

Clinopyroxene REE Geochemistry of the Red Hills Peridotite, New Zealand: Interpretation of Magmatic Processes in the Upper Mantle and in the Moho Transition Zone

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The Red Hills peridotite in the Dun Mountain ophiolite of South Island, New Zealand, is assumed to have been produced in a paleo-mid-ocean ridge tectonic setting. The peridotite is composed mostly of harzburgite and dunite, which represent residual mantle and the Moho transition zone (MTZ), respectively. Dunite channels within harzburgite blocks of various scales represent the MTZ component. Plagioclase- and clinopyroxene-bearing dunites occur sporadically within common dunites. These dunites represent products of melt–wall-rock interaction. Chondrite-normalized rare earth element (REE) patterns of MTZ clinopyroxenes show a wide compositional range. Clinopyroxenes in plagioclase dunites are extremely depleted in light REE (LREE) ($[Lu/La]_N > 100$), and are comparable with clinopyroxenes in abyssal peridotites from normal mid-ocean ridges. Interstitial clinopyroxenes in the common dunite have flatter patterns ($[Lu/La]_N \sim 2$) comparable with those for dunite in the Oman ophiolite. Clinopyroxenes in the lower part of the residual mantle harzburgites are even more strongly depleted in LREE ($[Lu/La]_N = 100–1000$) than are mid-ocean ridge peridotites, and rival the most depleted abyssal clinopyroxenes reported from the Bouvet hotspot. In contrast, those in the uppermost residual mantle harzburgite and harzburgite blocks in the MTZ are less LREE depleted ($[Lu/La]_N = 10–100$), and are similar to those in plagioclase dunite. Clinopyroxenes in the clinopyroxene dunite in the MTZ are similar to those reported from mid-ocean ridge basalt (MORB) cumulates, and clinopyroxenes in the gabbroic rocks have compositions similar to those reported from MORB. Strong LREE and middle REE

(MREE) depletion in clinopyroxenes in the harzburgite suggests that the harzburgites are residues of two-stage fractional melting, which operated initially in the garnet field, and subsequently continued in the spinel lherzolite field. The early stage melting produced the depleted harzburgite. The later stage melting was responsible for the gabbroic rocks and dunite. Strongly LREE–MREE-depleted clinopyroxene in the lower harzburgite and HREE-enriched clinopyroxene in the upper harzburgite and plagioclase dunite were formed by later reactive melt migration occurring in the harzburgite.

KEY WORDS: clinopyroxene REE geochemistry; Dun Mountain ophiolite; Moho transition zone; orogenic peridotite; Red Hills

INTRODUCTION

Complex magma behavior in the upper mantle and at the Moho transition zone (MTZ) has been investigated in many ophiolitic, orogenic, and oceanic peridotites (e.g. Kelemen *et al.*, 1995; Dijkstra *et al.*, 2003). Partial melting processes in the upper mantle region are generally thought to be multi-stage near-fractional melting from the garnet to spinel stability fields (Klein & Langmuir, 1987; Johnson *et al.*, 1990; Takazawa *et al.*, 1999; Hellebrand *et al.*, 2002a). However, the chemical processes that take place while melts move to the surface through the uppermost mantle and MTZ are still a matter of debate. For example, primary mid-ocean

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ridge basalt (MORB) generally cannot equilibrate with residual upper mantle harzburgite at low-pressure conditions (Stolper, 1980; Elthon & Scarfe, 1984). In contrast, dunite at the MTZ can be equilibrated with primary MORB (Kelemen *et al.*, 1995). This implies that MORB was present at a shallow level, such as the MTZ. Recent studies have established the existence of ultra-depleted melts, which are trapped in olivine melt inclusions in MORB or MOR (mid-ocean ridge) cumulates (Ross & Elthon, 1993; Sobolev & Shimizu, 1993). Evidence of chemical modification of partial melts in the upper mantle by reaction with wall-rocks has also been documented (Takazawa *et al.*, 1992; Garrido & Bodinier, 1999; Godard *et al.*, 2000; Lenoir *et al.*, 2001; Dijkstra *et al.*, 2003). Such studies combine to shed light on the complex history of basaltic magma generation.

Large discordant dunite bodies in the MTZ are key rock types for direct observation of melt modification process in the shallow mantle. The origin of large discordant dunites within surrounding harzburgites has been discussed extensively (e.g. Quick, 1981a, 1981b; Kelemen, 1990; Kelemen *et al.*, 1990, 2000; Suhr *et al.*, 2003). Kelemen *et al.* (1995) examined melt behavior in the uppermost mantle and MTZ in the Oman ophiolite, and concluded that the Oman dunites represented conduits generated by focused melt flow, and that the dunites had equilibrated with MORB. The Red Hills ultramafic body in the Dun Mountain ophiolite belt of New Zealand is another good example of an association of upper mantle harzburgites and MTZ discordant dunites (Sano, 1991). We report here the geology, petrology, and clinopyroxene REE geochemistry of the Red Hills ultramafic body. We also debate the presence of melt fractions with diverse rare earth element (REE) chemistry in the MTZ dunites and upper mantle harzburgites, and possible processes that generate MORB.

GEOLOGICAL BACKGROUND

The Red Hills ultramafic body is the largest body in the Dun Mountain ophiolite belt (Coombs *et al.*, 1976) of South Island, New Zealand (Fig. 1), and was largely unaffected by deformation during its emplacement. The Red Hills ultramafic body is exposed over an area of about 120 km² in the northern part of the South Island, and is about 15 km in length and 8 km in width. Red Hills is separated from the Red Mountain ultramafic body to the SW (Sinton, 1977, 1980) by movement along the Alpine Fault. The western border of the Red Hills body is a fault contact with basalts and gabbros of the Lee River Group (Waterhouse, 1964), which constitutes the crustal section of the ophiolite sequence. The eastern part of the Lee River Group is mainly composed of a sheeted dike complex of diabase or microgabbro, and the western part is dominated by both massive and pillow basalts. At the western end of the Lee River

Group, the pillow basalts are unconformably overlain by tuffaceous siltstone of the Permian Maitai Group (Johnston, 1981, 1982). At the western border of the Red Hills ultramafic body, strongly sheared and altered coarse-grained gabbroic rocks crop out in a serpentine mélange. The eastern border of the body is also in fault contact with metamorphosed sandstones and mudstones of the Permian to lower Mesozoic Caples Group (Bishop *et al.*, 1976; Turnbull, 1979). The age of the igneous stage of the Dun Mountain ophiolite is about 280 Ma, as determined by zircon U–Pb dates for plagiogranites associated with the Red Hills ultramafic body (Kimbrough *et al.*, 1992).

The geology of the Red Hills ultramafic body has been well described by Walcott (1969). It consists of two zones that can be distinguished in terms of both the composition and structure of the rocks. The lower part of the body consists of massive harzburgite with a strongly developed porphyroclastic texture, whereas the upper part is composed mainly of dunite with an equigranular texture (Walcott, 1969).

Challis (1965) argued that the Red Hills ultramafic rocks formed by crystal accumulation beneath a Permian island arc, based especially on the well-developed layering between dunite and harzburgite of the upper zone. Blake & Landis (1973) and Coombs *et al.* (1976) considered that the Red Hills ultramafic body and volcanic rocks in the Lee River Group collectively represent the ophiolite member of the Permian Dun Mountain ophiolite belt. Davis *et al.* (1980) concluded that both harzburgite and dunite in the Red Hills ultramafic body could be interpreted as residual mantle that formed the floor of a magma chamber, and that the basalts and gabbros of the Lee River Group were the differentiated products of that chamber. They also concluded that the basalts in the Lee River Group originated at a mid-ocean ridge, based on their chemical and isotopic characteristics. Sano (1991) reported that the ⁸⁷Sr/⁸⁶Sr isotopic ratios of clinopyroxene in the Red Hills ultramafic body are very low, ranging from 0.7019 to 0.7027. Such low ratios have never been reported from island-arc or back-arc basin rocks. The Sr isotope ratios of clinopyroxenes in the Red Hills ultramafic body are similar to those from MORB in the East Pacific Rise, the Gorda Ridge, and the Juan de Fuca Ridge (Sano, 1991). On the other hand, many late-stage basalt and dolerite dikes in the dunite dominant zone exhibit thermal aureoles against the surrounding ultramafic rocks. Sano *et al.* (1997) suggested that the dike rocks have island arc characteristics, based on their isotope and trace element chemistry. The available data suggest that the Dun Mountain ophiolite formed at a mid-ocean ridge, and was transported and accreted to the continental margin (see Davis *et al.*, 1980).

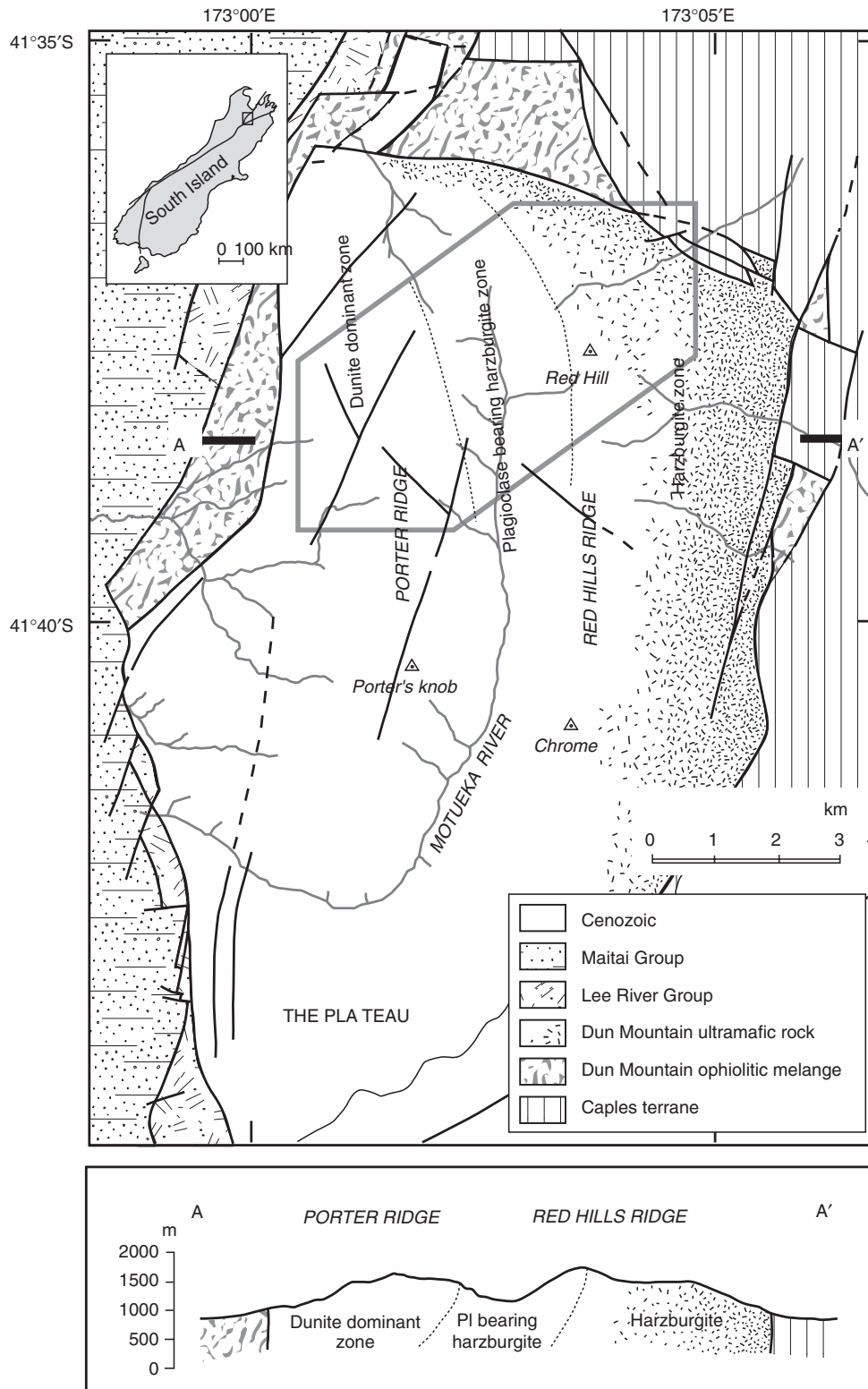


Fig. 1. Geological map of the Red Hills area, Dun Mountain ophiolite belt [modified from Walcott (1969) and Johnston (1982)]. The western part of the Red Hills peridotite body is composed mainly of dunite, whereas the eastern part is dominated by harzburgite. A typical cross section is given along A–A'. Grey rhomb indicates the location of Fig. 3.

ANALYTICAL METHODS

Mineral analyses were carried out by electron microprobe at the University of Otago, using mineral standards and Bence–Albee data correction. Whole-rock major elements were determined by X-ray fluorescence (XRF) at the University of Otago, and rare earth element (REE) abundances in clinopyroxene were determined by laser ablation–inductively coupled plasma mass spectrometry (LA-ICP-MS) at Fukushima University. Polished surfaces of clinopyroxenes in rock slabs were directly ablated using a 1063 µm IR Nd–YAG laser probe. The cores of the crystals were analysed. The crater size induced by the laser ablation for each analysed point was 120 µm. NIST SRM612 glass was used for calibration. ^{29}Si was used for internal standardization between SRM612 and the samples. Lower limits of detection are 1 ppb for La, Ce, Pr, Tb, Ho, Tm and Lu, 2 ppb for Eu, Dy, Er and Yb, 5 ppb for Nd and Gd, and 13 ppb for Sm. Analytical accuracy is better than 15% (1σ) for all REE when the element concentration is greater than 50 ppb. Analytical techniques follow those of Kimura *et al.* (1997, 2000). The REE standard values for NIST612 used were from Pearce *et al.* (1996).

RESULTS

Field observations

The Red Hills ultramafic body is divided into two parts, a dunite-dominant unit in the western part and a harzburgite-dominant unit in the eastern part (Walcott, 1969; Johnston, 1982; Fig. 1). As the compositional layering trends north–south and the dip is almost vertical, we constructed a 1/500 scale measured columnar section to crosscut the banding from west to east. Based on our field observations, we concluded that there is no significant tectonic gap in the section. A schematic section through the Red Hills ultramafic body and a sample location map are given in Figs 2 and 3, respectively. The thickness, including the harzburgite-rich parts, of the dunite-dominant unit (Upper Unit) is about 3 km. The Upper Unit is predominantly dunite that occurs as a matrix to the other lithologies. Sparse small-scale plagiogranite dikes (>5 cm width) and coarse-grained gabbro layers or sills occur only in the uppermost part of the Upper Unit. Late-stage diabase or microgabbro dikes often occur throughout the Upper Unit, and these show chilled margins against the surrounding dunite. Clinopyroxene-bearing lithologies (olivine clinopyroxenite and wehrlite) and plagioclase-bearing dunite are often observed in the Upper Unit (Fig. 4a and d). Harzburgite is observed as interbands or blocks in a dunite matrix. Field relationships between the harzburgite and dunite are illustrated in Fig. 5. The field relationship between harzburgite

and dunite in Fig. 5a is similar to that of the dunite in the Oman ophiolite, which has been interpreted as a replacive origin (Kelemen *et al.*, 1995).

The harzburgite-dominant unit (Lower Unit; Fig. 2) is composed of spinel harzburgite, plagioclase-bearing spinel harzburgite and a small amount of dunite. The uppermost part of the Lower Unit is characterized by the appearance of a plagioclase-bearing lithology (Fig. 4b and c). As shown in Fig. 4b, the alignment of plagioclase is oblique to the harzburgite foliation. Large irregular-shaped crystals of clinopyroxene are also observed in the uppermost part. The transition from the lowermost part of the Upper Unit to the uppermost part of the Lower Unit is indistinct. Small dunite bodies also occur rarely in the Lower Unit. In the field, transitions between the dunite and surrounding harzburgite are gradual. The harzburgite adjacent to dunite shows the most depleted characteristics, with low modal orthopyroxene contents. The grain size of olivine in the dunite can be up to a few centimeters.

Modal compositions

Modal compositions of the rocks (Fig. 6; Table 1) were determined by point counting, based on over 2000 points in each sample. Rock types are clearly divided into a dunite–olivine clinopyroxenite series and a dunite–harzburgite series.

Upper Unit

The Upper Unit is composed of olivine clinopyroxenite, wehrlite, troctolite, harzburgite and dunite. We use the terms ‘clinopyroxene-bearing dunite’ for olivine clinopyroxenite, wehrlite and dunite containing minor clinopyroxene, and ‘plagioclase-bearing dunite’ for troctolite and dunite containing minor plagioclase, because these lithologies are heterogeneous and it is difficult to apply the standard nomenclature for ultramafic rocks. Plagioclase dunite is almost free of clinopyroxene. The range of modal plagioclase is 4–24%. Harzburgite in the Upper Unit lies in the modal compositional range of oceanic peridotite (Fig. 6). The modal abundance of clinopyroxene in harzburgite is up to 2%, less than that of harzburgite in the Lower Unit.

Lower Unit

Samples from the Lower Unit are scattered throughout the harzburgite field, and fall within the oceanic peridotite field (Fig. 6). Modal clinopyroxene is up to 5%. Both plagioclase-bearing and plagioclase-free harzburgites plot in the same field.

Microscopic observations

Upper Unit

Rocks in the Upper Unit are generally characterized by coarse-grained, equigranular, recrystallized textures

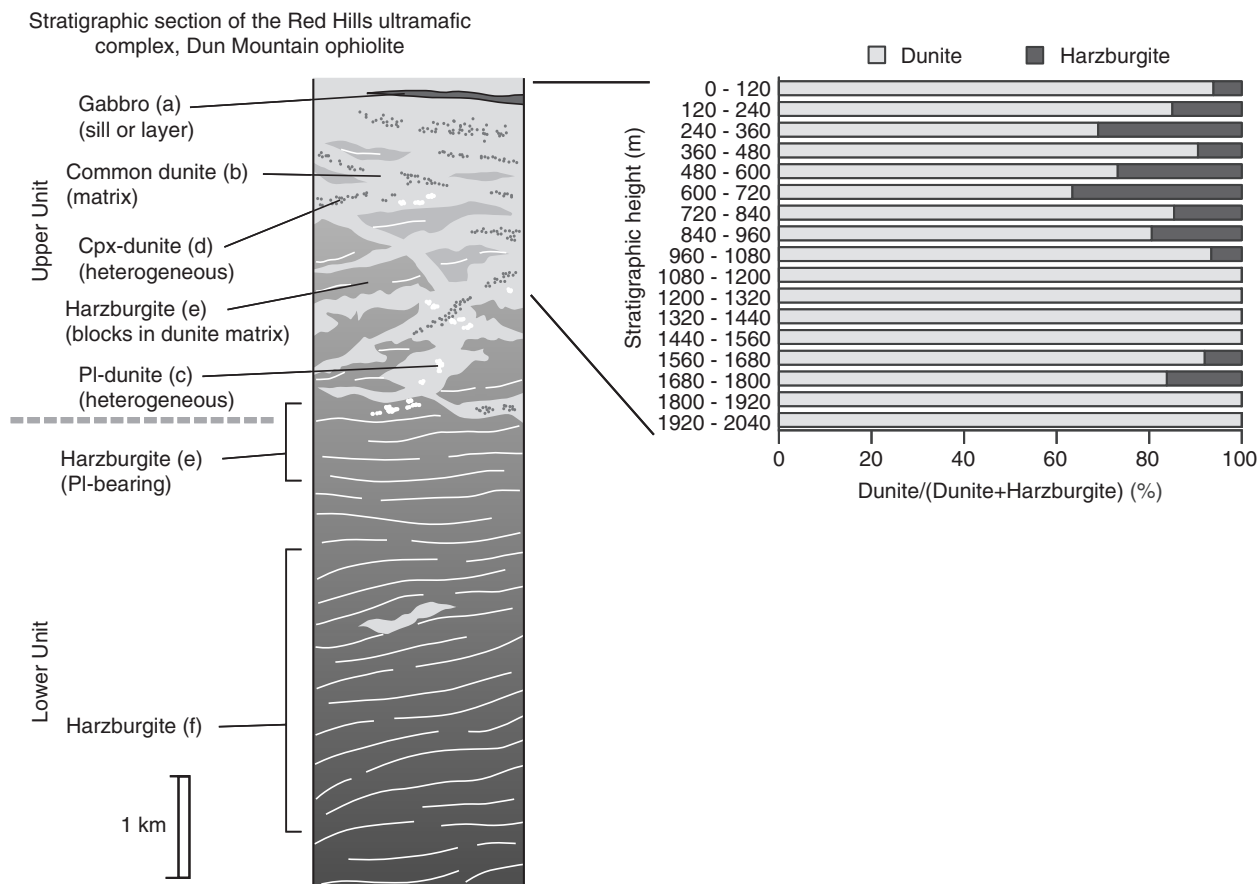


Fig. 2. Typical columnar section of the Red Hills peridotite. The Red Hills peridotite body is divided into two parts, a dunite-dominant zone (Upper Unit) and a harzburgite-dominant zone (Lower Unit). The main constituents of the Upper Unit are common dunite containing clinopyroxene or plagioclase, and harzburgite. Distribution of clinopyroxene and plagioclase in dunite is very heterogeneous. Modal proportions of harzburgite vs dunite at 120 m stratigraphic intervals in the upper part of the Upper Unit are indicated. The Lower Unit is composed mainly of harzburgite, plagioclase-bearing harzburgite, and rarely dunite. Letters in parentheses (a–f) following the rock names correspond to those in Fig. 12.

(Fig. 7a–d). Olivine crystals are polygonal in shape. Many 120° triple grain junctions are observed in dunites. Kink bands in coarse and equigranular olivines are observed in all dunites and harzburgite (Fig. 7a–d). Clinopyroxene in clinopyroxene dunite is coarse-grained and subhedral, and sometimes shows magmatic twinning (Fig. 7a). Plastic deformation in clinopyroxene is not observed. Plagioclase crystals surrounded by pargasite rims occupy melt-pocket shaped domains (Fig. 7c), and show no evidence of plastic deformation. Harzburgites in the dunite matrix in the Upper Unit (Fig. 7d) display high-temperature, low-stress porphyroclastic textures (Nicolas, 1986), which are interpreted as statically recrystallized textures. The harzburgites exhibit recrystallized textures, characterized by curved crystal boundaries and spherical spinel aggregations (Mercier & Nicolas, 1975).

Lower Unit

Harzburgites in the Lower Unit (Fig. 7e–h) display porphyroclastic textures (Ceuleneer *et al.*, 1988).

The harzburgites are tectonites, and kink band structures are strongly developed in olivine and orthopyroxene porphyroclasts. Plagioclase-bearing harzburgite occurs mostly in the uppermost part of the Lower Unit (Fig. 7f and g). The plagioclase crystals occupy melt-pocket shaped domains similar to those in the plagioclase dunites in the Upper Unit and in the plagioclase harzburgites in the Lower Unit. As shown in Fig. 7g, plagioclase appears along the grain boundaries of olivine porphyroclasts. The harzburgite fabric and the orientation of the plagioclase is clearly discordant. Irregular megacrysts of clinopyroxene (*c.* 5–6 mm) containing distinct lamellae of orthopyroxene are observed in the uppermost part of the Lower Unit (Fig. 7e).

Dunite in the Lower Unit has a coarse-grained porphyroclastic texture with sutured crystal boundaries. Distinct kink band structures are developed in olivine. Small rectangular spinels are scattered within the olivine grains, which have a grain size of about 2 cm. The texture of the Lower Unit dunite is distinctly different from that

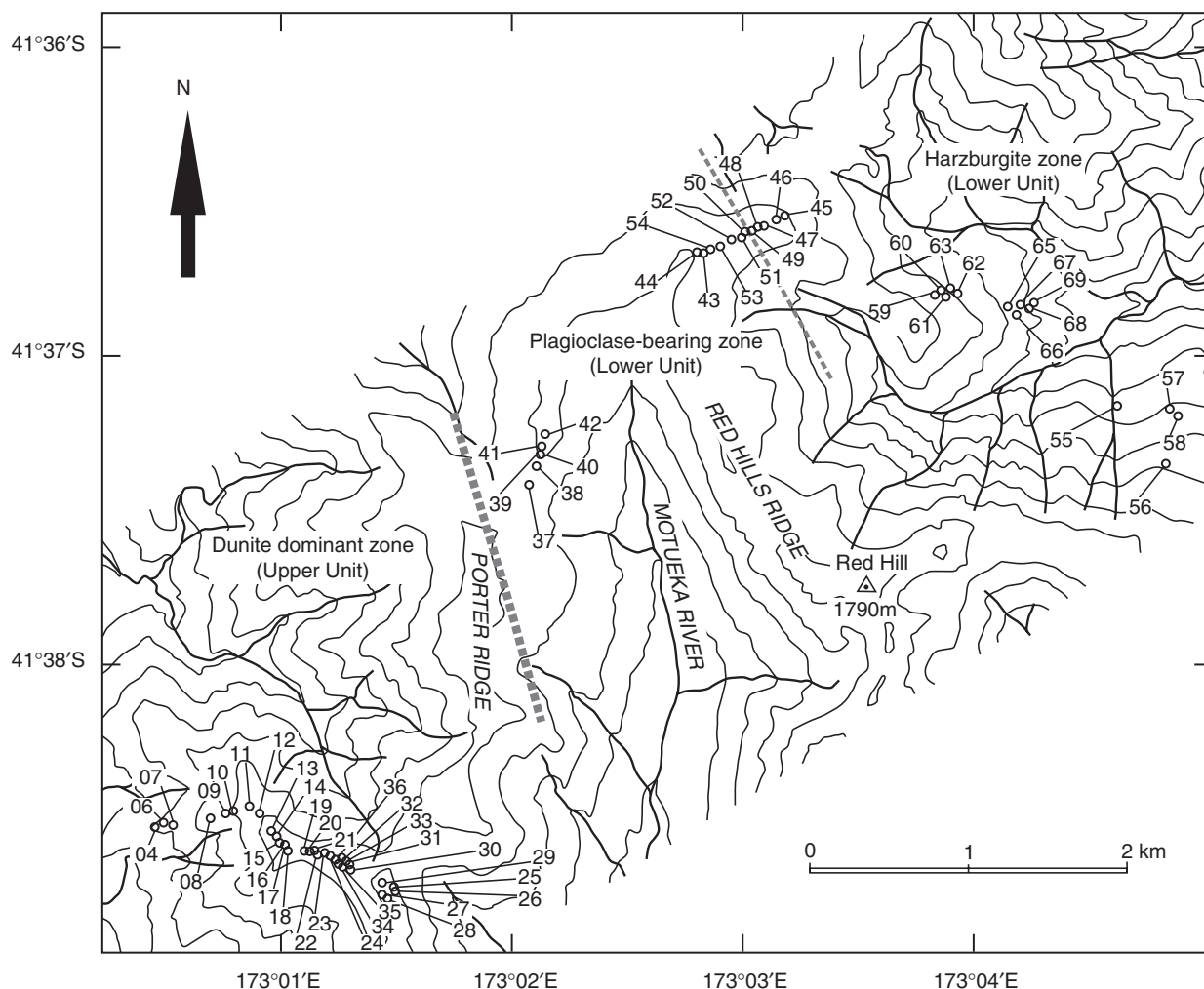


Fig. 3. Sample location map. The approximate boundary between the Upper and Lower Units is marked by the thick dashed line. The thinner dashed line in the Lower Unit represents the boundary between plagioclase-bearing and plagioclase-free harzburgite.

of the Upper Unit. The dunite contains small amounts of orthopyroxene and interstitial clinopyroxene.

Mineral chemistry

Olivine in the Red Hills ultramafic rocks has a wide compositional variation, ranging from Fo_{87} in Upper Unit clinopyroxene dunite to Fo_{93} in Lower Unit dunite (Fig. 8). Olivine in the Upper Unit dunite exhibits a bimodal compositional variation of $\text{Fo}_{88.5-90.5}$ and $\text{Fo}_{91.5-92.5}$. The high-Fo olivine composition is similar to that of olivine in the Lower Unit dunite, whereas the low-Fo olivine composition is similar to that of olivine in the plagioclase dunite and clinopyroxene dunite of the Upper Unit. Olivine in the Lower Unit harzburgites has a relatively uniform composition (Fo_{91}), whereas that in the dunite exhibits the most refractory nature ($\text{Fo}_{91.5-93.0}$).

The compositional range of cr-number [$=\text{Cr}/(\text{Cr} + \text{Al})$] and mg-number [$=\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$] in spinel lies within the field of ocean-floor peridotites (Dick & Bullen, 1984; Hellebrand *et al.*, 2002b) except for the most refractory dunite of the Lower Unit (Fig. 9). The composition of the high cr-number spinel in the dunite from the Lower Unit resembles that from the Western Pacific Margin (Ishii, 1985) or that in troctolite from the Hess Deep (Dick & Natland, 1996). Spinel in both the Upper Unit and the Lower Unit have almost the same cr-number, although the mg-number values of the spinels of the Upper Unit are lower than those of the Lower Unit. TiO_2 contents of spinels in the Upper Unit vary considerably, but plagioclase dunites and common dunites are characterized by high TiO_2 .

A negative correlation between the modal olivine and Al_2O_3 contents of coexisting orthopyroxene

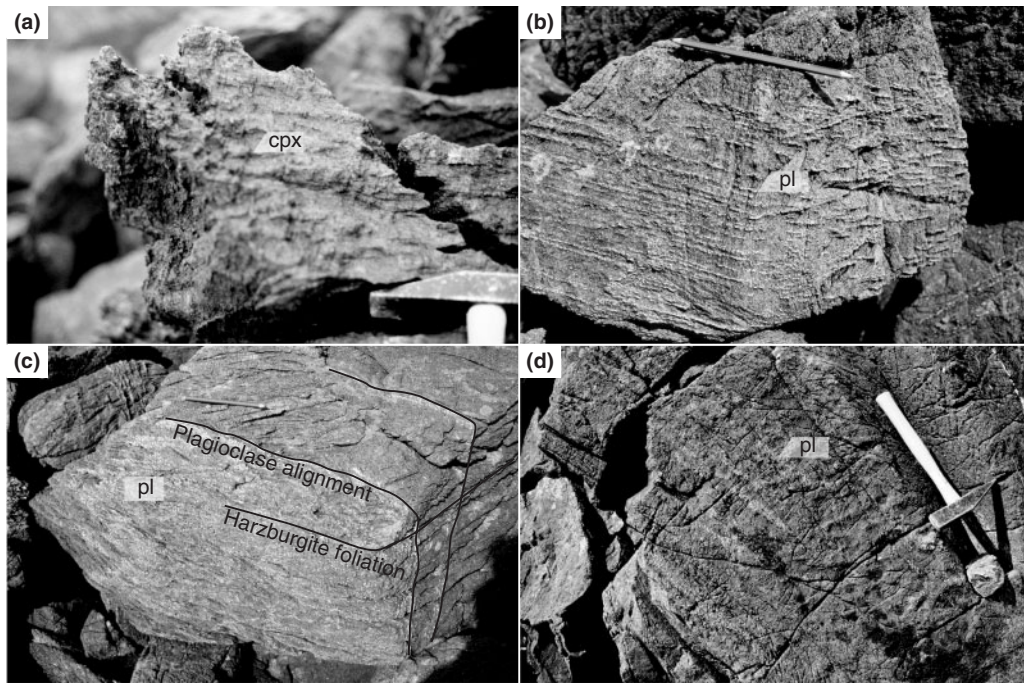


Fig. 4. Field occurrences of clinopyroxene and plagioclase seams in dunite and harzburgite. (a) Clinopyroxene grains in dunite (Upper Unit); (b) and (c) plagioclase grains in harzburgite (Lower Unit); (d) plagioclase grains in dunite (Upper Unit).

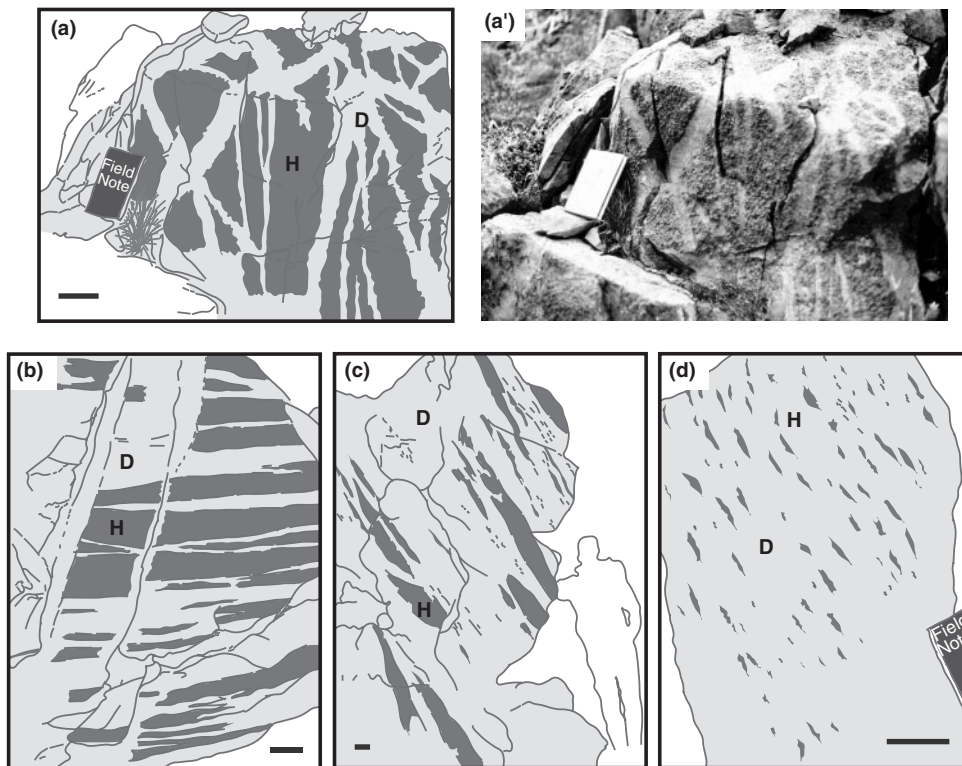


Fig. 5. Representative field relationships between common dunite (D) and harzburgite (H) in the Upper Unit. Scale bars represent 10 cm in each case. (a) Dunite replaces harzburgite. This is similar to the replacive dunite of Kelemen *et al.* (1995). (a') Original photograph of (a). (b) Parallel occurrence of dunite and harzburgite; this is the so-called 'layering'. (c) Harzburgite as lenses or blocks in dunite matrix. (d) Flaky occurrence of harzburgite in dunite matrix.

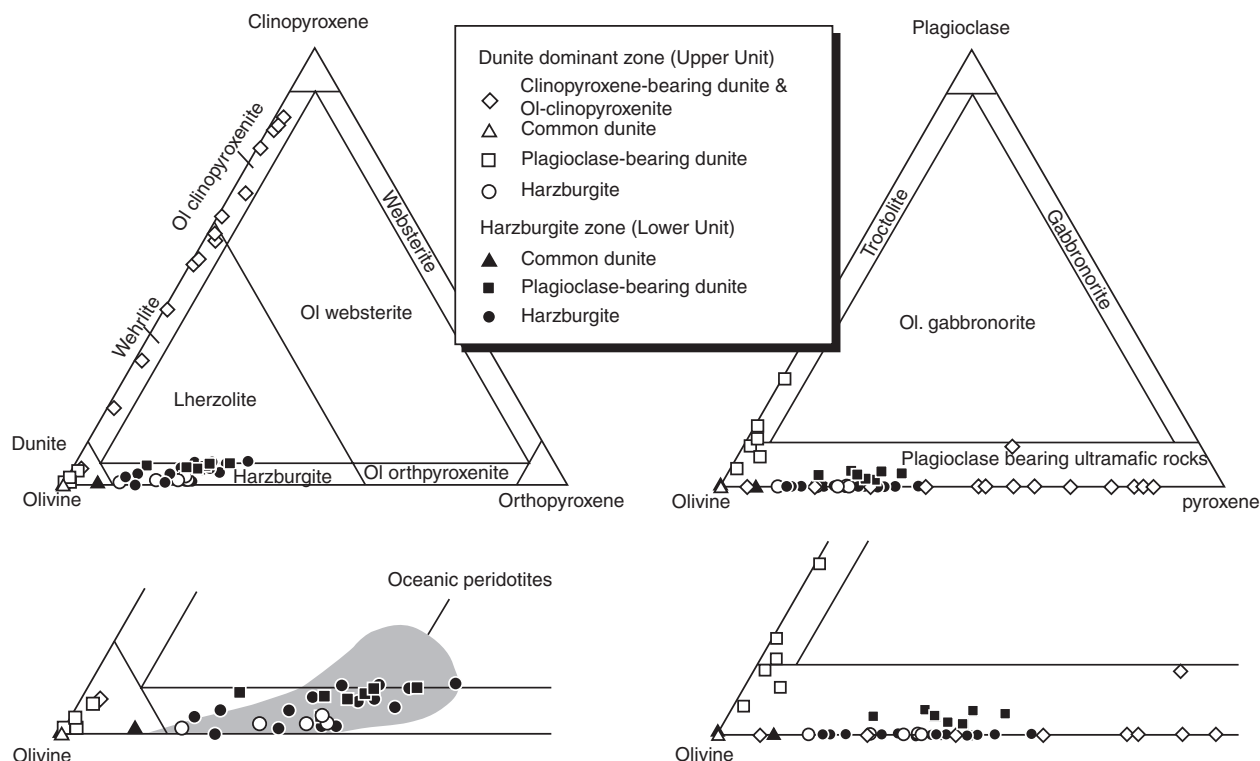


Fig. 6. Modal compositions of rocks from the Red Hills peridotite. Open symbols, Upper Unit; filled symbols, Lower Unit. Shaded area is the field of oceanic peridotites (Hamlyn & Bonatti, 1980; Dick *et al.*, 1984; Michel & Bonatti, 1985; Dick, 1989). Lower Unit rocks scatter across the oceanic peridotite field, which is also known as the residual upper mantle field.

is recognized in Lower Unit rocks (Fig. 10). This agrees with the residual harzburgite trend of oceanic peridotites (Dick *et al.*, 1984).

Whole-rock chemistry

Whole-rock major element compositions are reported in Table 2. All harzburgites in the Lower Unit have high MgO contents, and low Al₂O₃ and CaO contents (Fig. 11). Major element compositions of the Lower Unit harzburgites (filled symbols in Fig. 11) are homogeneous, and the compositional ranges are similar to those of oceanic, ophiolitic and alpine peridotites. Plagioclase-bearing harzburgites have less refractory compositions than plagioclase-free harzburgites, characterized by lower MgO and higher SiO₂, Al₂O₃ and CaO contents. In contrast, rocks from the Upper Unit show wide compositional ranges (open symbols in Fig. 11). The chemical compositions of clinopyroxene dunite are controlled by the modal abundance of clinopyroxene, and have higher CaO and Al₂O₃ contents than harzburgites from the Lower Unit. Chemical variation within the plagioclase dunites is controlled by plagioclase modal abundances, and the rocks have high Al₂O₃ contents. The chemical compositions of the Upper Unit harzburgites differ from those of the

Lower Unit. Blocky harzburgites in the Upper Unit are characterized by lower SiO₂, Al₂O₃ and CaO contents and higher FeO* than the Lower Unit harzburgites at a given MgO. Chemical variations in the Upper Unit harzburgites thus have different trends from those of the Lower Unit harzburgites (Fig. 11b and d). These whole-rock chemical characteristics of the harzburgite in the Upper Unit are consistent with the modal compositions (Fig. 6), in which modal clinopyroxene in the Upper Unit harzburgite is lower than that in the Lower Unit.

Clinopyroxene REE chemistry

REE abundances in clinopyroxenes in the Red Hills ultramafic rocks are listed in Table 3. Chondrite-normalized REE patterns of clinopyroxenes from the Lower Unit harzburgite have extremely steep slopes in the light REE–middle REE (LREE–MREE) region (Fig. 12f). Although some clinopyroxenes are similar to those of oceanic peridotites from normal ridge segments (Johnson *et al.*, 1990; Johnson & Dick, 1992; Seyler & Bonatti, 1997), the extent of LREE depletion is much higher, and is comparable with or even greater than that observed in the Bouvet hotspot (Johnson *et al.*, 1990; Johnson & Dick, 1992).

Table 1: Modal compositions (%) of rocks from the Red Hills ultramafic body

Upper Unit:	Harzburgite					Dunite					Clinopyroxene-bearing dunite and ol clinopyroxenite				
	RH-07	RH-08	RH-27	RH-30	RH-33	RH-20	RH-21	RH-22	RH-26	RH-32	RH-06	RH-09	RH-11	RH-13	RH-14
Olivine	71.9	80.7	76.5	72.1	74.0	97.5	97.8	97.7	97.6	99.1	17.7	29.6	15.9	79.4	93.6
Orthopyroxene	22.2	9.9	16.8	20.9	23.9	0	0	0	0	0	1.1	2.6	1.5	1.3	1.7
Clinopyroxene	1.9	0.5	1.1	1.0	1.3	0	0	0	0	0	80.3	64.8	80.8	17.2	3.6
Spinel	0.8	0.7	0.8	1.5	0.8	2.5	2.2	2.3	2.4	0.9	0	0.1	0	2.1	1.1
Plagioclase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others*	3.2	8.1	4.8	4.5	0	0	0	0	0	0	1.0	2.8	1.8	0	0

Upper Unit:	Clinopyroxene-bearing dunite and olivine clinopyroxenite									Plagioclase-bearing dunite					
	RH-16	RH-18	RH-19	RH-23	RH-25	RH-29	RH-31	RH-34	RH-35	RH-12	RH-15	RH-17	RH-24	RH-28	RH-36
Olivine	48.5	47.1	69.2	14.1	58.3	22.2	33.6	37.0	41.5	83.9	86.9	84.7	73.7	93.0	86.6
Orthopyroxene	0.6	0.9	1.3	1.7	0.5	0.5	0.7	1.2	2.2	0.1	0.8	0.4	0.4	0.8	1.4
Clinopyroxene	50.2	51.4	28.1	83.5	39.4	76.5	54.6	51.4	55.3	0.4	0.5	1.5	0	0.4	3.0
Spinel	0.6	0.6	1.4	0.7	1.7	0.7	0.7	1.4	0.9	2.0	2.2	2.1	1.6	1.7	2.4
Plagioclase	0	0	0	0	0	0	0	9.0	0	13.6	9.2	10.6	24.3	4.1	6.6
Others*	0	0	0	0	0	0	10.4	0	0	0	0.4	0.8	0	0	0

Lower Unit:	Harzburgite														
	RH-38	RH-41	RH-42	RH-44	RH-45	RH-46	RH-47	RH-48	RH-51	RH-55	RH-56	RH-57	RH-58	RH-60	RH-61
Olivine	65.1	72.8	68.1	84.5	75.7	72.4	71.7	60.0	66.8	67.8	73.9	75.0	67.3	74.9	79.0
Orthopyroxene	29.6	22.2	26.7	11.1	21.1	23.0	23.3	33.4	26.6	27.3	21.1	21.4	29.5	23.4	19.8
Clinopyroxene	4.8	3.7	3.7	1.9	2.4	3.5	4.3	5.4	5.2	3.8	4.1	2.4	2.9	0.8	0.7
Spinel	0.4	1.2	1.1	0.8	0.8	1.1	0.7	1.1	1.1	1.1	0.8	1.3	0.4	1.0	0.5
Plagioclase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Others*	0	0	0.3	1.7	0	0	0	0	0.4	0	0	0	0	0	0

Lower Unit:	Harzburgite						Plagioclase-bearing harzburgite						Dunite		
	RH-62	RH-63	RH-65	RH-66	RH-67	RH-68	RH-37	RH-49	RH-50	RH-52	RH-53	RH-54	RH-69	RH-43	RH-59
Olivine	70.0	71.0	77.1	82.2	73.5	71.7	69.8	65.9	62.1	71.2	75.6	68.2	85.3	98.4	92.4
Orthopyroxene	25.6	23.2	19.8	13.1	25.0	23.2	24.2	25.5	29.5	21.9	13.3	25.5	14.1	0.1	6.7
Clinopyroxene	3.5	5.2	2.6	2.6	1.0	4.3	3.5	4.5	4.7	3.8	4.1	4.2	0	0.1	0.4
Spinel	0.8	0.6	0.5	2.3	0.6	0.9	0.6	0.7	0.6	0.4	0.5	0.5	0.5	1.4	0.5
Plagioclase	0	0	0	0	0	0	1.8	3.3	3.1	2.7	2.4	1.6	0	0	0
Others*	0	0	0	0	0	0	0	0	0	0	4.1	0	0	0	0

*Serpentinite and altered minerals.

HREE abundances range between one and nine times chondrite; one of the most depleted samples is comparable with the most depleted of the Hess Deep peridotites (Dick & Natland, 1996).

Clinopyroxenes in harzburgite from the uppermost part of the Lower Unit and in blocky harzburgite in the Upper Unit exhibit different REE patterns from those in the Lower Unit (Fig. 12e). Although two samples have

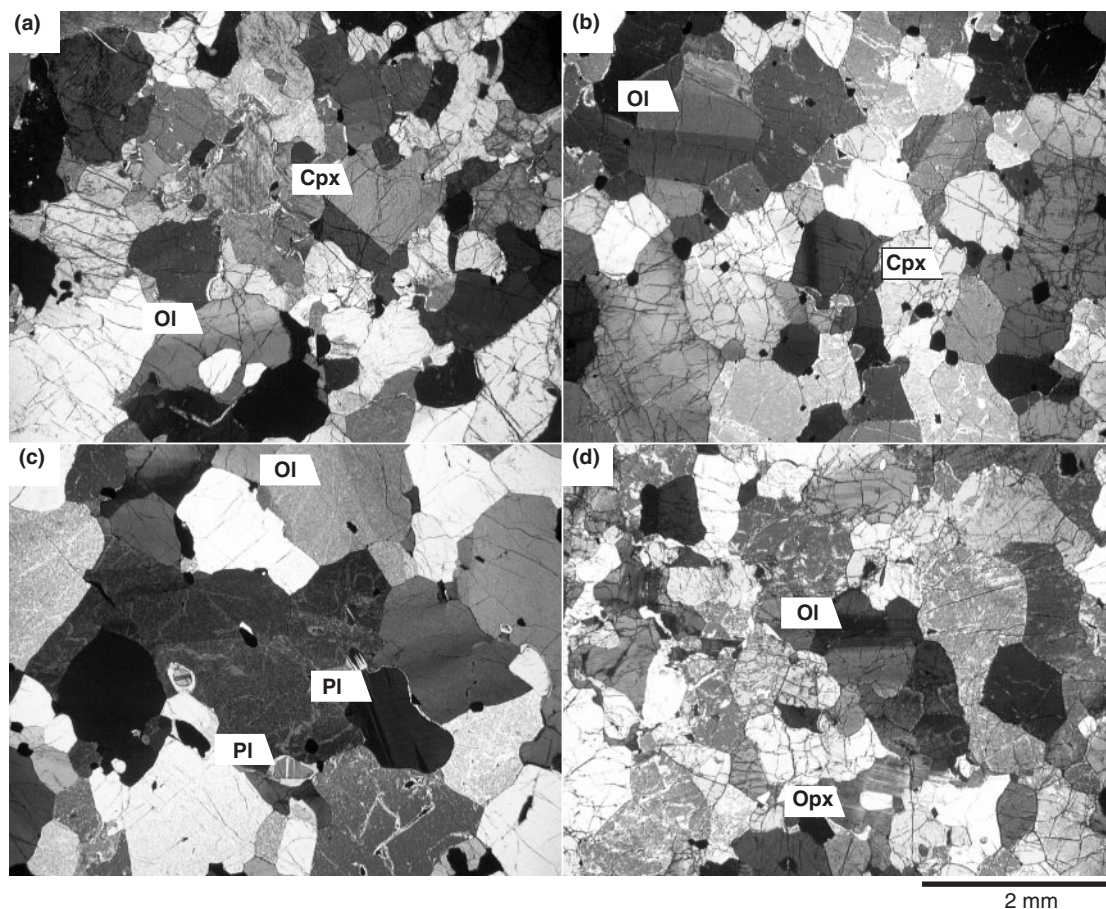


Fig. 7. (a–d) Photomicrographs of rocks from the Upper Unit (in cross-polarized light). (a) Clinopyroxene-bearing dunite (Sample 18). Some clinopyroxene crystals display magmatic twins. (b) Common dunite (Sample 20). Interstitial clinopyroxene rarely occurs between olivine crystals. (c) Plagioclase-bearing dunite (Sample 28). Droplet-shaped plagioclase within olivine crystals. (d) Harzburgite in dunite matrix (Sample 33). The harzburgite displays statically recrystallized texture. (e–h) Textures of rocks from the Lower Unit. (e) Occurrence of large, irregular crystals of clinopyroxene in harzburgite (Sample 38). (f) and (g) Plagioclase-bearing harzburgite. (h) Harzburgite.

very depleted HREE, LREE abundances are clearly an order of magnitude greater than those in the Lower Unit harzburgite.

Clinopyroxenes in common dunite, clinopyroxene dunite and plagioclase dunite from the Upper Unit show REE distinct patterns. Clinopyroxenes interstitial to olivine in common dunite have convex-upward patterns with Tb apices (Fig. 12b).

Clinopyroxenes from clinopyroxene dunite and plagioclase dunite also display strongly LREE-depleted patterns, whereas the MREE–HREE (heavy REE) abundances in the clinopyroxene from the plagioclase dunite are significantly greater than those in clinopyroxene dunite (Fig. 12c and d). The REE abundances and patterns of clinopyroxenes in the clinopyroxene dunite are in the range of those exhibited by mid-ocean ridge cumulates (Ross & Elthon, 1993), whereas those in plagioclase dunite are

very similar to those in normal ridge abyssal peridotite (Johnson *et al.*, 1990; Johnson & Dick, 1992).

DISCUSSION

Field and microscopic observations, modal compositions and geochemical characteristics of minerals and whole-rocks indicate that the Red Hills ultramafic body resembles the MTZ and residual mantle sections seen in many ophiolites (Quick, 1981a, 1981b; Benn *et al.*, 1988; Boudier & Nicolas, 1995). In the case of the Oman Ophiolite, the MTZ includes the melt-impregnated part of the residual mantle section. Our interpretation is that the MTZ in the Red Hills body is composed of the dunites of the Upper Unit and plagioclase harzburgite zone of the Lower Unit, whereas the plagioclase-free harzburgite in the Lower Unit corresponds to the

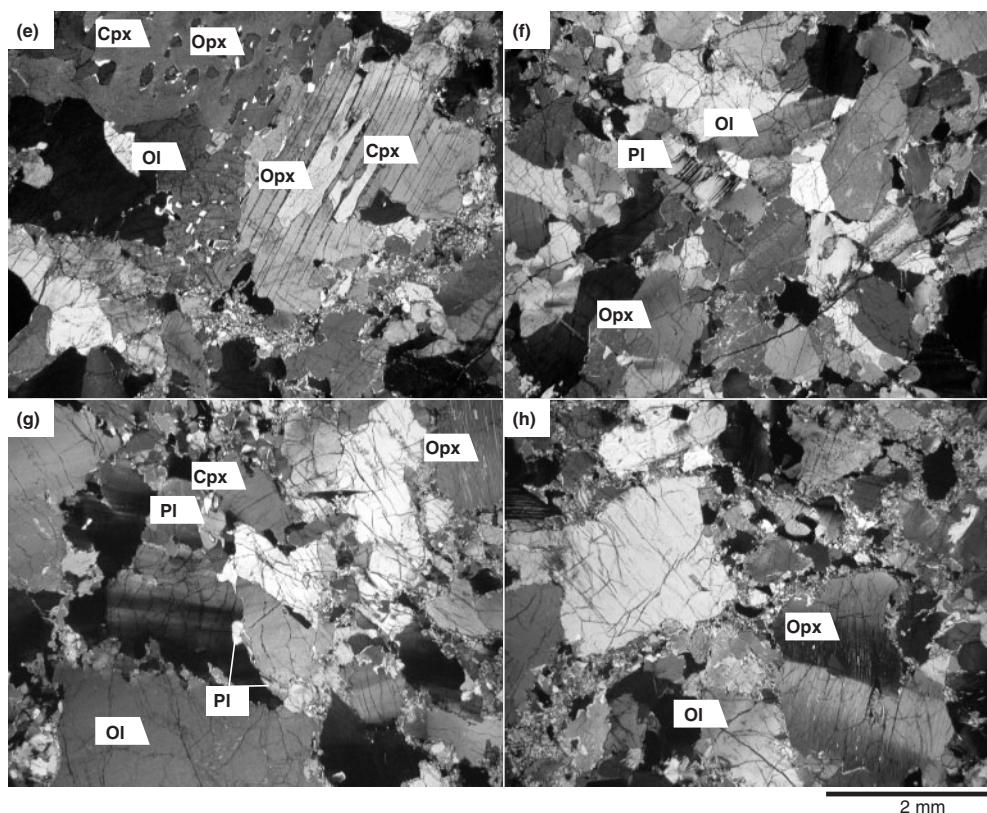


Fig. 7. Continued.

residual mantle section. In the following section we discuss the origin of the Red Hills peridotites using clinopyroxene REE chemistry. Fractional melting, refertilization, and reactive melt flow play key roles in the formation of these peridotites.

Formation of residual harzburgite by two-stage fractional melting

Clinopyroxenes in residual harzburgite from the mantle section show extreme LREE depletion (Fig. 12). Although the REE patterns of clinopyroxenes in the residual peridotites of normal mid-ocean ridges can be formed by fractional melting of a MORB-source mantle in the spinel field (Johnson *et al.*, 1990), the ultra-depleted LREE patterns observed here (Fig. 12) cannot be explained by simple spinel field processes. Johnson *et al.* (1990) also reported extremely MREE–LREE-depleted clinopyroxenes from the Bouvet and Discovery II fracture zones of the Southwest Indian Ridge. These fracture zones are thought to have been influenced by hotspot magma activity. Johnson *et al.* (1990) explained the characteristic REE patterns by dynamic melting that occurred in the source mantle in the garnet field, prior to melting in the spinel field. The ultra-depletion of LREE in the Red Hills mantle section harzburgites may also be explained by such polybaric melting processes.

To model the melting process, we assume fractional melting, because neither batch nor critical melting (Langmuir *et al.*, 1977; Sobolev & Shimizu, 1992) models can generate ultra-depleted LREE patterns. We used a MORB-source mantle (Salters & Stracke, 2004) for the model calculation. The distribution coefficients between minerals and melt, starting solid mode and melting mode parameters used are listed in Tables 4 and 5. The calculation scheme follows Shaw (1970) and Johnson *et al.* (1990). If a MORB-source mantle melts fractionally in the garnet field and garnet remains as a residual solid, the clinopyroxene in the residue shows REE patterns that are humped in the segment Nd to Er (Fig. 13b). Even after 15% melting in either the garnet or spinel fields, clinopyroxene REE patterns in the residual solid similar to those in the harzburgite cannot be achieved by the models (Fig. 13a and b).

We also tested a two-stage fractional melting model, with initial melting in the garnet field followed by melting in the spinel field. Four cases were calculated, for 1%, 5%, 10% and 15% melting in the garnet field. The residue compositions at each degree of melting are listed in Table 6. The garnet-bearing residual mantle changes in accordance with the subsolidus decompression reaction from olivine + garnet to 1.25 orthopyroxene + spinel + 0.75 clinopyroxene

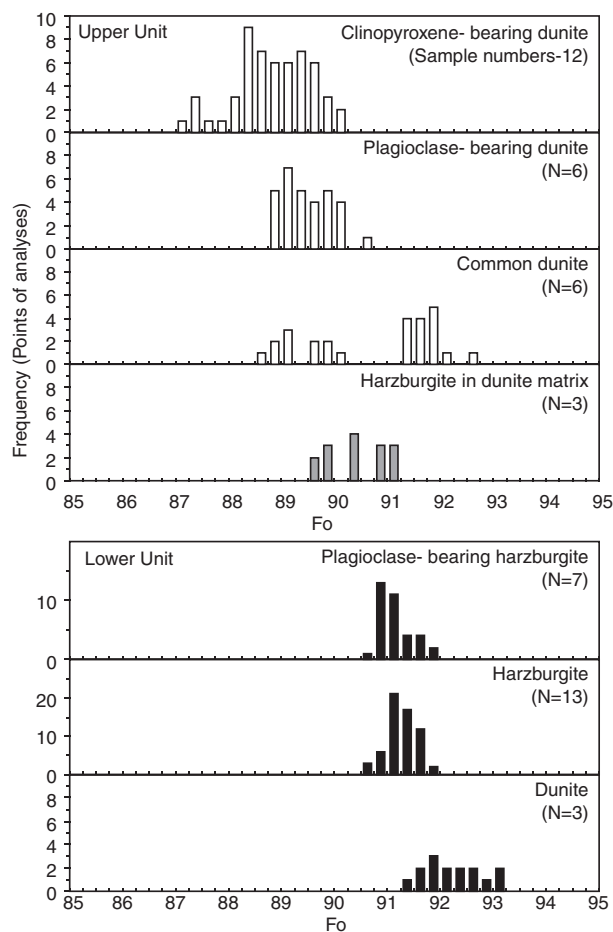


Fig. 8. Histograms of Fo contents in olivine in each rock type. Harzburgite and plagioclase-bearing harzburgite from the Lower Unit contain very homogeneous olivine (Fo_{91}), whereas dunite is characterized by olivine with higher Fo. In contrast, compositions of olivines in the Upper Unit are more variable and Fo contents are lower. It should be noted that two types of olivine ($Fo_{91.5-92.5}$ and $Fo_{88.5-90.5}$) occur in the common dunite, and that Fo contents of olivines in Upper Unit harzburgite are lower than those in Lower Unit harzburgite.

(Johnson *et al.*, 1990). The changes in modal abundances of the mantle source from the garnet field to the spinel field following this reaction are shown in Table 5. For example, the modal composition of the residue after 10% melting in the garnet field is olivine: orthopyroxene:clinopyroxene:garnet = 0.60:0.24:0.08:0.08 (Table 5). From the subsolidus decompression reaction above, the modal composition becomes olivine: orthopyroxene:clinopyroxene:spinel = 0.49:0.32:0.13:0.07 (Table 5). Accordingly, the clinopyroxene REE composition would change to preserve the appropriate inter-phase partitioning, as diffusion is probably sufficiently rapid at relatively high temperatures. The clinopyroxene REE pattern in the residue after 1% melting in the garnet field shown in Fig. 13b would change to that

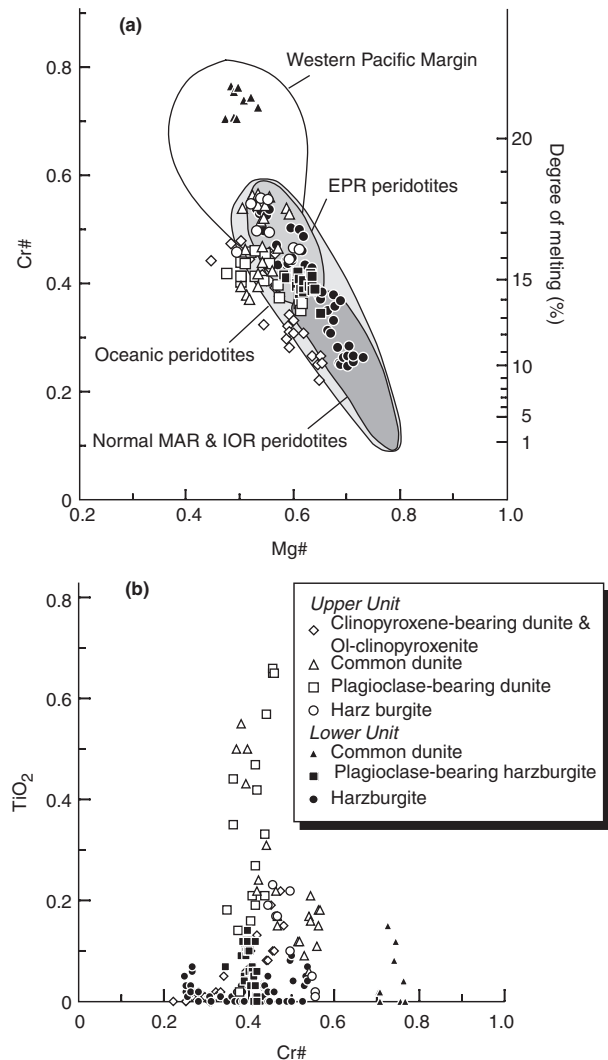


Fig. 9. (a) Mg-number vs cr-number in peridotite spinels. Data sources for the fields of oceanic peridotites are: Dick *et al.* (1984), Michel & Bonatti (1985) and Johnson *et al.* (1990) for normal Mid-Atlantic Ridge (MAR) and Indian Ocean Ridge (IOR); Hékinian *et al.* (1993), Constantin *et al.* (1995) and Dick & Natland (1996) for Garrett, Hess Deep and Terevaka near the East Pacific Rise (EPR); and Ishii (1985) for the western Pacific margin. It should be noted that spinels from the Upper Unit (open symbols) plot at lower mg-number than those from the Lower Unit (filled symbols). Degree of melting (%) calculated using the method of Hellebrand *et al.* (2001). (b) TiO_2 vs Cr-number in peridotite spinels. Spinels in the Upper Unit, especially plagioclase-bearing dunite and common dunite, are characterized by higher TiO_2 content at Cr-number 0.4.

indicated by the bold dashed line in Fig. 13c. Similarly, the clinopyroxene REE patterns in the residue after 5%, 10% and 15% melting in the garnet field (Fig. 13b) change to form the patterns displayed by the bold dashed lines in Fig. 13d–f, respectively. With the modal abundances newly equilibrated to the spinel field, melting calculations were performed for each residual

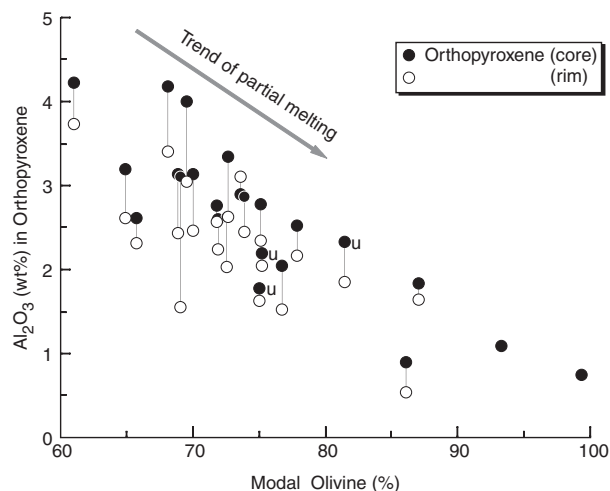


Fig. 10. Modal olivine contents in Upper and Lower Unit harzburgites and Lower Unit dunites vs Al_2O_3 in orthopyroxenes. Individual data points represent the averages in each sample. Data points labelled 'u' are from blocky harzburgites in the Upper Unit. The correlation demonstrates that they represent residues of variable degrees of partial melting (Dick *et al.*, 1984).

mantle source composition to estimate the residual clinopyroxene REE patterns after 1–25% melting in the spinel field (Fig. 13c–f). As a result, the ultra-depleted LREE patterns in clinopyroxenes can be explained by two-stage melting, with ~10% fractional melting of a MORB-source mantle in the garnet field, and ~12% further fractional melting in the spinel field. This corresponds to total melting of 10–22% through the garnet to spinel fields.

Johnson *et al.* (1990), Hellebrand *et al.* (2002a), and Barth *et al.* (2003) have previously pointed out that LREE-depleted clinopyroxenes in harzburgites cannot be explained by simple batch or fractional melting processes in the spinel field, and that multiple-stage fractional melting in the garnet and spinel stability fields is required. Barth *et al.* (2003) estimated that 4% near-fractional melting in the garnet field and an additional 12–20% near-fractional melting in the spinel field was required to model the clinopyroxene REE pattern from the Othris ophiolite. Hellebrand *et al.* (2001) developed a method for estimating the degree of melting in MOR peridotites based on spinel cr-number. The range of total melting estimated from the cr-number of the Red Hills harzburgites is about 10–18% (Fig. 9). This agrees well with the estimation from the clinopyroxene REE patterns (Fig. 13). Olivine and spinel compositions from the harzburgites in the Lower Unit plot on the residual mantle array (Fig. 14). The wide variation of spinel cr-number from 0.25 to 0.55 in a single mantle massif appears to indicate variable degrees of partial melt extraction. In contrast, the Red Hills MTZ dunites of all types plot well away from the mantle melting

array with lower Fo composition in olivine (Fig. 14), suggesting re-equilibration with MORB melts or a cumulate origin.

Refertilization in the uppermost part of the mantle section

The petrological characteristics of the plagioclase-bearing harzburgites in the uppermost part of the Lower Unit are similar to those of oceanic plagioclase peridotites (Seyler & Bonatti, 1997; Tartarotti *et al.*, 2002). Plagioclase peridotites have also been reported from ophiolites and peridotite massifs. For example, the Othris peridotite massif contains a large volume of plagioclase peridotite (Menzies, 1973; Dijkstra *et al.*, 2001; Barth *et al.*, 2003). Oceanic, ophiolitic and massif plagioclase peridotites are thought to have formed by melt impregnation of a depleted peridotite protolith (Rampone *et al.*, 1997; Seyler & Bonatti, 1997; Dijkstra *et al.*, 2001; Tartarotti *et al.*, 2002; Barth *et al.*, 2003). Crystallization of plagioclase can be regarded as evidence of refertilization of depleted peridotite by melt impregnation (Rampone *et al.*, 1997; Müntener *et al.*, 2004).

Plagioclase lenses are often observed in the harzburgite in the uppermost part of the mantle section at Red Hills (Fig. 4). The occurrence of the plagioclase is similar to that in the Othris massif. Plagioclase lenses are discordant to the foliation of the harzburgite in both cases. Under the microscope plagioclase crystals display rounded droplet- or bleb-like shapes (Fig. 7c, f and g). The plagioclase blebs are found along grain boundaries between mafic minerals. The field occurrence and microstructures of plagioclase in the harzburgite (Fig. 4b and c) support plagioclase crystallization by melt impregnation of the harzburgite.

Irregular aggregations of large crystals of clinopyroxene are observed in the harzburgite of the uppermost part of the mantle section (Fig. 7e). The occurrence of these clinopyroxene aggregations is similar to that in peridotites at the recrystallization front of the Ronda massif (Lenoir *et al.*, 2001). Lenoir *et al.* (2001) suggested that coarse-granular peridotite containing clinopyroxene aggregations was formed by partial solidification of percolating melt, leading to peridotite refertilization. Harzburgite blocks in the dunite matrix in the Red Hills MTZ are also characterized by identical recrystallization textures (Fig. 7d), which look like the statically recrystallized harzburgites in the Ronda peridotite, suggesting that melt impregnation and recrystallization took place in the uppermost residual mantle section and in the blocky harzburgite in the MTZ.

Clinopyroxenes in the uppermost harzburgite in the mantle section and those in the blocky harzburgite in the MTZ (Upper Unit) have LREE-depleted REE patterns; however, the degree of depletion is less marked than in the Lower Unit harzburgites (Fig. 12e).

Table 2: Whole-rock major element abundances of the Red Hills ultramafic body

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MnO	MgO	CaO	Na ₂ O	LOI	Total	Mg-no.
Upper Unit											
<i>Gabbroic sill</i>											
RH-03	44.40	0.13	13.39	4.96	0.08	18.71	13.12	2.15	2.71	99.65	0.882
<i>Clinopyroxene-bearing dunite and olivine clinopyroxenite</i>											
RH-06	49.64	0.03	3.01	5.41	0.11	22.20	17.65	0.10	1.28	99.43	0.891
RH-11	48.95	0.11	2.51	6.55	0.13	23.85	16.15	0	2.10	100.35	0.878
RH-13	42.61	0.06	1.21	9.41	0.15	40.27	5.28	0	0.14	99.13	0.895
RH-18	43.88	0.03	1.43	9.48	0.15	38.04	6.91	0.03	0.01	99.96	0.888
RH-19	42.49	0.04	1.18	9.74	0.15	39.96	5.59	0	0.15	99.30	0.891
RH-23	49.40	0.07	3.00	5.87	0.13	24.04	16.33	0.30	0.15	99.29	0.890
RH-25	43.93	0.06	1.31	9.61	0.15	37.26	7.40	0	0	99.72	0.885
RH-29	49.49	0.07	2.23	6.03	0.13	24.15	17.01	0	0.38	99.49	0.888
RH-34	45.99	0.06	2.94	7.53	0.13	31.86	10.93	0	0	99.44	0.893
RH-35	46.80	0.05	2.32	7.04	0.12	31.01	12.27	0.06	0.09	99.76	0.897
<i>Plagioclase-bearing dunite</i>											
RH-12	39.85	0.05	4.39	10.52	0.15	42.01	2.12	0.07	1.40	100.56	0.888
RH-15	40.03	0.07	3.91	11.35	0.17	41.08	2.63	0.23	0	99.47	0.878
RH-17	40.04	0.06	3.26	11.18	0.17	43.52	1.86	0.38	0.02	100.49	0.885
RH-24	39.48	0.03	5.07	9.73	0.14	40.53	2.72	0	1.50	99.20	0.892
RH-28	40.30	0.05	1.80	11.44	0.17	46.62	1.15	0	0	101.53	0.890
RH-36	40.43	0.05	3.19	11.38	0.17	41.37	3.36	0	1.05	101.00	0.878
<i>Common dunite</i>											
RH-20	39.62	0.04	0.45	9.72	0.15	49.13	0.15	0	0	99.26	0.909
RH-21	39.69	0.04	0.40	10.97	0.16	48.45	0.16	0	0	99.87	0.898
RH-22	39.57	0.05	0.52	9.70	0.15	49.02	0.14	0	0.44	99.59	0.909
RH-26	38.30	0.06	0.78	12.67	0.18	45.25	0.20	0	2.13	99.57	0.876
RH-32	40.21	0.04	0.19	9.75	0.14	49.26	0.20	0	0.16	99.95	0.909
<i>Harzburgite</i>											
RH-07	41.72	0.06	0.80	9.37	0.15	42.08	0.84	0	4.61	99.63	0.899
RH-08	42.05	0.04	0.49	9.51	0.14	46.56	0.50	0	1.68	100.97	0.907
RH-27	43.16	0.05	0.73	10.94	0.15	43.71	1.11	0	0.15	100.00	0.888
RH-30	42.05	0.04	0.61	9.14	0.13	43.01	0.72	0	4.31	100.01	0.903
RH-33	43.47	0.04	0.61	10.29	0.14	44.21	0.67	0	0.44	99.87	0.895
Lower Unit											
<i>Plagioclase-bearing harzburgite</i>											
RH-37	45.31	0.04	1.84	8.68	0.13	42.46	2.05	0	0.05	100.56	0.907
RH-40	44.43	0.04	1.94	8.94	0.13	42.07	2.22	0.49	0.03	100.29	0.903
RH-49	44.12	0.05	1.78	8.84	0.13	42.97	2.02	0	0	99.91	0.906
RH-50	44.57	0.06	1.96	8.82	0.14	42.77	2.13	0	0	100.45	0.906
RH-52	44.98	0.06	1.89	8.93	0.13	42.29	2.07	0	0	100.35	0.904
RH-53	44.25	0.05	1.96	8.88	0.14	41.63	2.42	0	0.57	99.90	0.903
RH-54	44.40	0.04	1.64	9.00	0.14	42.87	1.83	0	0	99.92	0.904
<i>Dunite</i>											
RH-43	40.55	0.03	0.16	8.58	0.12	49.95	0.12	0	0.24	99.75	0.920
RH-59	42.99	0.03	0.29	9.31	0.14	47.11	0.35	0	0	100.22	0.909

(continued)

Table 2: Continued

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MnO	MgO	CaO	Na ₂ O	LOI	Total	Mg-no.
<i>Harzburgite</i>											
RH-44	43.22	0.04	0.58	8.98	0.14	45.81	1.21	0	0.06	100.04	0.910
RH-45	43.94	0.04	0.73	8.95	0.14	45.48	1.11	0	0	100.39	0.910
RH-46	44.47	0.05	1.34	8.70	0.13	44.30	1.60	0	0	100.59	0.910
RH-47	44.22	0.04	0.90	8.87	0.14	44.73	1.23	0	0	100.13	0.909
RH-48	44.83	0.04	1.81	8.70	0.14	42.55	2.12	0	0	100.19	0.907
RH-51	44.05	0.05	1.68	8.80	0.14	43.38	1.88	0	0.10	100.08	0.907
RH-55	44.42	0.04	1.13	8.79	0.13	44.76	1.27	0	0	100.54	0.910
RH-63	44.18	0.04	0.91	9.01	0.13	45.25	1.18	0	0	100.70	0.909
RH-65	43.64	0.03	0.77	9.00	0.13	45.12	1.00	0	0	99.69	0.909
RH-66	43.25	0.05	1.06	9.24	0.14	45.13	1.19	0	0	100.06	0.906
RH-68	44.73	0.04	1.28	8.80	0.13	44.03	1.40	0	0	100.41	0.908
RH-69	42.77	0.04	0.25	8.92	0.13	47.45	0.28	0	0	99.84	0.913

*Total iron as Fe₂O₃.
LOI, loss on ignition.

The chondrite-normalized La abundance in the clinopyroxenes is $(La)_N = 0.05\text{--}0.1$, whereas that in the normal harzburgite in the mantle section is much lower [$(La)_N < 0.01$; Fig. 12f]. Relatively high LREE abundances in clinopyroxene in the uppermost harzburgite and in the blocky harzburgite may be caused by circulation of a small melt fraction. Godard *et al.* (2000) examined the REE patterns of peridotites in the residual mantle of the Oman ophiolite, and concluded that cpx-rich harzburgites showing ‘spoon-shape’ REE patterns were the products of a cpx-forming melt–rock reaction, indicating refertilization. The degree of selective LREE enrichment is probably related to the circulation of a small melt fraction through the peridotite (Bodinier & Godard, 2003). Spoon-shaped REE patterns or LREE enrichment of clinopyroxene have also been regarded as the products of chromatographic reaction between melt and wall-rock (Navon & Stolper, 1987; Takazawa *et al.*, 1992). The Red Hills clinopyroxenes with relatively high LREE abundances in the uppermost mantle section and in the blocky harzburgites could presumably be generated by refertilization of the depleted mantle by melt percolation. The varied lithologies that formed in the uppermost part of the residual mantle, ranging from plagioclase-bearing harzburgite and dunite to clinopyroxene-bearing dunite, can be explained by this secondary process.

Reactive melt flow model for harzburgite and dunite formation

An alternative model for mantle melting is a ‘chromatographic’ or a ‘reactive melt percolation’ process

(e.g. Navon & Stolper, 1987; Vernières *et al.*, 1997). Vernières *et al.* (1997) proposed a plate model for the geochemical simulation of melt reaction and migration in the mantle. We applied REE plate model calculations to simulate the reactive melt migration in the Red Hills harzburgites and dunites, to examine the role of percolated melts in depletion and refertilization in the upper mantle section.

For the harzburgite model, we used the bulk REE composition of a Red Hills harzburgite as the starting composition (Table 7). The Red Hills harzburgite itself is much more depleted than any mantle reservoir, such as primitive mantle (e.g. Sun & McDonough, 1989) or depleted MORB-source mantle (e.g. Salters & Stracke, 2004). To generate such marked depletion, near fractional melting in the garnet or spinel fields with about 10–18% melting is required, as discussed above. The melts generated under these conditions should have a MORB composition (Salters & Stracke, 2004). Consequently, the strongly depleted harzburgite composition observed at Red Hills is regarded as residual after melt extraction.

We assumed the initial mineralogy to be olivine:orthopyroxene:clinopyroxene in the proportions 0.70:0.20:0.10 (Table 7). This assumption is based on the sub-solidus mineralogy at 1 GPa of a depleted mantle source (Workman & Hart, 2005) after 10% MORB extraction. This was obtained from calculations using pMELTS (Ghiorso *et al.*, 2002) associated with the adiabat.lph program (Smith & Asimow, 2005). We set 20 vertical cells for the reaction model, using the following melting parameters: (1) 5% compaction

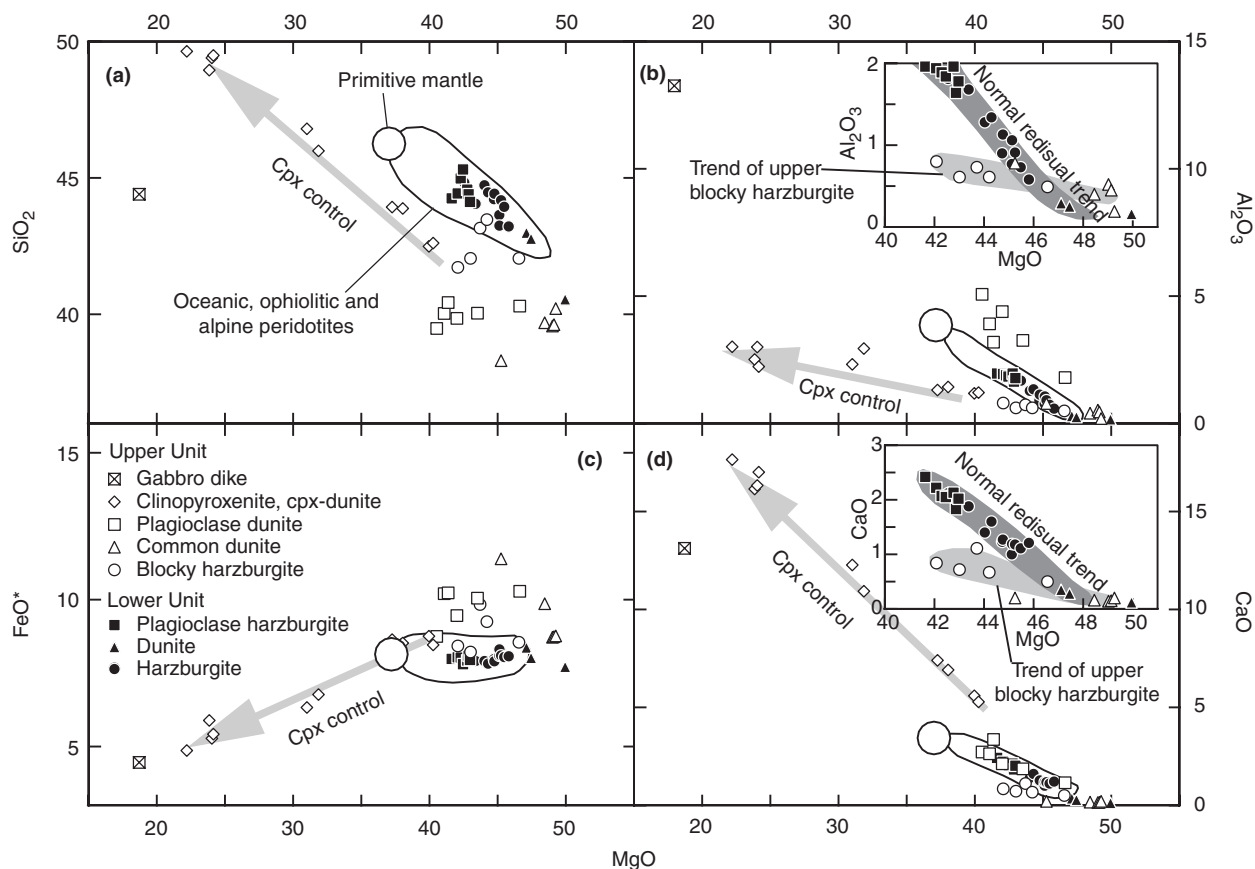


Fig. 11. Whole-rock oxide wt% plotted against MgO wt% for harzburgites and dunites. (a) MgO vs SiO₂; (b) MgO vs Al₂O₃; (c) MgO vs FeO*; (d) MgO vs CaO. Open symbols, Upper Unit; filled symbols, Lower Unit. The trend of harzburgites and dunites from the Lower Unit matches that of normal residual peridotites in (b) and (d). It should be noted that the trend of blocky harzburgites in the Upper Unit has a gentler slope. Data for oceanic, ophiolitic and alpine peridotites from Prinz et al. (1976), Ernst (1978), Frey et al. (1985), Bodinier (1988), Bodinier et al. (1988), Loney & Himmelberg (1989), Dick (1989), Rampone et al. (1995) and Niu (1997). Primitive mantle compositions are from McDonough & Sun (1995) and references therein.

limit; (2) melting mineralogy olivine:orthopyroxene:clinopyroxene = 0.0:0.1:0.99 in a cell at 5% melting; (3) no melt influx at the bottom cell. This model simulates melting occurring in the spinel field at the base of the column. The melts generated migrate upwards when degrees of partial melting exceed 5% in each cell [parameters from Vernières *et al.* (1997)]. The harzburgite mineralogy produced after 20 steps is designed to correspond to the observed harzburgites (modal clinopyroxene <5%). The clinopyroxene REE compositions in each cell were calculated from the interstitial melt compositions (Fig. 15).

The calculated results from the lower five cells reproduce the ultra LREE-depleted patterns of the clinopyroxenes in the Lower Unit harzburgites fairly well (Fig. 15a). The clinopyroxenes in the upper cells (cells 10–20) are less depleted in LREE and are enriched in HREE, similar to those from the plagioclase-bearing upper harzburgite and the plagioclase dunite

in the MTZ (Fig. 15b). Moreover, the interstitial melt compositions in the upper cells (cells 10–20) are similar to the LREE-depleted melts reported by Shimizu (1998) from olivine-hosted melt inclusions in MORB from the FAMOUS area (Fig. 15a–c).

The model calculations suggest that the clinopyroxenes in the lower harzburgite and plagioclase harzburgite and plagioclase dunite with variable compositions can be generated by reactive melt flow in the spinel field, if upward reactive melt percolation occurred in the system. The advantages of this model are two-fold: (1) the vertical spatial variation in the clinopyroxene REE chemistry is reasonably explained by upward melt migration; (2) melt compositions generated at the top of the harzburgite column are similar to those actually observed in MOR. This model is also consistent with the lower Fo contents of olivine in the plagioclase dunite and upper plagioclase-bearing harzburgite (Fig. 14).

Table 3: REE concentrations (ppm) of clinopyroxene from the Red Hills ultramafic body

Sample	<i>n</i>	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
<i>Gabbroic sill (Upper Unit)</i>															
RH-03	10	0.048	0.41	0.13	1.06	0.64	0.22	1.03	0.23	1.60	0.35	0.95	0.14	0.91	0.13
<i>Plagioclase-bearing dunite (Upper Unit)</i>															
RH-17	8	0.014	0.14	0.059	0.59	0.49	0.24	0.97	0.25	1.62	0.42	1.12	0.19	1.19	0.19
RH-28	13	0.011	0.13	0.069	0.84	0.74	0.36	1.50	0.33	2.43	0.56	1.66	0.26	1.82	0.27
<i>Clinopyroxene-bearing dunite (Upper Unit)</i>															
RH-23	11	0.029	0.16	0.042	0.32	0.23	0.10	0.40	0.090	0.64	0.15	0.41	0.063	0.42	0.063
RH-29	16	0.0056	0.041	0.015	0.16	0.16	0.066	0.33	0.077	0.58	0.13	0.37	0.057	0.37	0.054
RH-34	17	0.024	0.15	0.043	0.35	0.24	0.11	0.39	0.085	0.60	0.14	0.39	0.059	0.40	0.061
<i>Common dunite (Upper Unit)</i>															
RH-20	2	0.19	0.56	0.11	0.64	0.27	0.11	0.48	0.10	0.66	0.14	0.34	0.046	0.26	0.036
RH-32	4	0.18	0.50	0.087	0.54	0.22	0.12	0.41	0.099	0.63	0.13	0.33	0.044	0.25	0.035
<i>Harzburgite (block in dunite matrix of the Upper Unit and the uppermost part of the lower Unit)</i>															
RH-27	3	0.015	0.11	0.042	0.39	0.34	0.14	0.51	0.16	1.13	0.26	0.73	0.11	0.71	0.10
RH-33	3	0.022	0.11	0.026	0.21	0.14	0.057	0.20	0.047	0.34	0.078	0.23	0.037	0.27	0.039
RH-38	11	0.012	0.043	0.0078	0.051	0.029	0.015	0.081	0.026	0.20	0.052	0.16	0.025	0.18	0.027
RH-40	2	0.011	0.058	0.012	0.081	0.092	0.049	0.41	0.13	1.14	0.30	0.93	0.15	0.95	0.14
<i>Harzburgite (Lower Unit)</i>															
RH-45	9	0.0014	0.0034	0.0010	0.0073	n.d.	0.0037	0.038	0.017	0.18	0.052	0.18	0.032	0.24	0.039
RH-46	4	—	—	—	0.0089	0.023	0.018	0.19	0.071	0.67	0.19	0.60	0.099	0.70	0.10
RH-47	10	0.0016	0.0051	0.0026	0.013	0.039	0.012	0.091	0.032	0.28	0.080	0.25	0.044	0.31	0.050
RH-48	4	n.d.	0.0011	0.0019	0.045	0.15	0.079	0.60	0.17	1.38	0.36	1.08	0.17	1.13	0.17
RH-50	6	n.d.	0.0021	0.0026	0.085	0.29	0.12	0.90	0.26	1.88	0.49	1.32	0.21	1.30	0.20
RH-44	6	0.0020	0.0063	0.0026	0.044	0.18	0.081	0.64	0.19	1.46	0.38	1.10	0.17	1.10	0.17
RH-55	1	—	—	—	—	—	0.0034	0.079	0.032	0.39	0.12	0.45	0.080	0.59	0.095
Chondrite *		0.237	0.612	0.095	0.467	0.153	0.058	0.2055	0.0374	0.2540	0.0566	0.1655	0.0255	0.170	0.0254
MORB source mantle†		0.234	0.772	0.131	0.713	0.270	0.107	0.395	0.075	0.531	0.122	0.371	0.060	0.401	0.063

Results are averaged for each sample. *n*, number of points analysed for each sample. n.d., not determined; —, below detection limit.

* Sun & McDonough (1989).

† Salters & Stracke (2004).

A discrepancy occurs in the LREE compositions of some clinopyroxenes from harzburgites, which have slightly elevated LREE and 'spoon-shaped' REE patterns as described above. This feature could be generated by influx of less depleted melts in the percolation column (e.g. Vernières *et al.*, 1997). It is possible that the harzburgite had both relatively focused and diffuse melt flow regimes, which allowed complex 3D variations in the melt migration pathways.

The REE pattern of the melt estimated from the Red Hills gabbros is not fractionated, and is similar to that of the MORB glass composition reported by Niu & Hekinian (1997) (Fig. 15). Therefore, it is probable that the gabbroic rock is a product from normal mid-ocean

ridge basalt (N-MORB). The clinopyroxenes in clinopyroxene dunite and some clinopyroxenes in harzburgite in the Upper Unit have different REE patterns with flatter and lower HREE regions (Fig. 15c). The patterns are similar to those in MOR cumulates reported elsewhere (Ross & Elthon, 1993), suggesting derivation from pooled MORB melts. This view is consistent with the observation that the modal clinopyroxene content in the clinopyroxene dunite exceeds 45% and may reach 83% (clinopyroxenite; see Table 1 and Fig. 6). The clinopyroxene chemistries of the gabbroic rocks and the clinopyroxene dunite may be explained by precipitation from MORB melts, rather than by the reactive flow model.

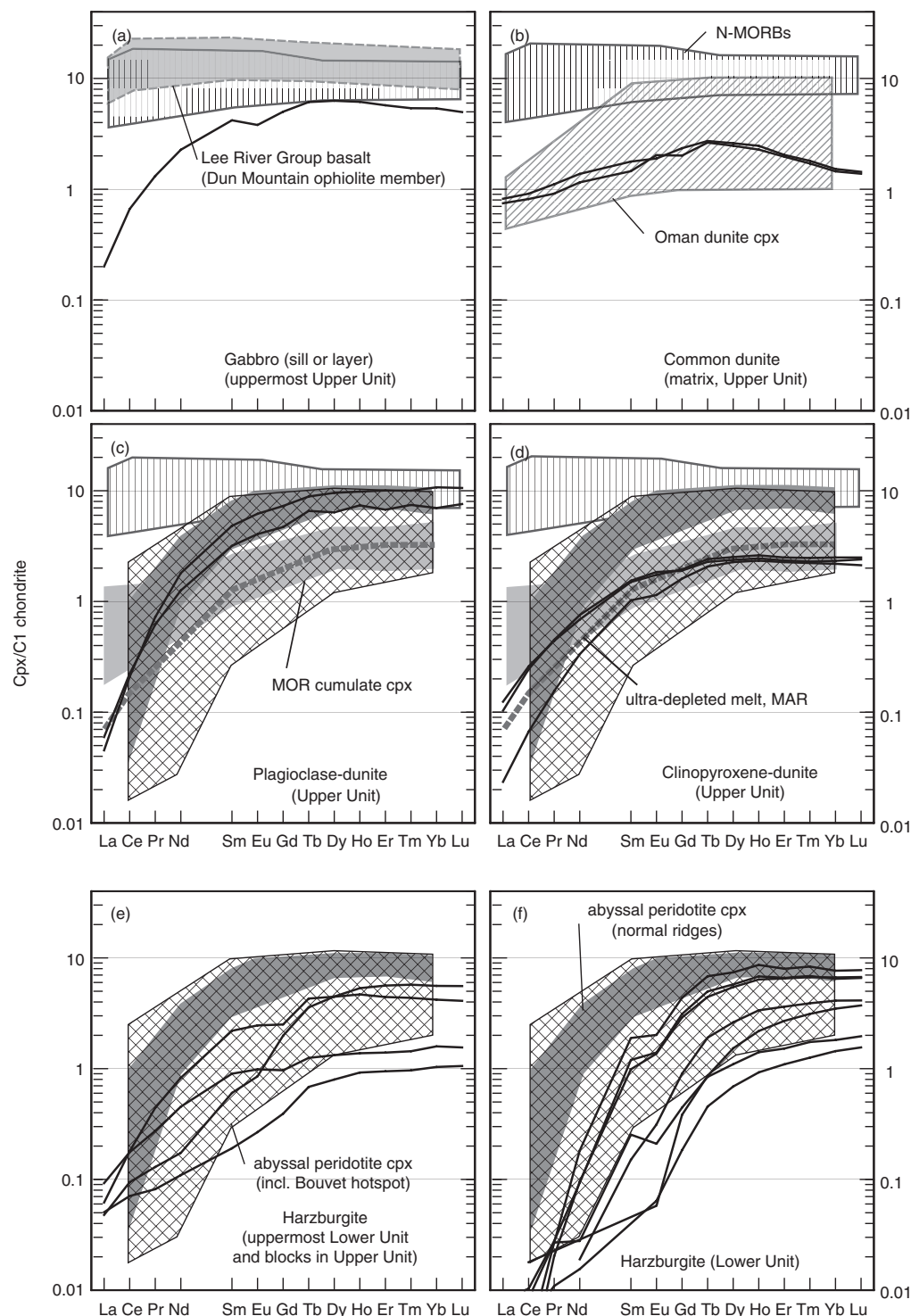


Fig. 12. (a–d) REE abundances of cpx in dunites and a gabbro from the Upper Unit. Chondrite normalization values are from Anders & Grevesse (1989). (a) Cpx in gabbro in the uppermost part of the unit. (b) Cpx in common dunite. (c) Cpx in plagioclase-bearing dunite. (d) Cpx in clinopyroxene-bearing dunite. Compositional fields of N-MORB and MOR cumulate cpx are from Ross & Elthon (1993). REE compositional field of the Lee River Group basalts in (a) is from Sano *et al.* (1997), and the field of the Oman dunite cpx in (b) is from Kelemen *et al.* (1995). The composition of ultra-depleted melt, MAR, in (c) and (d) is from Sobolev & Shimizu (1993), and the field for MOR cumulate cpx in (c) and (d) is from Ross & Elthon (1993). (e) and (f) REE abundances in cpx from harzburgites. (e) Cpx in harzburgite from the uppermost part of the mantle section and in blocky MTZ harzburgite. (f) Cpx in harzburgite. Fields of abyssal peridotite cpx in (e) and (f) are from Johnson & Dick (1992) and Johnson *et al.* (1990).

Table 4: Distribution coefficients used in the model calculations

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Olivine*	0.0004	0.0005	0.0008	0.001	0.0013	0.0016	0.0015	0.0015	0.0017	0.0016	0.0015	0.0015	0.0015	0.0015
Orthopyroxene*	0.002	0.003	0.0048	0.0068	0.01	0.013	0.016	0.019	0.022	0.026	0.03	0.04	0.049	0.06
Clinopyroxene†	0.06	0.094	0.1325	0.171	0.25	0.288	0.32	0.348	0.378	0.392	0.41	0.4025	0.399	0.39
Spinel*	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Garnet*	0.01	0.021	0.054	0.087	0.217	0.32	0.498	0.75	1.06	1.53	2.00	3.00	4.03	5.5

*After McKenzie & O’Nions (1991).

†After Vernières *et al.* (1997).

The origin of the MREE-enriched clinopyroxenes in the common dunite is still problematic. However, a plate model using the conditions of (1) source dunite with its REE composition and modal mineralogy similar to those in the Red Hills, (2) slightly LREE-enriched MORB melt infiltration, and (3) fully fractional reaction (Table 7) can generate MREE-humped clinopyroxenes in the bottom cells (cells 1 and 2, Fig. 15d). In this case, the trace amount of interstitial clinopyroxenes present in the common dunite would be the result of secondary impregnation by incipient melt infiltration after formation of the dunite body. An alternative model is simpler. If the host dunite had an extremely depleted composition, the MREE-enriched patterns could also be generated by simple precipitation of the clinopyroxene from residual interstitial MORB melt. The lowermost cells (cells 1 and 2) in the reactive flow model correspond to this condition.

Origin of common dunite in the Lower Unit and MTZ

A problem with the ‘reactive melt flow after depletion’ model is the formation mechanism of the massive common dunite and clinopyroxene dunite in the MTZ. As melts percolate from the bottom to the top of the reaction column, incremental melting would produce dunite in the lower column rather than in the upper column. This model may explain the Lower Unit dunite, which has a more depleted nature as shown by high $cr\text{-number} = 0.7\text{--}0.8$ in spinel (Fig. 14). Although focused melt flow can generate dunite conduits by the same mechanism, the formation of massive common dunite in the MTZ still seems difficult.

Common dunite in the MTZ could represent a MORB cumulate. In this scenario, the common dunite would have been refertilized by an incipient MORB melt to form the MREE-humped clinopyroxene during the later stage. However, it is difficult to form the more than 2 km thickness of common dunite in the MTZ by this mechanism. An alternative explanation is that intensive melt

extraction by reactive flow occurred during the early melting stage. If this is the case, dunite can be formed by channeled flow and at the same time as depleted harzburgite by porous flow (Kelemen, 1990). MREE-enriched clinopyroxenes in the dunite can also be formed by the residual interstitial MORB melt in an extremely depleted dunite host, as discussed above. This model seems reasonable, because MORB melts extracted in the early stage could also form the Red Hills gabbroic rocks and clinopyroxene dunite. Generation of a huge volume of MORB is also a prerequisite for the MOR system. With this model, compositionally varied clinopyroxenes in the harzburgite were generated in the later melting stage after a massive volume of MORB components had been extracted.

Mantle melting regime beneath mid-ocean ridge systems

Trace element geochemistry suggests that MORB do not equilibrate with residual abyssal peridotites (Johnson *et al.*, 1990; Johnson & Dick, 1992). This discrepancy between MORB and residual peridotite compositions at shallow levels suggests that the melt must be transported to the surface without complete re-equilibration with the surrounding peridotite (Kelemen *et al.*, 1995). Diffuse porous flow melt transport should cause intensive chemical re-equilibration and reaction, and therefore focused flow in spatially restricted conduits is needed for melt aggregation and transport, the remnant of which might be represented by dunite channel networks in the MTZ (Kelemen *et al.*, 1995). Reaction of melts against host peridotite during transport also causes significant modification and variations in melt REE composition (Vernières *et al.*, 1997). The same relationship between residual harzburgites and dunites is observed in the Red Hills mantle–MTZ section.

Our study of the major and REE element compositions of clinopyroxenes from the Red Hills residual mantle–MTZ section suggests the following important conclusions for the mantle melts in the MOR system.

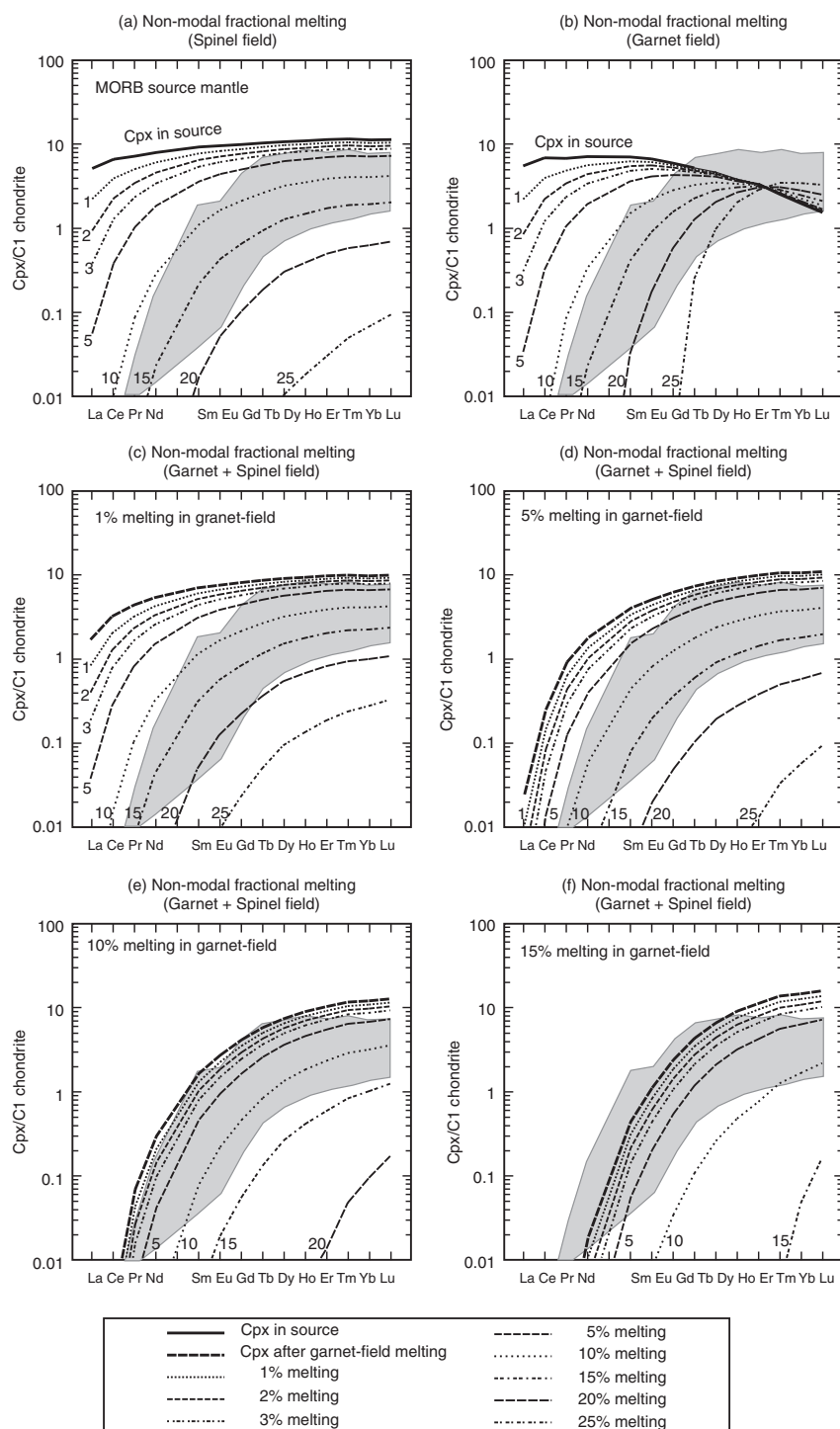


Fig. 13. Clinopyroxene chondrite-normalized REE patterns calculated for a range of upper mantle partial melting models. (a) Non-modal fractional melting in spinel field; (b) non-modal fractional melting in garnet field; (c)–(f) non-modal fractional melting in spinel field of the residue which had previously experienced 1%, 5%, 10%, or 15% fractional melting in the garnet field. Model calculations for further spinel field melting were made at 1, 2, 3, 5, 10 and 15% melting for each residue (c)–(f). The shaded field represents the compositional range of clinopyroxene in Red Hills Lower Unit harzburgite (excluding cpx in the uppermost part of the Lower Unit). To explain the strong LREE depletion, we fitted only the fractional melting process. The calculation method and parameters used in the model follow those of Johnson et al. (1990). The parameters are also shown in Tables 4–6. The patterns with strong LREE depletion cannot be explained by simple non-modal fractional melting in either the spinel (a) or garnet fields (b), even after 10–15% of partial melting. A multi-stage melting process is required to produce the cpx REE patterns (c).

Table 5: Parameters for model calculation

Phase	Phase and melting proportions used in the model			
	Garnet stability field		Spinel stability field	
	Starting mode*	Melt mode†	Starting mode*	Melt mode‡
Olivine	0.55	0.08	0.55	-0.22
Orthopyroxene	0.20	-0.19	0.25	0.38
Clinopyroxene	0.15	0.81	0.18	0.71
Spinel	—	—	0.02	0.13
Garnet	0.10	0.30	—	—
Modal abundance of the residual solid after 1–15% melting in the garnet field				
Phase	1% melting of DM§	5% melting of DM	10% melting of DM	15% melting of DM
Olivine	0.55	0.57	0.60	0.63
Orthopyroxene	0.20	0.22	0.24	0.27
Clinopyroxene	0.14	0.12	0.08	0.03
Garnet	0.10	0.09	0.08	0.06
Reaction: Olivine + Garnet = 1.25Orthopyroxene + Spinel + 0.75Clinopyroxene (after Johnson <i>et al.</i> , 1990)				
Reaction products¶				
Phase	1% melting of DM	5% melting of DM	10% melting of DM	15% melting of DM
Olivine	0.42	0.45	0.49	0.53
Orthopyroxene	0.30	0.31	0.32	0.33
Clinopyroxene	0.20	0.17	0.13	0.08
Spinel	0.09	0.08	0.07	0.06

*Starting modes from Johnson *et al.* (1990).

†Melt mode from Walter (1998).

‡Melt mode from Baker & Stolper (1994).

§DM represents depleted mantle for MORB source (Salters & Stracke, 2004).

¶Modal abundance of the residual solid after above decompression reaction of previously melted rock in the garnet field.

- (1) Clinopyroxene compositions in the residual harzburgite in both the Lower Unit and the MTZ can be explained by two-stage melting in the garnet and spinel fields with reactive melt flow migration taking place in the spinel field. The harzburgite body would essentially have been formed in the early stage as a result of MORB extraction.
- (2) Plagioclase dunite in the MTZ formed by impregnation of the dunite by melts extremely enriched in HREE. Such melts can be generated by reactive melt flow in the spinel field. LREE-depleted MORB melt (Shimizu, 1998) is generated by this process.
- (3) Clinopyroxene dunite in the MTZ formed by impregnation by a larger amount of MORB melt.
- (4) The thick common dunite in the MTZ formed by melt reaction during MORB extraction in the early stage. MREE-enriched clinopyroxene in common dunite formed from residual N-MORB.

- (5) Clinopyroxenes in the gabbroic rock indicate precipitation from a typical MORB melt.

These observations indicate that the melts beneath the Red Hills MOR system can be classified into two types: (1) depleted-MORB to N-MORB type melts, which may be related to first stage depletion of the MORB-source mantle peridotite in the garnet or spinel fields; (2) extremely LREE-depleted and HREE-enriched melts, both of which are related to intra-harzburgite reactive melt flow. The MORB-type melts occur only in the MTZ, and hence are always related to regions in which the presence of massive volumes of melt can be expected. The melts with extreme compositions occur largely in or near the harzburgite bodies with depleted melt in the Lower Unit and enriched melt in the upper MTZ.

The above observations lead us to conclude that a consecutive two-step melting model operated, with the processes of (1) early stage intensive MORB melt

Table 6: REE concentrations (ppm) in residual mantle after non-modal fractional melting in the garnet field

	Residue after 1% melting of DM*	Residue after 5% melting of DM	Residue after 10% melting of DM	Residue after 15% melting of DM
La	0.09	0.001	6.78E-07	3.42E-12
Ce	0.43	0.029	2.95E-04	1.65E-07
Pr	0.09	0.016	0.001	1.11E-05
Nd	0.54	0.16	0.020	0.001
Sm	0.23	0.11	0.036	0.007
Eu	0.09	0.055	0.023	0.006
Gd	0.36	0.24	0.12	0.049
Tb	0.07	0.052	0.032	0.016
Dy	0.50	0.40	0.28	0.17
Ho	0.12	0.10	0.08	0.054
Er	0.36	0.32	0.26	0.20
Tm	0.059	0.054	0.048	0.040
Yb	0.40	0.38	0.35	0.31
Lu	0.063	0.061	0.058	0.053

*DM = MORB source mantle (Salters & Stracke, 2004).

extraction by both focused and diffused flow systems, generating the dunites and the depleted harzburgites, respectively, and (2) late-stage reactive melt flow in the depleted harzburgites. The former process generated the gabbroic rocks, clinopyroxene dunite and depleted harzburgite. The latter process generated the ultra LREE-depleted clinopyroxenes in the harzburgite and the HREE-enriched clinopyroxenes in the upper plagioclase-bearing harzburgite and plagioclase dunite in the Red Hills peridotite. The MOR melt extraction system consists of a combination of diffuse and focused flow regimes (e.g. Iwamori, 1993; Kelemen *et al.*, 1995), and the Red Hills case study described here provides a good example. The composite melt transport mechanism could have existed either in the early melting stage or in the later melting stage. The model presented here appears to best explain the variation of melts present in the Red Hills mantle–MTZ section, and provides the missing link between the MORB and MOR mantle residual melts.

CONCLUSIONS

The Red Hills peridotite body of the Dun Mountain ophiolite belt can be divided into the MTZ and residual

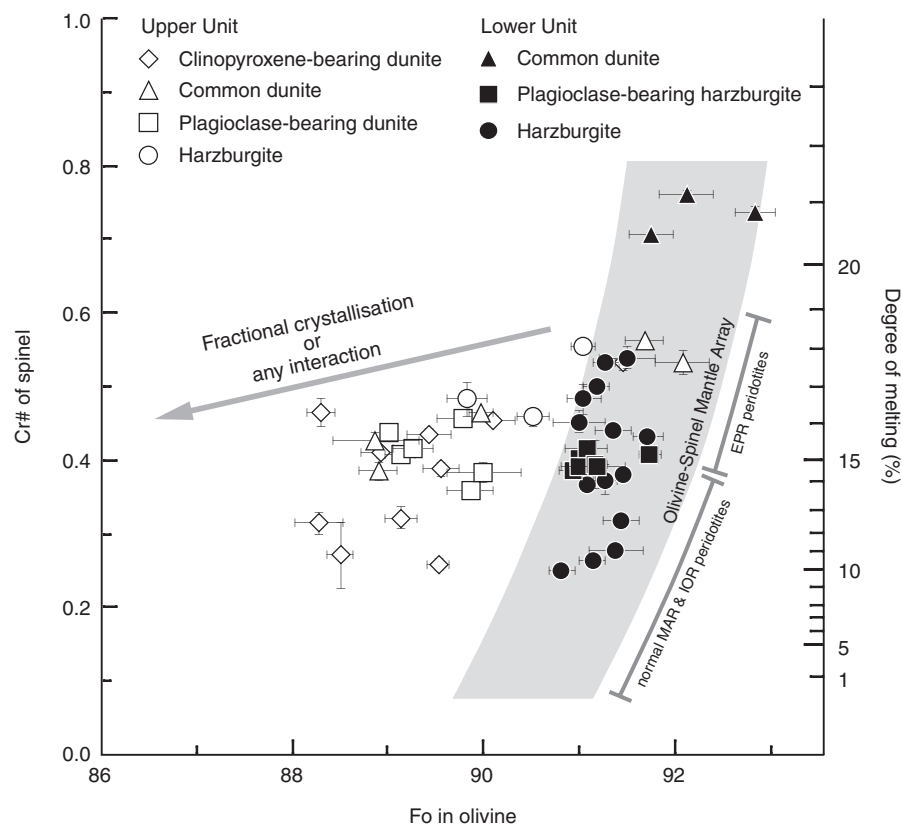


Fig. 14. Relationship between Fo in olivine and Cr-number in spinel. Individual data points represent the average for each sample. The olivine–spinel mantle array (OSMA) is that proposed by Arai (1994). Degree of melting (%) follows the method of Hellebrand *et al.* (2001).

Table 7: Model parameters for reactive porous flow calculations using plate model

Element:	Harzburgite model													
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Harzburgite bulk (ppm)*	0.0024	0.0122	0.0031	0.0210	0.0148	0.0074	0.0405	0.0099	0.0848	0.0230	0.0793	0.0142	0.1081	0.0178
Influx melt (ppm)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Influx rate	—													
Compaction limit	0.05													
Melting rate	0.05													
Crystallizing rate	0													
Mineralogy:†	OI	Opx	Cpx											
Initial mode	0.70	0.20	0.10											
Melting	0.00	0.01	0.99											
Element:	Common dunite model													
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Dunite bulk (ppm)*1	0.0154	0.0306	0.0050	0.0177	0.0103	0.0022	0.0066	0.0010	0.0099	0.0022	0.0073	0.0015	0.0119	0.0025
Influx melt (ppm)	5.93	13.77	1.90	9.11	2.91	1.07	3.60	0.65	4.19	0.84	2.12	0.27	1.65	0.21
Influx rate	0.003													
Compaction limit	0.003													
Melting rate	0.01													
Crystallizing rate	0													
Mineralogy:†	OI	Opx	Cpx											
Initial mode	0.99	0.00	0.01											
Melting	0.01	0.00	0.00											

*Harzburgite and dunite bulk are assumed from partition coefficients of minerals equilibrated with depleted MORB.

†Mineralogy is assumed from existing mineralogical mode of harzburgite and dunite.

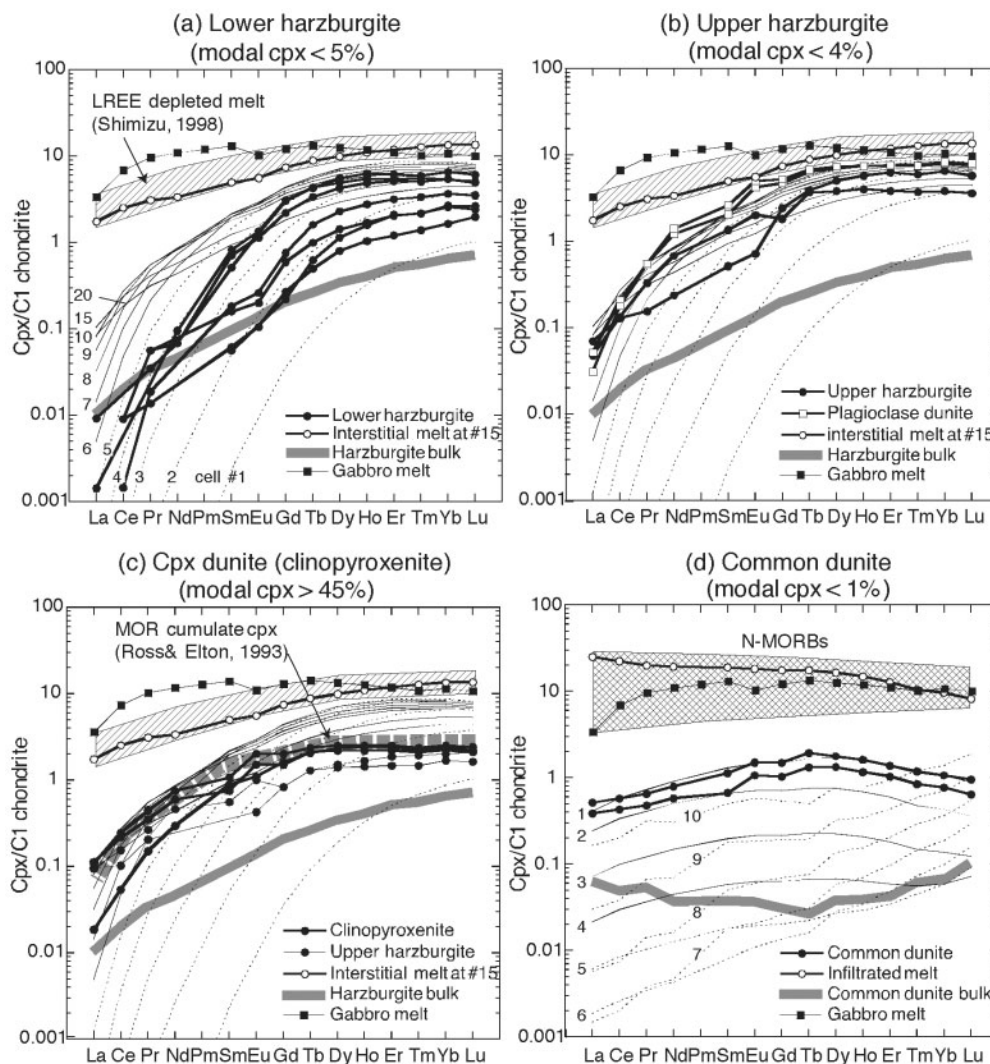


Fig. 15. Clinopyroxene REE patterns in the Red Hills peridotite and modeled patterns for reactive melt flow in the harzburgite and dunite using a plate model (Vernières *et al.*, 1997). (a)–(c) clinopyroxene compositions from the Lower Unit harzburgite, upper harzburgite, and clinopyroxene dunite. For (a)–(c), fine dotted lines labelled cell #1–5 indicate clinopyroxene composition in the lower five cells; fine continuous lines labelled cell #6–20 indicate clinopyroxene compositions in the upper cells; thick grey line shows source harzburgite composition; shaded area is for LREE-depleted olivine-hosted melt inclusions from the FAMOUS area (Shimizu, 1998); bold continuous line with open circles indicates estimated interstitial melt composition in cell 15. The dashed grey line in (c) indicates MOR cumulate clinopyroxene composition (Ross & Elthon, 1993). (d) REE compositions of clinopyroxenes in the common dunite. Thin lines with numbers indicate modeled clinopyroxene compositions; thick grey line indicates source dunite composition, shaded area is for N-MORB; bold continuous line with open circles indicates infiltrated melt composition. Source harzburgite and dunite compositions (Table 7) were determined by solution ICP-MS. Model calculation parameters are given in Table 7.

mantle. Harzburgite in the mantle is the residue after multi-stage fractional melting, which operated initially in the garnet stability field, and continued in the spinel field. In contrast, discordant dunites in the MTZ record a complex magma migration process with melt influx and reaction under varying conditions. Formation of the massive dunite in the MTZ and harzburgite in the residual mantle may have been related to an early MORB extraction stage with both focused melt flow and diffuse melt flow regimes, respectively. A later melting

stage in the depleted harzburgite generated extreme melt compositions by reactive melt flow. Evidence for the two-stage melting is recorded in the clinopyroxene REE chemistry. Traces of N-MORB and depleted-MORB melt compositions are found in the clinopyroxenes in the gabbroic rocks and the possible MOR cumulate clinopyroxenes in the clinopyroxene dunite in the MTZ. Extreme melt compositions are exhibited by clinopyroxenes in depleted harzburgite and in the refertilized plagioclase dunite in the MTZ. The formation processes

of the melts with extreme compositions were successfully simulated by upward migration of reactive melt in the harzburgite in the spinel field. The combination of early melt depletion followed by later reactive melt migration successfully explains the variations in REE chemistry of the clinopyroxenes from the Red Hills peridotite.

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