mg}	Al_2O_3	CaO	MnO	Cr_2O_3	CaO/Al_2O_3
n	–	–	14	14	14	12	14	14
Range	85.7–89.4	1.1–4.40	0.90–0.91	2.72–5.55	0.57–2.19	0.08–0.27	0.36–1.01	0.21–0.39
Average			0.905	4.07	1.24	0.16	0.68	0.30

Figure 2. Compositional ranges of olivines and pyroxenes in Darvel Bay harzburgite, displayed on Deer's *et al.* (1966) diagram.
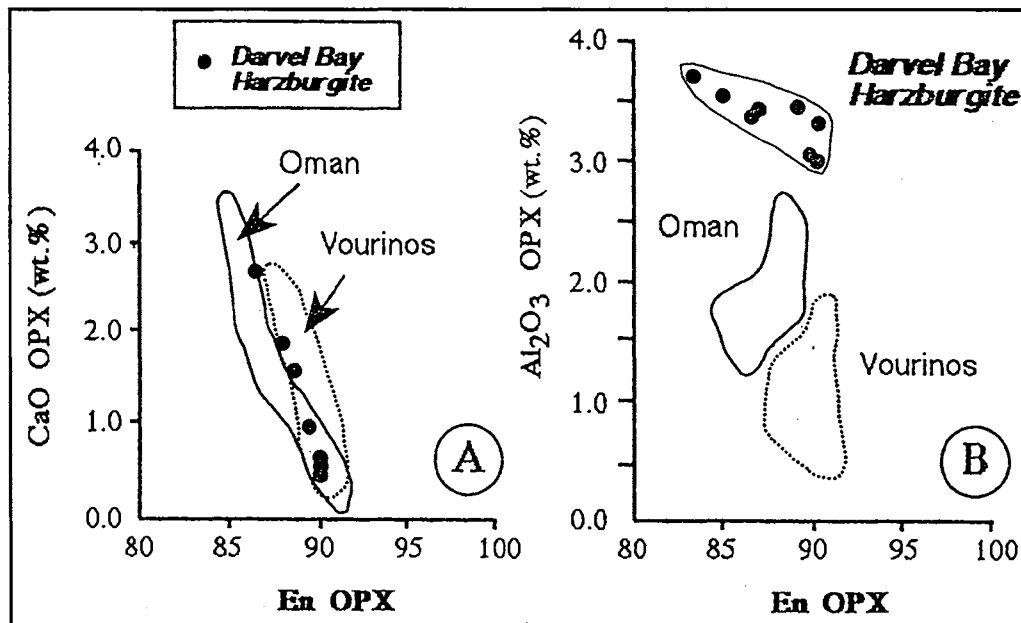

Figure 3. (A) En versus CaO (wt.%) and (B) En versus Al_2O_3 (wt.%) plots for orthopyroxene of the Darvey Bay harzburgite. Data from Oman and Vourinos mantle peridotites (Roberts, 1992) is for comparison.

(X_{Cr} = 0.62) and the Vourinos harzburgite (Fig. 4) but fall within the range of the Oman harzburgite (Fig. 4). However, this spinel value of the Darvel Bay harzburgite is higher than in Halmahera lherzolite (X_{Cr} = 0.17; Table 1). Also, this X_{Cr} value of Darvel Bay spinel is much lower compared to the X_{Cr} in the harzburgite spinel of other complexes (Tables 5 and 6). This X_{Cr} value of the Darvel Bay harzburgite reflects that the Darvel Bay harzburgite represents a mantle residue after extraction of MORB magma by low to intermediate degree of partial melting in the mantle source region (e.g. Dick and Bullen, 1984). About 15–20% of degree of partial melting has estimated that occurred in the mantle source region to produce MORB melt, leaving the Darvel Bay harzburgite. Darvel Bay spinels which show decreasing X_{Mg} (0.59–0.62) with increasing X_{Cr} (0.38–0.39) are compatible with Cr-spinel from the mantle section of the Bay of Islands Ophiolite, Newfoundland (Calk and Coleman, 1979) and Josephine Ophiolite, NW California (Dick and Bullen, 1984). The Darvel Bay spinels composition fall within 'Alpine-type peridotite' and abyssal peridotites spinel compositional field (Fig. 6), with a slight tendency towards lower X_{Mg}, possibly due to the effect of sub-solidus reequilibration of some grains, with the Mg-rich silicate at lower temperatures (e.g. Ozawa, 1983).
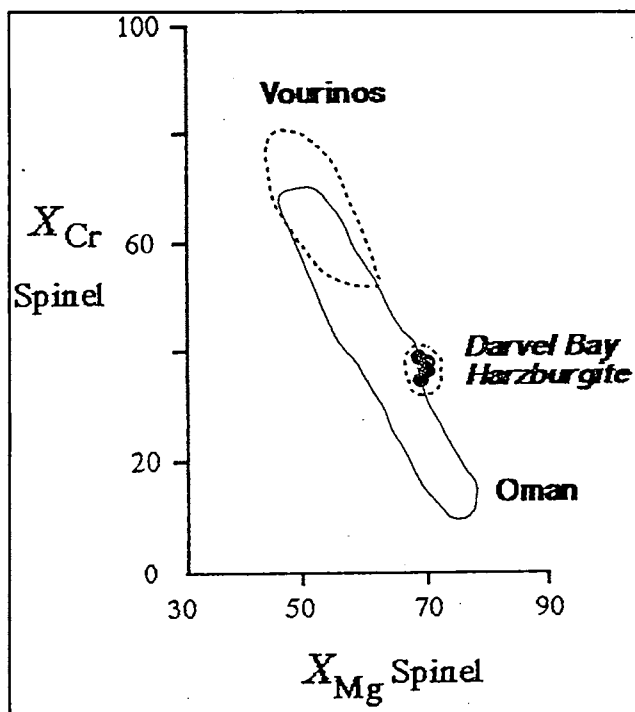

Figure 4. X_{Mg} versus X_{Cr} for chrome-spinel of the Darvel Bay harzburgite. Data from Oman and Vourinos mantle peridotites (Roberts, 1992) is for comparison.

Amphibole

Amphibole is the main hydrous phase in the harzburgite of the Darvel Bay Ophiolite. It has a tremolite composition (Shariff, 1993), according to the amphibole nomenclature of Deer et al. (1966) and Leake (1978). The Na_2O content of the tremolite is very low and ranges from 0.33 to 0.48 wt.%. The K_2O and TiO_2 contents are always below the microprobe detectable limit. The Cr_2O_3 content is less than 0.2 wt.%. The X_{Mg} of the tremolite ranges from 0.024 to 0.074 with average X_{Mg} of 0.05 (n = 7).

Chlorite

The X_{Mg} of the chlorite ranges from 0.108 to 0.143 [average X_{Mg} = 0.130 (n = 37)]. These chlorites are the product of the hydrothermal alteration of pyroxene and amphibole. They are intermediate to low Si-rich chlorite according to Shariff (1993). The composition ranges between clinochlore and penninite. The chlorite contains 13.20–19.08 wt.% of Al_2O_3, 6.10–8.29 wt.% of FeO and 0.57–0.85 wt.% of Cr_2O_3. The Na_2O and CaO contents are less than 0.29 wt.%. TiO_2 content is always below microprobe detectable limit.

BULK-ROCK GEOCHEMISTRY

Bulk-rock geochemical analyses of three harzburgites are presented in Table 2. Certain peridotites analyses were selected from the literature for comparison (Table 3). The Darvel Bay harzburgites have undergone varying degrees of serpentinization, indicate by LOI (loss on ignition at 1,100°C) values around 6% and accordingly the analyses, as with all bulk-rock analyses in this thesis, are presented as a volatile-free basis.

Major Element Geochemistry

The refractory mineralogy of harzburgites is reflected in their highly magnesian bulk composition (100 Mg/(Mg + Fe^{2+}) rations ~ 90; Table 2). The Darvel Bay harzburgites are unusually rich in CaO and Al_2O_3, and appreciably less depleted than non-cumulus peridotites described from other ophiolites (see Tables 2 and 3). Whereas, other 'magmaphilic' major elements such as TiO_2, Na_2O and K_2O are very low. Comparing the chemistry among the Darvel Bay harzburgite samples reveal that sample TI2 is relatively higher in TiO_2, Fe_2O_3 and especially in Al_2O_3 and CaO, but lower in MgO than those of sample PS8 and SQ1. This is compatible with the petrographic observation that the sample TI2 contents high proportion of clinopyroxene (up to 2%) in the rock, or probably due to the alteration and/or serpentinisation process. K2O contents usually high in sample SQ1 than the two samples probably due to alteration.

Table 2. Geochemical analyses for the harzburgites of the Darvel Bay Ophiolite. Oxides in wt.% and trace elements in ppm. Total iron as $Fe_2O_3^*$ ($Fe_2O_3 = FeO$ x 1.111). $mg = 100 \, Mg/(Mg + Fe)$ where $Mg = MgO/40$ and $Fe = (Fe_2O_3 \times 0.9)/72$. n.d. = below detection limit. Data presented on a volatile-free basis. LOI = Loss on ignition at 1,100°C.

| OXIDES/ ELEMENTS	SAMPLE NO.		
	PS8	SQ1	TI2
SiO_2	44.17	44.78	44.09
TiO_2	0.025	0.027	0.123
Al_2O_3	1.57	1.94	3.48
$Fe_2O_3^*$	8.92	8.48	9.13
MgO	42.93	41.44	39.69
MnO	0.125	0.114	0.132
CaO	2.11	2.04	3.22
Na_2O	0.05	0.37	0.14
K_2O	0.000	0.104	0.005
P_2O_5	0.012	0.006	0.009
Total:	99.91	99.31	100.01
LOI	6.94	5.54	6.50
Al_2O_3 + CaO	3.68	3.98	6.70
CaO/Al_2O_3	1.344	1.052	0.925
mg	90.5	90.7	89.7
Ni	1997	2231	2034
Cr	2974	3152	2528
V	62	68	85
Sc	14	14	17
Pb	0.6	0.3	0.4
Sr	14.5	1.4	52.8
Rb	0.0	2.5	0.1
Ba	3	6	5
Th	n.d.	n.d.	n.d.
Zr	0.5	0.3	2.7
Nb	0.4	n.d.	n.d.
Y	0.8	0.8	3.2
La	0.0	0.3	0.3
Ce	n.d.	1	n.d.
Nd	1	2	1
Zn	52	51	59
Cu	n.d.	17	13
Cl	277	26	1258
Ga	2	2	3
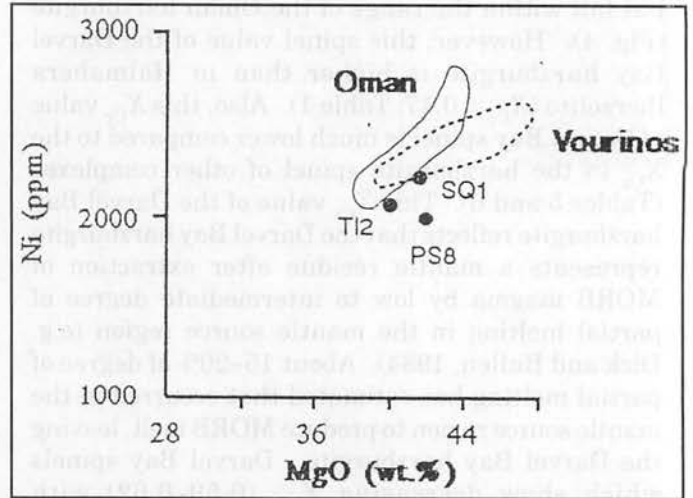
Figure 5. MgO (wt.%) versus Ni (ppm) plot for whole-rock data of the Darvel Bay harzburgite. Data from Oman and Vourinos mantle peridotites (Roberts, 1992) is for comparison.
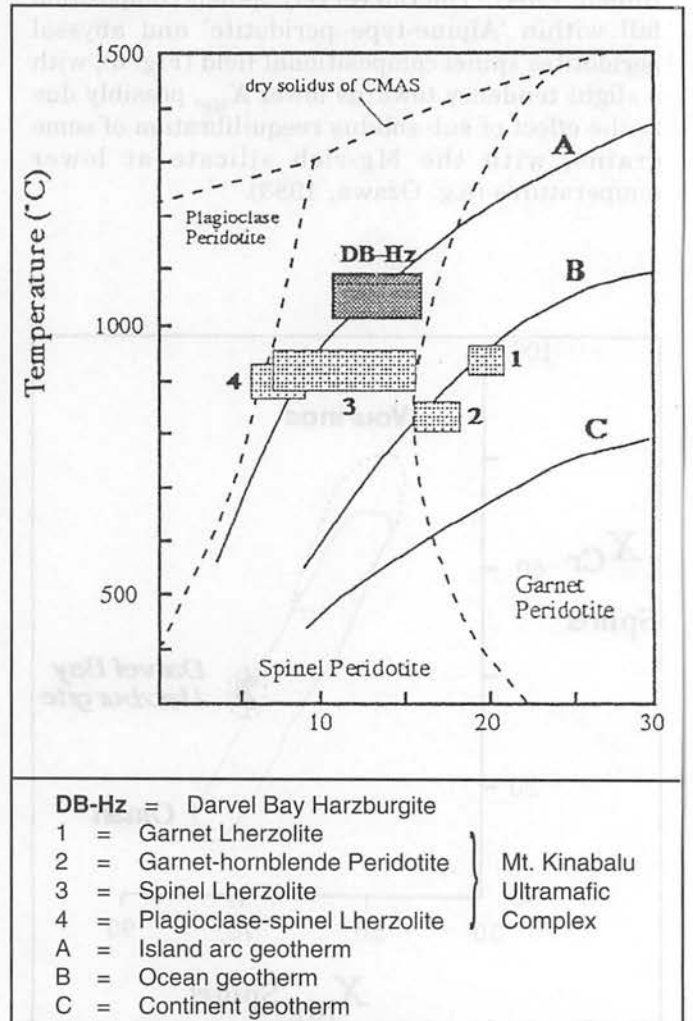

DB-Hz = Darvel Bay Harzburgite
1 = Garnet Lherzolite
2 = Garnet-hornblende Peridotite } Mt. Kinabalu
3 = Spinel Lherzolite   Ultramafic
4 = Plagioclase-spinel Lherzolite Complex
A = Island arc geotherm
B = Ocean geotherm
C = Continent geotherm

Figure 6. P-T condition for the Darvel Bay harzburgite. P-T conditions from Mt. Kinabalu Ultramafic Complex are for comparison (Imai and Ozawa, 1991).

Table 3. Bulk-rock geochemistry parameters of mantle sequence peridotite from selected ophiolite complexes for comparison with the Darvel Bay mantle sequence peridotite. (1) Original or undepleted (upper) mantle (Harris *et al.*, 1967), (2) Average of 9 plagioclase-free serpentinized lherzolites, Liguria (Ernst and Piccardo, 1979), (3) Average of 4 serpentinized lherzolites of Ballantrae Ophiolite (Jelinek *et al.*, 1984), (4a) Average of 3 serpentinized lherzolites of Halmahera Ophiolite (Ballantyne, 1990, 1991, 1992), (4b) Average of 4 serpentinized harzburgites of Halmahera Ophiolite (Ballantyne, 1990), (5) Fresh harzburgite of Oman Ophiolite (Lippard *et al.*, 1986), (6) Average of 8 harzburgites of Troodos Ophiolite (Menzies and Allen, 1974), (7) Average of 4 harzburgites of Papua Ophiolite (Jaques and Chapell, 1980), (8) Tonga Trench dredged 'peridotite' (Fisher and Engel, 1969), and (9) Serpentinized harzburgite of Mariana Trench (Bloomer and Hawkins, 1983). Total iron as Fe_2O_3 ($Fe_2O_3{}^* = Fe_2O_3 + FeO \times 1.111$). $Al_2O_3 + CaO$ parameter recalculated to 100% volatile-free (H_2O^+, H_2O^-, CO_2). $mg = 100\ Mg/(Mg + Fe)$, where $Mg = MgO/40$ and $Fe = Fe_2O_3 \times 0.9)/72$.

	Undepleted Upper Mantle (1)	Liguria Lherzolite (2)	Ballantrae Lherzolite (3)	Halmahera Lherzolite (4a)	Halmahera Harzburgite (4b)	Oman Harzburgite (5)	Troodos Harzburgite (6)	Papua Harzburgite (7)	Tonga Trench Peridotite (8)	Mariana Trench Harzburgite (9)	Darvel Bay Harzburgite
SiO_2	44.20	44.50	39.57	41.91	43.42	45.00	43.50	43.20	44.60	42.60	44.48
TiO_2	0.10	0.15	0.04	0.043	0.03	0.03	0.01	< 0.002	–	0.08	0.026
Al_2O_3	2.70	2.97	2.04	2.03	0.56	0.93	0.47	0.05	0.16	2.78	1.75
$Fe_2O_3{}^*$	1.10	8.64	5.79	8.056	7.843	–	5.44	1.71	0.51	3.86	8.70
MgO	41.30	40.30	39.07	38.90	43.67	43.51	45.70	48.10	46.35	36.84	42.19
MnO	0.15	0.13	0.12	0.11	0.12	0.15	0.15	0.12	–	0.13	0.119
CaO	2.40	2.23	0.88	1.88	0.55	1.12	0.77	0.04	0.09	2.87	2.08
$Na2O$	0.25	0.10	0.08	0.03	0.02	–	< 0.01	0.01	0.10	0.10	0.21
K_2O	0.02	< 0.01	0.01	–	–	–	< 0.01	< 0.005	< 0.02	0.01	0.104
P_2O_5	–	–	0.01	0.05	0.053	–	–	–	–	–	0.009
$Al_2O_3 + CaO$	5.10	5.22	2.915	4.17	1.16	2.05	1.24	0.08	0.25	5.98	3.83
CaO/Al_2O_3	0.89	0.75	0.43	0.93	0.99	1.204	1.64	0.78	0.56	1.03	1.19
mg	98.76	90.32	93.11	90.62	91.76	–	94.38	98.28	99.48	95.05	90.63
Ni	1,573	1,959	2,109	2,324	2,552	2,766	2,124	2,770	3,000	2,010	2,114
Cr	2,053	2,487	2,328	2,828	2,967	2,193	2,668	2,315	3,700	2,070	3,063

Comparing the chemistry of the Darvel Bay harzburgites with the lherzolite chemistry from the other ophiolites (Table 3), especially the Al_2O_3 and CaO contents, Al_2O_3 + CaO values and CaO/Al_2O_3 ratios, show a similarity. However, comparing with the Mariana Trench harzburgite (Table 3, No. 9), the Darvel Bay harzburgite chemistry also shows a similarity, with the exception of Al_2O_3 + CaO and Al_2O_3 contents. The high CaO contents in the Darvel Bay harzburgites (especially TI2) should be treated with scepticism as it is likely to be increased as a consequence of the amphibole- and ferritchromit-forming Ca-metasomatism or because of isochemical alteration (Thirlwall, *pers. comm.*). However, the CaO/Al_2O_3 ratios of the Darvel Bay harzburgite are comparable to that of the Oman, Halmahera and Mariana Trench harzburgites.

Trace Element Geochemistry

Incompatible trace elements are extremely low in the harzburgites. Lithophile elements such as Sr (< 52.8 ppm), Rb (< 2.5 ppm) and Ba (< 5.6 ppm) are relatively high compare to the other harzburgites from ophiolites (e.g. Coleman, 1977). High concentrations of these elements in the Darvel Bay Harzburgite are probably due to metasomatic enrichment and/or alteration, which could also explain the high CaO + Al_2O_3 relative to the other harzburgites (see Table 3). Such extreme depletion in lithophile elements, is consistent with their representing depleted upper mantle residual, after extraction of basaltic melt. Concentrations of La, Ce and Nd are also very low, suggesting that these peridotites contain very low levels of the light rare earth elements. Y (a heavy rare earth analogue) concentrations are much higher (~ 3.0 ppm) in sample TI2 compared to the other two samples (*ca.* 0.8 ppm, as is Zr, and Ca, Al, Ti).

The Darvel Bay harzburgites are also characterised by a slightly high compatible elements content (Ni, Cr) compared with Mariana Trench harzburgite and relatively low in V (~ 62–85 ppm) and Sc (~ 14–17 ppm) contents. Concentration of Ni of the Darvel Bay harzburgite chemistry is lower than those of the Oman and Vourinos harzburgites (Fig. 5). Low concentrations of compatible elements (V and Sc) in the Darvel Bay harzburgite are likely to be held in pyroxene lattice (e.g. Deer *et al.*, 1992). Such depletion in these elements, suggests that the Darvel Bay harzburgite to represent a residual piece of upper mantle, after MORB extraction. High Sc/Ga ratios (~ 9.5) of the Darvel Bay harzburgite also imply that this rock represents a refractory mantle (Thirlwall, *pers. comm.*). This value is similar to that of Halmahera harzburgite (Sc/Ga ~ 9.0) but higher compared to the Halmahera lherzolite (Sc/Ga ~ 7.0). Certain minor elements

(e.g. Cu, Ga) are low in the harzburgite (Table 2). According to McKay and Mitchell (1988), spinel is the main Ga host in spinel peridotites and they estimated upper mantle Ga content is about 1.90 ppm. The Darvel Bay harzburgite content of Ga is between 1.5–3.0 ppm. Zn is slightly enriched in the Darvel Bay harzburgite (~ 52–60 ppm), compared to the Papuan harzburgite (~ 42–44 ppm) and the Halmahera harzburgite (~ 47–56 ppm).

GEOTHERMOMETRY

The presence of spinel in the harzburgite indicates that the physical conditions of formation of the Darvel Bay mantle sequence rock were between garnet lherzolite (high pressure rock) and plagioclase lherzolite (low pressure rock) stability fields. The approximate stability field of garnet lherzolite is 1,200°C at 8–16 kbar, and 800°C at 5–12 kbar of plagioclase lherzolite (Obata, 1976). The absence of garnet and plagioclase lherzolites in the study area can be used as a constraint on the P-T conditions of the Darvel Bay mantle sequence formation.

For estimation of the P-T environment of formation of the Darvel Bay harzburgite, geothermometers based on co-existing mineral phases proposed by several authors were used in this study. In the residual mantle sequence rocks, geothermometry can be used to estimate the temperature of mantle partial melting, or at least the temperature at which the residual material was last in equilibration with the melt, although the effects of lower temperature re-equilibrium and/ or recrystallisation must be borne in mind.

Basically, three types of geothermometers can be applied to the Darvel Bay mantle sequence rock:
(1) geothermometer based on Ca partitioning between co-existing clinopyroxene and orthopyroxene (Wood and Banno, 1973; Lindsley, 1983; Lindsley and Andersen, 1983). This geothermometer should be restricted to a pyroxene composition in which En + Fs + Wo > 90%. All of the harzburgitic pyroxenes of the present study contain more than 90% of these components. This geothermometer was applied to the Darvel Bay harzburgite at 10 and 15 kbar pressure based on the Lindsley (1983) geothermometer and the results are presented in Table 4.
(2) geothermometer based on the partitioning of Mg^{2+} and Fe^{2+} between co-existing spinel and olivine (Irvine, 1965; Fabries, 1979; Engi, 1983). The theoretical foundation for the study of the distribution of Mg and Fe^{2+} between spinel and co-existing olivine was provided by Irvine (1965). Fabries (1979) calibrated the exchange

Table 4. P-T estimates of the harzburgite of the Darvel Bay Ophiolite. Abbreviations: Ol = olivine, Opx = orthopyroxene, Cpx = clinopyroxene, and Sp = spinel.

	Wood & Banno (1973): Opx-Cpx	Lindsley (1983): Opx-Cpx	Gasparik & Newton (1984): Ol-Opx-Sp	Gasparik & Newton (1984): Ol-Opx-Sp	Gasparik (1987): Opx-Cpx-Ol-Sp	Gasparik (1987): Opx-Cpx Ol-Sp	Fabries (1979): Ol-Sp
Sample No.	SQ1	SQ1	SQ1	SQ1	SQ1	SQ1	SQ1
n	4	4	4	4	6	6	4
Temperatur range (°C)	1,084–1,181	1,050–1,100	626–703	621–698	1,043–1,148	1,048–1,126	683–1,201
Average Temperature (°C)	1,083	1,075	665	660	1,098	1,103	821
Pressure (kbar)	–	10–15	10	15	10	15	–

equilibrium empirically and provided a scheme for normalising the distribution coefficient to a Fe^{3+}–free basis. The temperature of the equilibrium is then calculated from the resulting normalised distribution coefficient and the proportion of Cr atoms in the octahedral sites of the spinel structure. This geothermometer was also used for estimating the temperature of the Darvel Bay harzburgite, and the results are given in Table 4.

(3) geothermometer based on the Al-content of orthopyroxene co-existing with clinopyroxene, olivine and spinel (Gasparik and Newton, 1984; Gasparik, 1987). This geothermometer, which approximately describes the variation of the Al-content of orthopyroxene in the CaO-MgO-Al_2O_3-SiO_2 (CMAS) system and calculating the Al occupancy of the M1 octahedral pyroxene site. The results of this geothermometer are presented in Table 4.

P-T Estimate of the Darvel Bay Harzburgite

P-T conditions of the harzburgite of Darvel Bay Ophiolite Complex were obtained for some mineral pairs on the basis of previously published geothermometers (Table 4). These values do not indicate the exact temperature and pressure of equilibrium, but give rough estimates of the physical conditions of igneous formation and the cooling event history. Two-pyroxene thermometry of Wood and Banno (1973) gives a temperatures of 1,081°C–1,084°C (average ~ 1,083°C). Gasparik and Newton (1984) method gives a low temperature of 660°C–665°C compared with the other methods. This lower temperature is probably due to preferential leaching of Al_2O_3 from upper mantle orthopyroxenes during partial melting (Mercier et al., 1984). They also stated that the Al in ophiolitic peridotites can

only be a sensitive geothermometer after appropriate corrections are made for compositional variations with degree of partial melting, therefore they suggested the Al-content of orthopyroxene does not accurately reflect upper mantle temperature, but is a measure of the degree of melt depletion from their host peridotites. Nevertheless, as shown in Table 4, using the Gasparik (1987) geothermometer based on the Al-content of orthopyroxene co-existing with clinopyroxene, olivine and spinel gives temperature of 1,098°C to 1,103°C. The Lindsley (1983) geothermometer, using two pyroxene pairs, gives a temperature of 1,050°C to 1,100°C. However, the geothermometer using olivine-spinel of Fabries (1979) give a temperature of 821°C. This low temperature which is obtained by Fabries method reflects Mg-Fe equilibrium (diffusional exchange between olivine and spinel) with cooling in the rocks with high olivine-spinel modal ratios (e.g. Ozawa, 1983, 1986; Bloomer and Fisher, 1987). Thus, the Wood and Banno (1973), Lindsley (1983), Gasparik (1987) and perhaps Fabries (1979) geothermometers presumably provide the best estimated of the temperature of the upper mantle equilibrium temperature in the Darvel Bay region. Assuming the results do reflect the temperatures pertaining when the rocks passed from the solidus into the sub-solidus fields, and applying them to the boundary between the plagioclase and spinel peridotite stability fields determined by Obata (1976) leads to minimum pressure estimates of approximately 7 and 8 kbar for harzburgites and lherzolites respectively. Pressure conditions for the Darvel Bay harzburgite were estimated between 10–15 kbar based on the Lindsley's (1983) geothermobarometry. The P-T conditions of the Darvel Bay harzburgite peridotite is shown in

Figure 6. This P-T estimate lies on the island-arc geotherm of Kushiro (1987). Compared with the P-T conditions of other ophiolite complexes which are shown in Table 5, this indicates that a temperature at c. 1,000°C and pressure c. 10–15 kbar of the Darvel Bay harzburgite is consistent for the partial melting that produced the harzburgite.

DISCUSSION

Mantle Tectonite Fabric

Porphyroblastic and neoblast textures which are preserved in the Darvel Bay harzburgite indicate high temperature upper mantle plastic deformation (Spray, 1984). These fabrics are considered to result from deformation occurring at or near the peridotite solidus during the plastic flow of upwelling mantle beneath a spreading centre (e.g. Boudier and Coleman, 1981; Nicolas and Violette, 1982; Nicolas and Rabinowicz, 1984). According to Nicolas and Violette (1982), the flow in the asthenospheric mantle beneath a spreading ridge results from the combination of two causes; (1) a regional cause responsible for a large-scale motion which is either internally driven convection or, more probably, the drifting away of the growing lithosphere (Nicolas and Rabinowicz, 1984; Fig. 1), and (2) a local gravity instability developing in the rising diapir due to a difference in density with surrounding mantle as a consequence of partial melting.

Spinel Chemistry and Its Implications

Spinel chemistry is very important. This is because it shows wide major element variation, such as Cr and Al contents, not seen in the compositionally homogeneous silicates, and spinels normally retain their primary chemistry, at least in terms of the X_{Cr} values. During partial melting Cr is strongly partitioned into the solid and Al into the melt (Jaques and Chapell, 1980; Mercier et al., 1984; Dick and Bullen, 1984). Therefore, the composition of a spinel provides a sensitive indication of the degree of partial melting recorded by the host mantle sequence peridotite. The Darvel Bay harzburgite spinels are enriched in Cr relative to Al (average $X_{Cr} = 0.4$), with compositions that cluster mostly within the range for spinel of abyssal (MOR) peridotite (Fig. 7A) and Alpine-type peridotite spinel (Alpine Type I; $X_{Cr} < 0.60$) (Fig. 7B). These demonstrate that the Darvel Bay harzburgite is a section of ocean lithosphere formed at mid-ocean ridge (e.g. Dick and Bullen, 1984). However, on the Pearce's et al. (1984) diagram (Fig. 8) the Darvel Bay harzburgites fall within the fields of supra-subduction zone (SSZ) ophiolites and mid-ocean ridge basalt (MORB) ophiolites.

The degree of partial melt extraction recorded by a peridotite, as reflected by the covariation between bulk ($Al_2O_3 + CaO$), olivine Fo, orthopyroxene Al_2O_3 and spinel X_{Cr} has been discussed for spinel-bearing peridotites from several of ophiolitic complexes (e.g. Ishiwatari, 1985) and various oceanic tectonic settings (e.g. Dick and Bullen, 1984; Bonatti and Michael, 1989). These parameters of the Darvel Bay harzburgite are given in Table 6, and compared to the published data from other peridotites, including harzburgites dredged from the forearc slopes of the Mariana and Tonga Trenches. The comparison shows that the Darvel Bay harzburgite represents a mantle sequence less depleted than the mantle sequence of the Tethyan Ophiolite of Oman and Troodos, the Halmahera harzburgite, the Tonga and Mariaha harzburgites, the Papuan and Vourinos Ophiolites (Duncan and Green, 1979, 1980). However, the X_{Cr} value of the Darvel Bay harzburgite is almost the same as that of the Mt. Kinabalu spinel harzburgite. Compared with the lherzolitic peridotites (less depleted mantle sequence) listed in Table 6, the spinel X_{Cr} of Darvel Bay harzburgite is more depleted. No lherzolitic peridotite has found in the study area. Leong (1974) analysed the major element chemistry for a single lherzolite sample (NB10441A) from the Sungai Diwata (situated in the southern part of the main body of the peridotite) (see Fig. 1). This lherzolite is characterised by total bulk ($Al_2O_3 + CaO = 2.97$ wt.%) and CaO/Al_2O_3 ratio of about 1.4. The association of two types of peridotite in the Darvel Bay Ophiolite Complex suggests a multi-stage mantle melting history (Pallister, 1984). According to Ozawa (1986), the juxtaposition of both depleted and less depleted peridotite can be explained by melting of a lherzolitic mantle wedge above a subducting slab, promoted by addition of a H_2O fluid derived from the subducted slab, leaving a residue of harzburgite peridotite and forming a magma which ascends diapirically through the overlying lherzolite mantle, incorporating lherzolitic blocks into the main mass of harzburgite by a process of magmatic stopping.

Partial Melting and Magma Generation

The generation of the Darvel Bay harzburgite required approximately 20% degree of mantle partial melting and/or a less depleted mantle source, indicated by X_{Cr} and orthopyroxene Al_2O_3 contents (Table 6). Geothermometry (Table 5) indicates temperature around 1,100°C for the partial melting that produced the harzburgites, considerably lower than the mantle potential temperature (Tp) of 1,280°C that generate basaltic melts at mid-ocean ridge (McKenzie and Bickle, 1988). About half the melt is removed by low pressure fractional
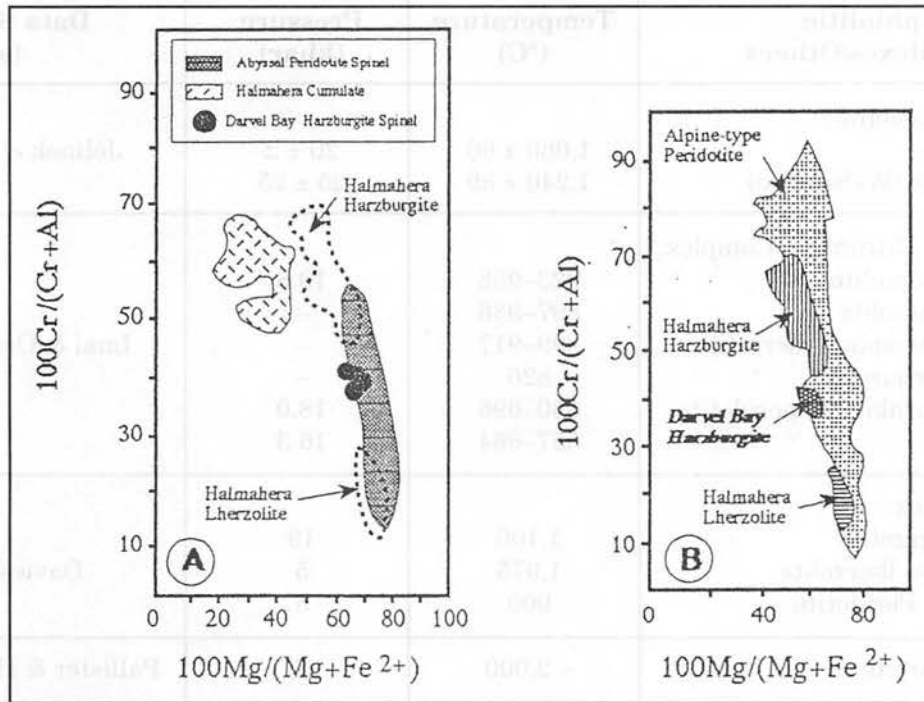
Figure 7. Composition of chrome-spinel for the Darvel Bay harzburgite compared to (A) the Abyssal peridotite spinel (Dick and Bullen, 1984) and Halmahera peridotites and cumulates (Ballantyne, 1991), and (B) the Alpine-type peridotites (Dick and Bullen, 1984) and Halmahera peridotites (Ballantyne, 1991).
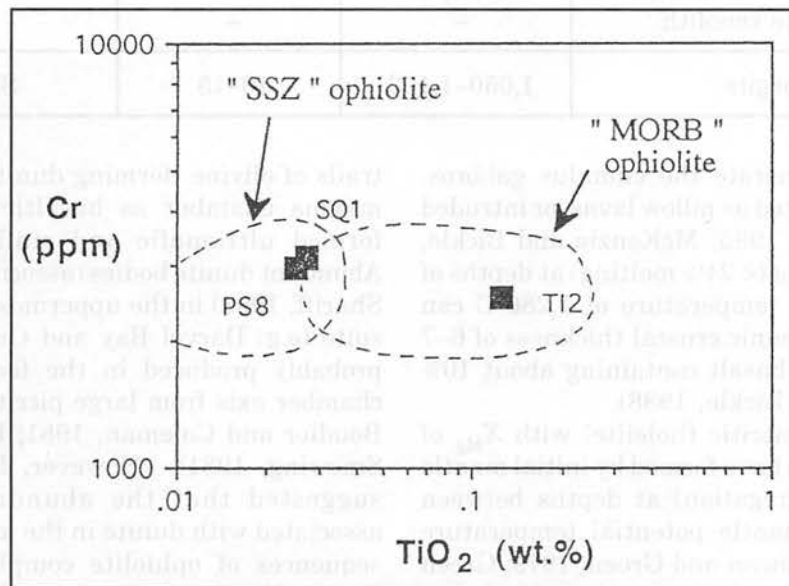

Figure 8. Log TiO_2 (wt.%) versus log Cr (ppm) plot for Darvel Bay harzburgite. Fields from Pearce *et al.* (1984). The 'SSZ' ophiolite mantle residue is generally more residual (carries less TiO_2) than that of the 'MORB' ophiolites (Pearce *op. cit.*). SSZ = *Supra-subduction zone*; MORB = *Mid-ocean ridge basalt*.

Table 5. P-T conditions of ophiolitic and xenolith peridotites from various complexes compared to the Darvel Bay harzburgite.

Ophiolitic Complexes/Others	Temperature (°C)	Pressure (kbar)	Data Source (s)
Ballantrae Ophiolite: 1. Lherzolite 2. Pyroxenite (Websterite)	1,060 ± 60 1,240 ± 89	20 ± 2 25 ± 25	Jelinek *et al.* (1984)
Mt. Kinabalu Ultramafic Complex: 1. Garnet lherzolite 2. Spinel lherzolite 3. Plagioclase-spinel lherzolite 4. Spinel harburgite 5. Garnet-hornblende peridotite	923–958 897–936 899–917 826 680–696 557–664	19.8 – – – 18.0 16.3	Imai & Ozawa (1991)
Lizard Complex: 1. Spinel lherzolite 2. Plagioclase lherzolite 3. Pargasite Peridotite	1,100 1,075 900	19 5 5	Davies (1984)
Oman harzburgite	~ 2,000	7	Pallister & Hopson (1981)
Halmahera Ophiolite: 1. Lherzolite 2. Harzburgite	1,150–1,250 950–1,150	10–15 10–15	Ballantyne (1990, 1991)
Mantle Xenolith: 1. Garnet lherzolite xenolith 2. Spinel lherzolite xenolith	900–1,150 –	– –	Wilson (1989)
Darvel Bay Harzburgite	1,050–1,103	10–15	Shariff (1993)

crystallisation to generate the cumulus gabbros. The other half is erupted as pillow lavas, or intruded as dykes (McKenzie, 1985; McKenzie and Bickle, 1988). Mantle melting (< 24% melting) at depths of about 40 km and at temperature of 1,280°C can produce the mean oceanic crustal thickness of 6–7 km and generates a basalt containing about 10% MgO (McKenzie and Bickle, 1988).

Primary melts (picritic tholeiite) with X_{Mg} of 0.75 are considered to have formed by initial mantle melting (magma segregation) at depths between 40–50 km and at mantle potential temperature (Tp) of ~ 1,300°C (Duncan and Green, 1979; Green *et al.*, 1979; Duncan and Green, 1980; McKenzie and Bickle, 1988). These partial melts coalesce to form diapirs that rise through the ascending host peridotite. Melting and diapir formation probably occurred mainly in the zone between two mantle convection cells (Pallister, 1984). On the way to the crustal magma chamber, melt diapirs reacted to varying degrees with the host peridotite and left

trails of olivine (forming dunite), and reached the magma chamber as basaltic melts where they formed ultramafic and mafic cumulate rocks. Abundant dunite bodies (associated with chromites, Shariff, 1993) in the uppermost part of the mantle suite (e.g. Darvel Bay and Oman Ophiolites) are probably produced in the feeder zone near the chamber axis from large picritic melt diapirs (e.g. Boudier and Coleman, 1981; Hopson *et al.*, 1979; Smewing, 1981). However, Pearce *et al.* (1984) suggested that the abundance of chromites associated with dunite in the mantle and cumulate sequences of ophiolite complexes (e.g. Troodos, Oman, Vourinos) are related to the subduction process. The gabbro-pegmatite dykes associated with the Darvel Bay harzburgite probably represent products of flow crystallisation of an olivine- poor tholeiite magma produced by melting at shallow depths and injected after the deformation of the asthenosphere as it moved fro the spreading centre (e.g. Pallister, 1984) or may be represents a

Table 6. Composition of chemical parameters of some ophiolitic and ocean-floor peridotites for a comparison with the Darvel Bay harzburgite. Oxides in wt.%, Opx = Orthopyroxene and X_{Cr} = 100 Cr/(Cr + Al). Data sources are: (1) Ernst and Piccardo (1979), (2) Jelinek *et al.* (1984), (3) Imai and Ozawa (1991), (4) Davies (1984), (5) Wilson (1989), (6) Brown (1980); Pallister and Hopson, (1981); Lippard *et al.* (1986), (7) Menzies and Allen (1974); Greenbaum (1977), (8) Davies and Jaques, 1984, (9) Ballantyne (1990, 1991, 1992), (10) Bloomer and Hawkins (1987) and (11) Fisher and Engel (1969), Bloomer and Fisher (1987).

PERIDOTITE TYPE	Bulk Rock (Al_2O_3 + CaO)	Olivine (Fo)	Opx (Al_2O_3)	Spinel (X_{Cr})	Data Source (s)
Liguria lherzolite	5.22	90.1	4.11	25.8	1
Ballantrae lherzolite	2.32	91	3.57	32.6	2
Mt. Kinabalu lherzolites: 1. Garnet lherzolite 2. Spinel lherzolite 3. Plagioclase-spinel lherzolite	– – –	– – –	4.28 4.71 5.23	49 51 51.3	3 3
Lizard lherzolites: 1. Spinel lherzolite 2. Plagioclase lherzolite	– –	– –	– –	13–14 64–68	4
Peridotite xenolith: 1. Spinel lherzolite 2. Garnet lherzolite	3.97 2.73	– –	– –	7.0–31.7 7.0–18.6	5
Oman harzburgite	2.05	91.3	1.6	56.6	6
Troodos harzburgite	1.24			55.3	7
Papua harzburgite (Ultramafic belt)	0.08	93	~ 0.09	~ 90	8
Halmahera harzburgite	1.16	91.6	1.04	61.6	9
Mariana Trench harzburgite	?5.98	91.6	1.29	55.2	10
Tonga Trench harzburgite	?0.25	91.6	1.29	57.3	11
Mt. Kinabalu Spinel harzburgite	–	–	1.54	46	3
Darvel Bay Harzburgite	3.40	90.1	3.41	40	Shariff (1993)

small melt fraction from lherzolite underlying the harzburgite (Thirlwall, *pers. comm.*).

For the Darvel Bay Ophiolite, the occurrence of two types of peridotite (Shariff, 1993) suggests a multi-stage melting history (e.g. Halmahera Ophiolite). Significantly, no frozen picritic tholeiite or olivine-poor tholeiitic melts were found within the harzburgite. Considering the dynamic uprise of magmatic melts on and near a spreading axis, it is unlikely that any of the primary melts can be trapped within the harzburgite (Boudier and Coleman, 1981). On the other hand, there is abundant evidence that crystal fractionation of these primary melts is important in their evolution and rise through the upper mantle (e.g. Boudier and Coleman, 1981). These observations support the viewpoint of O' Hara *et al.* (1975) that any primary melt derived from the mantle undergoes crystal fractionation before it reaches the surface.

Serpentinization and Its Implication

The Darvel Bay harzburgite shows a variable degree of serpentinization with olivine and orthopyroxene sometimes replaced partially or

completely by prismatic and pale-green hydrated magnesium silicates of the serpentine group and sometimes replaced by amphibole minerals (tremolite species). High degrees of serpentinization occur near the margin of the harzburgite body and locally along fault zones (Shariff, 1993). Where serpentinization is extensive, a mesh texture of fine-grained serpentine is developed in which tiny grains of black Fe-oxides (magnetite) provides the only evidence of the former Fe content of the olivine or orthopyroxene. These oxide grains show a trace polygonal pattern in highly serpentinized rocks (Shariff, 1993) which preserve the former positions of the boundaries of olivine crystals. Serpentine veins are commonly seen in olivine porphyroclasts. The amount of LOI (~ 7%) of the harzburgite whole-rock analyses listed in Table 2 probably reflects the degree of serpentinization of the rocks, from which it is inferred that the serpentinization occurred through the input of Cl-bearing, marine-derived water into harzburgites. Detailed oxygen isotope study of the Oman Ophiolite by Gregory and Taylor (1987) demonstrated the local penetration of marine H_2O into mantle sequence peridotite. Coleman (1977) indicate that the sea water modifier by hydrothermal heating is responsible for the serpentinization of oceanic peridotite. However, Magaritz and Taylor (1981) reported evidence for three stages of serpentinization in the Troodos Ophiolite, including one involving meteoric ground waters. On the basis of experimental studies on the system $MgO-SiO_2-H_2O$, Magaritz and Taylor (1981) have indicated that serpentines cannot form at temperatures above 500°C, and that formation of serpentine by the action of water on olivine can occur only below 400°C (Deer et al., 1966), this is implying that the serpentinization of the Darvel Bay harzburgite occurred syn-/post-emplacement.

CONCLUDING REMARKS

The predominant lithology of the Darvel Bay mantle sequence is less depleted harzburgite relatively to those of Troodos, Oman, Halmahera and Vourinos Ophiolites. The Darvel Bay harzburgite is characterised by (spinel $X_{Cr} = 39$, $X_{Mg} = 61$, olivine Fo = 90, orthopyroxene En = 88–90, $Al_2O_3 = 3.4$ wt.%, CaO = 1.8 wt.%, whole-rock MgO = 42.2 wt.%, whole-rock $CaO/Al_2O_3 = 0.9$–1.2), reflecting a residue of melting of previously depleted source which has undergone a moderate degree of partial melting and requires melting in supra-subduction (SSZ)-setting under hydrous melting. These chemical characteristics indicate about 20% melting of the source. The source could be less depleted lherzolites. Melting temperature for ~ 20% partial melting of undepleted mantle is ~

1,300°C. Melting temperature of depleted mantle would be even higher. These characteristics suggest of SSZ-setting which is supported by TiO_2 contents of harzburgite.

The magmaphilic elements (Al, Ca, Na, K) and incompatible elements (Ti, Zr, Nb, Y) are depleted in the Darvel Bay harzburgite, consistent with less depleted than some other ophiolites (e.g. Vourinos Ophiolite). No lherzolite or "fertile" mantle was observed.

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