A kilometre-scale highly refractory harzburgite zone in the mantle section of the northern Oman Ophiolite (Fizh Block): implications for flux melting of oceanic lithospheric mantle

NAMI KANKE1,2* & EIICHI TAKAZAWA3
1Graduate School of Science and Technology, Niigata University, 2-8050 Ikarashi, Nishi-ku, Niigata, 950-2181, Japan
2Asaka High School, 5-25-63, Kaisei, Koriyama, Fukushima, 963-8851, Japan
3Department of Geology, Faculty of Science, Niigata University, 2-8050 Ikarashi, Nishi-ku, Niigata, 950-2181, Japan
*Corresponding author (e-mail: f12n008a@mail.cc.niigata-u.ac.jp)

Abstract: We report the major element compositions of constituent minerals in 278 harzburgites and of 101 whole rocks from the northern Fizh mantle section in the northern Oman Ophiolite to investigate the formation and evolution of oceanic lithospheric mantle. Olivine Fo varies from 90 to 92 whereas spinel Cr# (\(=\)Cr/(Cr + Al) atomic ratio) varies from 0.15 to 0.78. The Cr# of spinels in a large number of harzburgites exceeds 0.6, which is the upper bound for abyssal peridotites. In the northern Fizh mantle section, highly refractory harzburgites with spinel Cr# greater than 0.7 are distributed in a 3-km-wide band along a NW–SE-striking shear zone. We infer a two-stage depletion process in the northern Fizh mantle section. In the first stage, asthenospheric mantle was partially melted beneath a mid-ocean ridge, producing a harzburgitic residual column. In the second stage during detachment of oceanic lithosphere an H2O-rich fluid, released from the metamorphic sole due to thermal metamorphism of altered oceanic crust, extensively infiltrated the northern Fizh mantle section where the ridge segment boundary region was previously located. The residual harzburgites were subjected to flux melting, resulting in a highly refractory harzburgite zone with spinel Cr# greater than 0.7.

Supplementary material: Locality map, names of the wadis and UTM coordinates and further analytical data are available at http://www.geolsoc.org.uk/SUP18679

The Oman Ophiolite is the world’s largest ophiolite, measuring 80 km in width and extending 500 km along the Arabian coast. The primary structure and stratigraphy of oceanic lithosphere in the ophiolite has been well preserved and includes mantle peridotite, layered gabbro, sheeted dyke complexes and pillow lavas in the sequence from the base to the top without significant stratigraphic disturbance (e.g. Lippard et al. 1986; Nicolas 1989). The vast, intact exposure of uppermost mantle beneath the palaeo-Moho in the Oman Ophiolite is well suited for investigating the spatial variability of structure and composition in the oceanic lithospheric mantle. Structural studies of the Oman Ophiolite have been conducted by the Montpellier group led by Adolphe Nicolas and Françoise Boudier (e.g. Nicolas 1989; Nicolas et al. 2000). Recently, Le Mée et al. (2004) and Monnier et al. (2006) presented results regarding chemical variability along the 400-km-long palaeo-ridge axis of the Oman Ophiolite. The variations of mathematically processed spinel Cr# along the palaeo-ridges defined four segments, each 50–100 km long, and numerous 10–20-km shorter segments. However, those authors’ observations were limited by the sampling being distributed mainly along basal thrusts in the ophiolite. It is important to carefully examine spatial variability in mineral and whole-rock compositions inside the Oman mantle section because these data should lead to a more thorough understanding of melting and melt migration in the upper mantle.

The debate as to whether the Oman Ophiolite was generated at a mid-ocean ridge setting (e.g. Nicolas 1989) or at a spreading axis above a subduction zone (e.g. Alabaster et al. 1982; Pearce et al. 1984; Lippard et al. 1986) has not yet been settled. Based on the geochemical characteristics of extrusive sequences, the older volcanic rocks (Geotimes or V1 unit) are related to mid-ocean ridge basalt (MORB) melt whereas the younger volcanic rocks (Alley or V2 unit) are island-arc related (Alabaster et al. 1982; Ernewein et al. 1988). Recently, Ishikawa et al. (2002) reported boninitic lavas in the Alley volcanic sequence and
dykes from the northern Oman Ophiolite and suggested that they formed during an early stage of the subduction zone setting. In the mantle section, spinels with Cr\# greater than 0.6 and low TiO₂ (<0.3 wt\%) have been reported, indicating island-arc (IA) affinity (Arai et al. 2006, 2011; Tamura & Arai 2006). Rollinson (2008) reported two different types of chromitites in the northern Oman Ophiolite. Low-Cr\# chromitites with MOR affinity occur in the upper part of the mantle section whereas high-Cr\# chromitites with IA affinity are found deeper in the mantle section. Ahmed & Arai (2002) and Miura et al. (2012) described the presence of both the low-Cr\# (c. 0.6) chromitites with MOR affinity and high-Cr\# (c. 0.7) chromitites with IA affinity at the same stratigraphic level in the Salahi mantle section of the northern Oman Ophiolite. The former type is discordant with the planar structure of host harzburgite, whereas the latter type is discordant with the structure of host harzburgite and is enriched in platinum group elements (PGE). Furthermore, Dare et al. (2009) constructed diagrams based on oxygen fugacity–Cr\# and on Ga–Ti–Fe\# systematics for spinel, which discriminate between mid-ocean ridge (MOR) and IA affinities. Those authors concluded that the Oman Ophiolite evolved from MOR to IA affinity. Goodenough et al. (2010) supported a similar two-stage magmatism model based on a petrological study of the ophiolite in the United Arab Emirates. Pyroxenite and gabbroic dykes in the Oman mantle section have been classified into two groups: a MORB-related group and a boninitic-to-andesitic melt-related group (Python & Ceuleneer 2003; Python et al. 2008). It is important to discover how these two genetically distinct groups are distributed in the mantle section.

In this study, we report the chemical compositions of harzburgites in the northern Fizh mantle section where we have previously conducted structural mapping and for which we have also reported geochemical characteristics of basal lherzolites (Takazawa et al. 2003). Our new results presented here reveal that a highly refractory harzburgite zone (referred to here as the HRH zone) is distributed as a linear band in the northern Fizh Block, with an orientation oblique to the palaeo-Moho and nearly parallel to the NW–SE-striking sinistral shear zone in Wadi Zabin. Our discovery of the HRH zone holds the key to connecting the inferred palaeo-ridge segment ends identified by Miyashita et al. (2003) based on a study of the crustal section, and by Le Mée et al. (2004) and Monnier et al. (2006) based on studies of basal peridotites. We are also able to shed light on the processes responsible for the formation of the HRH zone.

Geological setting and previous work

The Fizh Block is located in the northern part of the Oman Ophiolite (Fig. 1). The palaeo-Moho separates the block into the crust section in the east and the mantle section in the west. The structural features of the Fizh mantle section have been summarized by Takazawa et al. (2003). The mantle section is composed mainly of harzburgite and dunite accompanied by minor amounts of pyroxenite and gabbroic dykes. The dunite commonly occurs discordantly or discordantly relative to the foliation in the harzburgite (Arai et al. 2006, 2011). In the basal part of the mantle section, the harzburgite and dunite form a conspicuous banded unit, and in some places are in contact with the metamorphic sole along the basal thrust (Searle & Malpas 1980; Lippard et al. 1986). Basal lherzolites occur near or at the basal thrust of the northern Fizh Block, alternating with harzburgite and dunite of the banded unit (Lippard et al. 1986; Takazawa et al. 2003). Pyroxenite, websterite, gabbronorite, olivine gabbro and wehrlite commonly occur as dykes or sills. Orthopyroxenite dominates among these lithologies in the mantle section, except at the palaeo-Moho, and occasionally forms banded and folded structures accompanied by harzburgite and dunite.

In the Fizh mantle section, peridotites with high-temperature, coarse, granular microstructures are distributed within 5 km of the palaeo-Moho, whereas the central part of the mantle section is dominated by harzburgite with porphyroclastic microstructures (Takazawa et al. 2003). The preservation of high-T deformation features near the palaeo-Moho could have resulted from conductive cooling from the top of the oceanic lithosphere without further influence from deformation at deeper levels, which developed a porphyroclastic structure. The basal shear zone, which comprises a 2–3-km-thick layer above the basal thrust, consists of low-T deformation features including mylonitic microstructures. These microstructures are related to the detachment of the ophiolite (Boudier et al. 1988; Nicolas et al. 2000). The Fizh mantle section is characterized by NW–SE-striking shear zones that penetrate both the mantle and the lowermost crust section (Boudier et al. 1988; Nicolas et al. 1988, 2000; Takazawa et al. 2003; Michibayashi et al. 2006). The shear zones are subvertical in the mantle section and their mylonitic foliation crosscuts high-T deformation structures. Between Wadi Rajmi and Wadi Zabin, the palaeo-Moho is offset by a NW–SE-striking sinistral shear zone over a lateral distance of 5 km. This shear zone is traced across the Moho into the crustal sequence where layered gabbro has been metamorphosed to amphibolite within a 10-m-wide ductile shear zone (Boudier et al. 1988; Nicolas et al. 2000). The dip of
palaeo-Moho becomes steeper towards the north from Wadi Zabin to Wadi Rajmi across the shear zone. Dyke swarms in the crustal sequence near this shear zone are subparallel and oriented WNW–ESE (Smewing 1980; Boudier et al. 1988; Reuber 1988; Umino et al. 1990; MacLeod & Rothery 1992; Nicolas et al. 2000; Adachi & Miyashita 2003; Miyashita et al. 2003). The WNW–ESE sheeted dyke complexes cut across earlier north–south-oriented sheeted dyke complexes (Umino et al. 1990; MacLeod & Rothery 1992). Bonitites have been reported from the WNW–ESE dykes (Ishikawa et al. 2002).

The northern Figh Block has been considered a site of propagating and failing ridge segments that were separated by a 10–20-km-wide transform zone (Nicolas et al. 2000; Adachi & Miyashita 2003; Miyashita et al. 2003). However, there is disagreement concerning the direction of ridge propagation based either on the structure of the mantle section (Nicolas et al. 2000) or on the crustal sequence (Adachi & Miyashita 2003; Miyashita et al. 2003).

**Descriptions of samples**

The peridotite samples used in this study comprise 278 harzburgites collected from homogeneous harzburgite outcrops distant from dykes and exposed in wadis in the northern Figh mantle section. At least one to two samples were chosen within every 1 km² area. The harzburgite contains olivine, orthopyroxene, clinopyroxene and spinel as primary phases. Alteration phases include serpentine and small amounts of brucite, magnetite and calcite veins. Olivine and orthopyroxene have been replaced by serpentine ± brucite by as much as 25–30% and 5–6% in mode, respectively. Mineral modes of primary phases were calculated using a least-squares mass-balance of the whole-rock and primary mineral compositions for 83 samples. The results are plotted in the classification of ultramafic rocks (Fig. 2; Le Maitre 2002). The majority of samples lie within the harzburgite field, although a few samples contain slightly greater than 5% clinopyroxene and are classified as lherzolite. The results are compared in Figure 2 with data from basal lherzolite in the northern Figh mantle section (Takazawa et al. 2003).

The microstructure of peridotites was examined under an optical microscope using thin-sections cut perpendicular to the foliation and parallel to the lineation (i.e. XZ-sections). Takazawa et al. (2003) classified the texture of harzburgites in the northern Figh mantle section into four types based on the classifications by Nicolas (1986) and
Mercier & Nicolas (1975). The harzburgites with high-T coarse granular texture are composed mainly of olivine grains of 2 mm in size. Orthopyroxene and spinel occur at olivine grain boundaries. Spinel sometimes contains inclusions of other primary phases and rarely includes amphibole (hornblende). The harzburgites with porphyroclastic to planar equigranular texture are characterized by stretched olivine porphyroclasts with irregular grain boundaries accompanied by planar olivine neoblasts. The size of olivine porphyroclasts gradually decreases as the texture changes from porphyroclastic to planar equigranular, and the size of olivine neoblasts increases. Orthopyroxene commonly shows undulatory extinction with curved cleavage. The harzburgites with mylonitic texture in the basal part of the ophiolite contain remarkably elongated olivine porphyroclasts accompanied by fine-grained olivine (0.05–0.10 mm). Spheroidal or elongated forms of orthopyroxene are common, and the mineral is characterized by a remarkable undulatory extinction and curving cleavage. Spinel is fine grained and elongated. The harzburgite with mylonitic texture in the shear zone near Wadi Zabin contains dominant olivine neoblasts with grain sizes ranging from 0.1 to 0.2 mm, slightly larger than those in the basal mylonites.

**Analytical methods**

Major element compositions of primary minerals (olivine, orthopyroxene, clinopyroxene and spinel) in 278 harzburgites were determined using an electron probe microanalyzer with wavelength-dispersive X-ray spectrometry (EPMA-WDS) (JEOL JXA-8600SX) at Niigata University, Japan. Operating conditions were 15 kV accelerating voltage, 13 nA beam current and c. 1 µm beam diameter, using oxide ZAF matrix corrections which are composed of atomic number (Z) correction, atomic weight (A) correction and fluorescence (F) correction. Three to five grains were selected for each primary mineral in thin-section and used for microprobe analysis. Major element compositions of olivines in 205 harzburgites were measured using EPMA-WDS, and compositions of olivines in 69 harzburgites were determined using a scanning electron microprobe (JEOL JSM-5600) with energy-dispersive X-ray spectrometry (Oxford Link ISIS-310) (SEM-EDS) at Niigata University. Operating conditions were 15 kV accelerating voltage, 1.0 nA beam current and c. 1 µm beam diameter, using ZAF matrix correction. Olivine Fo contents determined by SEM-EDS were about 0.5 lower than the values obtained using EPMA-WDS. No correction was performed on Fo contents because the difference is too small to influence the conclusions made in this study. Whole-rock major element compositions of 101 samples were analysed using X-ray fluorescence spectrometry (RIGAKU RIX3000) at Niigata University following the analytical method of Takahashi & Shuto (1997) with an optimization for ultramafic rocks.

**Results**

**Mineral compositions**

Averaged major element compositions of primary minerals in representative samples are listed in Table 1. The average values are used for plotting primary mineral compositions in the figures. Also, as the Cr# is generally a reliable indicator for the degree of partial melting (Dick 1977; Dick & Bullen 1984; Arai 1994; Hellebrand et al. 2001), mineral compositions are plotted against spinel Cr# in most of the figures. According to the results, spinel Cr# in a sample varies within ±0.01 from the average for 187 samples out of 276, within ±0.02 for 75 samples, within ±0.03 for 11 samples and within ±0.04 for three samples. The relationship between forsterite molar percent (Fo) of olivine and the Cr# of spinel presents a positive correlation along the olivine–spinel mantle array (OSMA; Arai 1987; Fig. 3). Olivine Fo content varies from 90.0 to 92.2 except for two samples (Fo 86.9 and 88.1) collected from the shear zone. The lower Fo contents are the result of partial equilibration with numerous gabbroic veins that intruded peridotites along the shear zone. The
Table 1. **Major element compositions (wt%) of primary minerals in representative peridotites from the northern Fizh mantle section**

| Reference no., locality, UTM coordinate<sup>a</sup> | Mineral | Mode (wt%) | SiO<sub>2</sub> | TiO<sub>2</sub> | Al<sub>2</sub>O<sub>3</sub> | Cr<sub>2</sub>O<sub>3</sub> | FeOT<sub>b</sub> | MnO | NiO | MgO | CaO | Na<sub>2</sub>O | K<sub>2</sub>O | Total | Mg<sup>c,d</sup> | Cr<sup>d</sup> | Fe<sup>3+</sup><sup>e</sup> |
|--------------------------------------------------|---------|------------|---------------|----------------|----------------|----------------|-------------|-----|-----|-----|-----|-------------|-------------|-------|------------|----------|----------------|
| 99112804 Rayy / 0424.05 | olivine | 69.21 | 41.85 | 0.01 | 0.00 | 0.01 | 8.57 | 0.07 | 0.40 | 50.94 | 0.02 | 0.00 | 0.00 | 101.87 | 0.914 |
| 2711.63 | opx | 26.52 | 58.20 | 0.02 | 1.01 | 0.41 | 5.73 | 0.09 | 0.06 | 34.77 | 0.71 | 0.01 | 0.00 | 101.02 | 0.915 |
| 99121410 Wadi Zabin / 0419.47 | cpx | 55.05 | 0.01 | 1.04 | 0.59 | 1.85 | 0.08 | 0.04 | 18.29 | 24.15 | 0.04 | 0.00 | 0.00 | 101.14 | 0.946 |
| 99112102 Wadi Rajimi / 0422.37 | spinel | 0.94 | 0.25 | 0.08 | 15.08 | 53.37 | 20.83 | 0.30 | 0.03 | 10.44 | 0.01 | 0.03 | 0.00 | 100.42 | 0.500 |
| 99120216 Wadi Shuwayah / 0421.58 | olivine | 69.56 | 40.77 | 0.01 | 0.00 | 0.01 | 8.89 | 0.08 | 0.33 | 51.76 | 0.03 | 0.00 | 0.00 | 101.12 | 0.912 |
| 2722.05 | cpx | 28.49 | 56.76 | 0.02 | 2.25 | 0.74 | 5.68 | 0.14 | 0.06 | 34.33 | 0.56 | 0.01 | 0.00 | 101.29 | 0.915 |
| 2722.05 | opx | 26.21 | 57.50 | 0.02 | 1.20 | 0.46 | 5.72 | 0.15 | 0.10 | 35.59 | 0.77 | 0.01 | 0.00 | 101.44 | 0.948 |
| 99120903 Wadi Hayl 0417.79 / 0421.58 | cpx | 55.09 | 0.02 | 1.30 | 0.77 | 1.74 | 0.05 | 0.09 | 17.82 | 24.41 | 0.14 | 0.00 | 0.00 | 101.35 | 0.944 |
| 2707.32 | spinel | 69.04 | 58.72 | 0.07 | 3.92 | 1.32 | 2.06 | 0.07 | 0.07 | 16.44 | 24.05 | 0.09 | 0.00 | 0.00 | 100.86 | 0.934 |

<sup>a</sup>UTM coordinate (WGS84) = vertical/horizontal 1 km reference, 40R as grid zone designation, DN as 100 km<sup>2</sup> identification;

<sup>b</sup>Total Fe as FeOT;

<sup>c</sup>Mg# = Mg/(Mg + FeT) atomic ratio;

<sup>d</sup>For spinel, Mg# = Mg/(Mg + Fe<sup>3+</sup>) and Fe<sup>3+</sup> = Fe<sup>3+</sup>/ (Cr + Al + Fe<sup>3+</sup>) are calculated assuming spinel stoichiometry.

<sup>e</sup>Analytical results of seven oxide compositons by SEM-EDS.
Cr# of spinels varies widely from 0.15 to 0.78 in the study area. Values are less than 0.4 in the basal lherzolites and greater than 0.4 in the harzburgites (Takazawa et al. 2003; this study). Moreover, about half the harzburgite samples have a spinel Cr# greater than 0.6. Generally speaking, the upper limit of spinel Cr# in abyssal peridotites is 0.6 (Dick & Bullen 1984; Arai 1994). A negative correlation is observed in the relationship between the Cr# of spinel and its Mg/(Mg + Fe²⁺) atomic ratio (Mg#) (Fig. 4). This correlation is parallel to the compositional field of spinels in abyssal peridotites, although the Oman spinels are slightly uniformly shifted to a lower Mg# relative to the abyssal peridotites, indicating re-equilibration under subsolidus condition (Dick & Bullen 1984; Fig. 4). The TiO₂ content of spinel ranges from 0.01 to 0.31 wt% (Fig. 5). The majority of spinels have a TiO₂ content lower than 0.1 wt% although some harzburgites have higher TiO₂ contents (>0.1 wt%), especially at spinel Cr# values greater than 0.7.

The Al₂O₃ contents of orthopyroxene and clinopyroxene are negatively correlated with the Cr# of spinel (Fig. 6a, c). The ranges of Al₂O₃ contents of both pyroxenes are almost equal to those of abyssal peridotites, although the former have slightly lower Al₂O₃ contents (by 0.5–1.0 wt%) than the latter. The diagram for the Cr₂O₃...
contents of orthopyroxene and clinopyroxene plotted against the Cr# of spinel (Fig. 6b, d) shows a convex-upwards parabola-shaped relationship, as previously reported for some mantle xenoliths and massive peridotites (Nagata et al. 1983). The Cr$_2$O$_3$ contents of both pyroxenes reach their maxima when spinel Cr# is about 0.4. A similar parabola-shaped pattern is also observed for abyssal peridotites (Fig. 6b, d). Both the pyroxenes in the Oman peridotites have slightly lower Cr$_2$O$_3$ values than the abyssal peridotites. The TiO$_2$ content of clinopyroxenes is lower than 0.35 wt% and shows a steep decrease from lherzolite to harzburgite with increasing spinel Cr#, similar to the pattern for abyssal peridotites (Fig. 6e). The TiO$_2$ content of clinopyroxenes in the majority of harzburgites is lower than 0.1 wt%. The Na$_2$O content of clinopyroxenes is lower than 0.5 wt% and decreases from lherzolite to harzburgite with increasing spinel Cr# up to 0.5, similar to the pattern for abyssal peridotites (Fig. 6f). However, clinopyroxenes in the harzburgites with spinel Cr# greater than 0.5 are variously enriched in Na$_2$O.

Spatial distribution of mineral compositions

To examine the spatial distribution of the degree of melting in the Fizh mantle section, the average values of spinel Cr# and clinopyroxene Na$_2$O content for each sample were plotted on the topographical map (Fig. 7a, b). The spinel samples with Cr# lower than 0.5 are distributed widely in
Fig. 7. Spatial variation of mineral compositions in harzburgites and lherzolites from the northern Fizh mantle section. Each number in (a) represents the average of 100 ≥ Cr# for spinels in an individual sample, and in (b) represents the average of 100 ≥ Na2O for clinopyroxenes. Numbers are colour coded according to the range of spinel Cr# and cpx.
the study area, except near Wadi Zabin. The basal lherzolites occur in close proximity to the basal thrust (Takazawa et al. 2003). In contrast, refractory harzburgites with spinel Cr# greater than 0.7 are distributed as a 3-km-wide linear band from Rayy to Wadi Zabin (Fig. 7a). This highly refractory harzburgite (HRH) zone is almost parallel to the NW–SE-striking sinistral shear zone in Wadi Zabin. Clinopyroxene with Na 2O content lower than 0.15 wt% is widely distributed in the study area (Fig. 7b). In the HRH zone in particular, the Na 2O content of clinopyroxene is lower than 0.15 wt% although it increases slightly from the basal part of the mantle section toward the palaeo-Moho. Conversely, the distribution of clinopyroxene with Na 2O content greater than 0.15 wt% is limited mainly to the coarse granular domain and to the basal part of the mantle section. In the coarse granular domain, clinopyroxene becomes more enriched in Na 2O with decreasing distance from the palaeo-Moho. Clinopyroxenes with notably high Na 2O (>1 wt%) are present in the Type II lherzolites at the basal thrust (Takazawa et al. 2003).

Figure 8 shows the variations of mineral compositions as a function of distance from the shear zone in the northern Fizh mantle section. We tentatively set a reference line through the shear zone from which the distance to each sample was measured. The data are projected onto the horizontal axis that is taken as perpendicular to the shear zone. The distance is measured from the shear zone as shown in Figure 7.

![Fig. 8. Compositional variation of minerals in the peridotites analysed in this study from the northern Fizh mantle section plotted against distance from the shear zone. The data are projected onto the horizontal axis that is taken as perpendicular to the shear zone. The distance is measured from the shear zone as shown in Figure 7.](image-url)
measured (Fig. 7). This treatment is meaningful because the Cr# of spinel is nearly symmetrically distributed on both sides of the HRH zone. The Fo content of olivine gradually increases from the base (SW) to the palaeo-Moho (NE) (Fig. 8a). However, it decreases abruptly immediately beneath the palaeo-Moho. The harzburgites with significantly low Fo are located within the shear zone where numerous gabbroic veins intrude parallel to the vertical shear plane of mylonitized harzburgites. The NiO contents of olivine gradually decrease with increasing distance from the base to the palaeo-Moho (Fig. 8b).

The Mg# of spinel has a lowest value of 0.5 in the HRH zone (Fig. 8c). The upper bound for the range of Mg# in spinel gradually decreases from 0.7 near the basal thrust towards 0.6 near the palaeo-Moho, whereas the lower bound for the range of Cr# in spinel gradually increases from 0.25 near the basal thrust to 0.43 near the palaeo-Moho. A few samples with low Cr# (<0.4) are found at 5.0–7.5 km from the reference line (e.g. Fig. 8d). This is an artefact however, as these samples are the basal lherzolites located at Rayy and Wadi Shuwayhah in the NW corner of the northern Fizh mantle section (Fig. 7).

The TiO2 content of spinel is limited to less than 0.1 wt%, although some spinels in the shear zone and near the palaeo-Moho have TiO2 contents greater than 0.1 wt% with a maximum value of 0.3 wt% (Fig. 8e). The MnO content of spinel has a maximum value of 0.35 wt% in the HRH zone, whereas the lower bound gradually increases from 0.1 wt% near the base towards 0.2 wt% near the palaeo-Moho (Fig. 8f).

The upper bound for the range of Al2O3 content of orthopyroxene gradually decreases from 4 wt% near the basal thrust towards 2.7 wt% near the palaeo-Moho (Fig. 8g). The Al2O3 content of clinopyroxene and the Cr2O3 content of both pyroxenes also show some similarity in pattern to the Al2O3 content of orthopyroxene (Fig. 8h, k, l). The TiO2 content of clinopyroxene is lower than 0.1 wt% except for a few clinopyroxenes at the base, in the shear zone and near the palaeo-Moho, which have higher Na2O contents up to 0.3 wt% (Fig. 8i). The Na2O content of clinopyroxenes is mostly lower than 0.2 wt%, although some clinopyroxenes have higher Na2O contents up to 0.5 wt% near the base, the shear zone and the palaeo-Moho, similar to the pattern of TiO2 content (Figs 7b & 8j).

**Whole-rock chemistry**

Whole-rock major element compositions of representative samples are presented in Table 2. Whole-rock compositions of the Oman harzburgites define either linear or curved arrays for oxides versus spinel 100 × Cr# diagrams, similar to those defined by upper mantle xenoliths and other massive peridotites (Takazawa et al. 2000). Whole-rock SiO2, TiO2, Al2O3, CaO and Na2O contents decrease with increasing spinel Cr# whereas FeOT, MgO, Cr2O3 and NiO contents increase (Fig. 9). Abundances of Al2O3 and CaO show well-defined inverse linear correlations with spinel Cr#. In contrast, TiO2 and Na2O contents present convex-downwards trends from the basal lherzolites (spinel Cr# <0.4; Takazawa et al. 2003) to the harzburgites.

**Discussion**

**Formation of residual peridotite by partial melting**

Peridotites in the Fizh mantle section consist of harzburgite, dunite and rarely lherzolite. These peridotites have been considered as a part of the oceanic lithospheric mantle formed as residues after melt extraction from asthenospheric upper mantle (Takazawa et al. 2003). To examine how the degree of partial melting is distributed in the Fizh mantle section, the Cr# of spinel is used as an index for the degree of melt extraction (Jaques & Green 1980; Dick & Bullen 1984; Arai 1987).

**Table 2. Major element compositions (wt%) of representative whole-rock peridotites from the northern Fizh mantle section**

| Reference no. | SiO2 | TiO2 | Al2O3 | FeOTa | MnO | MgO | CaO | Na2O | K2O | P2O5 | Cr2O3 | NiO | Total | Mg# | LOI |
|---------------|------|------|-------|-------|-----|-----|-----|------|-----|------|-------|-----|-------|-----|-----|
| 99112804      | 41.09| 0.008| 0.338 | 7.43  | 0.121| 40.66| 0.532| 0.009| 0.003| 0.001| 0.422 | 0.283| 100.07| 0.907| 9.2 |
| 99121410      | 40.02| 0.006| 0.325 | 7.48  | 0.119| 41.92| 0.422| 0.008| 0.003| 0.001| 0.372 | 0.302| 99.75 | 0.909| 8.8 |
| 99112102      | 41.22| 0.007| 0.678 | 7.30  | 0.116| 40.82| 0.775| 0.005| 0.003| 0.001| 0.376 | 0.293| 99.97 | 0.909| 8.4 |
| 99120216      | 40.74| 0.008| 0.779 | 6.85  | 0.111| 39.84| 0.832| 0.004| 0.003| 0.001| 0.359 | 0.290| 99.81 | 0.912| 10.0|
| 99120903      | 41.01| 0.016| 1.12  | 7.01  | 0.116| 39.49| 1.09 | 0.006| 0.003| 0.001| 0.416 | 0.273| 99.55 | 0.909| 9.0 |

a Total Fe as FeOT;
b Mg# = Mg/(Mg + FeT);
c LOI = loss on ignission.
First, we examine the factor that controls the Cr# of spinel in the Oman mantle section. In the peridotites from the Fizh mantle section, the amount of modal spinel stays almost constant regardless of the Cr# of spinel (0.4–1.0 modal%, Fig. 10); that is, the amount of modal spinel stays virtually constant even if the degree of partial melting increases. Moreover, whole-rock Cr2O3 content also stays virtually constant (Fig. 9). Whole-rock Cr# has a negative correlation with whole-rock Al2O3 content and a positive correlation with spinel Cr# (Fig. 11). This suggests that the factor controlling the Cr# of both whole rock and spinel is the amount of whole-rock Al2O3 rather than Cr2O3. It confirms that whole-rock Al2O3 content is also an index of the degree of partial melting, in addition to the Cr# of spinel (Bodinier 1988; Hellebrand et al. 2001).

In the northern Fizh mantle section, the Cr# of spinel varies over a wide range from 0.24 to 0.78 whereas the olivine composition is limited to Fo values 90–92. The compositions of olivine and spinel are distributed in the OSMA, indicating their residual origin (Arai 1987; Fig. 3). Moreover, many harzburgites include spinels with Cr# greater than 0.6, the upper limit for abyssal peridotites (Dick & Bullen 1984; Arai 1994). This indicates that the maximum degree of partial melting for the Oman peridotites is greater than that for the adiabatically ascending upper mantle beneath a mid-ocean ridge. The negative correlations between the Cr# of spinel and both the Al2O3 and Cr2O3 contents of both pyroxenes (Fig. 6a–d) are consistent with the residual origin of these harzburgites by partial melting (Dick 1977). The slight offsets of both pyroxenes to lower Al2O3 and Cr2O3 contents compared with abyssal peridotites in Figure 6a–d are caused by the difference in cooling rate. The Oman peridotites were overlain by a normal crustal section until subaerial erosion took place, whereas abyssal peridotites were relatively rapidly exposed on the ocean floor; the abyssal peridotites have therefore cooled more quickly from the melting to the subsolidus conditions. During the cooling of the Oman peridotites, both Al and Cr in pyroxenes were transferred to spinel. This reduced both the Al2O3 and Cr2O3 contents of pyroxenes, although this effect is minor and does not greatly influence the Cr# of spinel (Hellebrand et al. 2005).

Next, we examine the change in mineral mode associated with the progress of partial melting.

![Fig. 9](image-url)
Figure 10 shows the relationship between the Cr# of spinel and the mineral modes that were calculated using a least-squares method for whole-rock harzburgites and their mineral compositions. With an increasing Cr# of spinel and an increasing degree of melting, the modes of orthopyroxene and clinopyroxene decrease; those of olivine and spinel increase. The melting reaction stoichiometry calculated from the modal changes by the linear fits in Figure 10 is $0.79 \text{opx} + 0.35 \text{cpx} = 1 \text{melt} + 0.13 \text{ol} + 0.01 \text{sp}$ (in wt%). Clinopyroxene in the harzburgite occurs as fine-grained neoblasts that might have secondarily exsolved from the orthopyroxene during cooling. Small amounts of spinel may also have been exsolved from pyroxene during subsolidus equilibration, as inferred from the reduction of the Al$_2$O$_3$ and Cr$_2$O$_3$ contents of pyroxene (Fig. 7a–d). However, we ignore this effect because the modal amount of spinel is insignificant in the melting reaction. When the clinopyroxene is included in the orthopyroxene, the reaction becomes $1.14 \text{opx} = 1 \text{melt} + 0.13 \text{ol} + 0.01 \text{sp}$. Based on the experiments of Kinzler & Grove (1992), the melting reaction after clinopyroxene-out is $1.06 \text{opx} + 0.04 \text{sp} = 1 \text{melt} + 0.1 \text{ol}$, which is very similar to our calculated reaction. The compositions of harzburgites in the Fizh mantle section may therefore reflect melt extraction from clinopyroxene-free spinel harzburgite, which is governed by the decrease of orthopyroxene and increase of olivine.

**Spatial variability in the degree of melting in the northern Fizh mantle section**

The HRH zone is distributed as a linear band on the west side of the sinistral shear zone in Wadi Zabin (Fig. 7). According to the spatial distribution of spinel Cr#, the degree of partial melting apparently rises from the basal thrust and from the palaeo-Moho towards the HRH zone in the northern Fizh mantle section (Figs 7 & 8). This contradicts the findings of Plank & Langmuir (1992) that the partial melting of mantle under mid-ocean ridge forms a series of residual peridotite and that the degree of partial melting rises towards the Moho from the deep mantle (Fig. 12a). Conversely, when the selected peridotite samples with spinel Cr# less than 0.6 are examined (Fig. 8), Fo mol%, spinel Mg# and Cr# and MnO content of olivines
all monotonically increase from the basal thrust towards the palaeo-Moho, whereas the Al\textsubscript{2}O\textsubscript{3} and Cr\textsubscript{2}O\textsubscript{3} contents of pyroxenes gradually decrease. This indicates that peridotites with spinel Cr# less than 0.6 preserved the chemical variation expected for the residual mantle column generated beneath a mid-ocean ridge (Plank & Langmuir 1992); this statement does not, however, exclude a model of a spreading centre above a subduction zone (i.e. a back-arc basin). The Cr# of spinels in abyssal peridotites is generally lower than 0.6 (Arai 1994), indicating that the partial melting of MORB source mantle is probably limited due to low potential temperature and anhydrous conditions. The generation of highly refractory harzburgites with spinel Cr# greater than 0.6 therefore requires an additional melting process such as flux melting of residual harzburgites along a shear zone.

The distribution of highly refractory harzburgites (spinel Cr# >0.7) in the northern Oman Ophiolite can be modelled as follows. During intra-oceanic thrusting, the Oman Ophiolite was forced to be located above an incipient subduction zone (Fig. 12b; Boudier et al. 1988; Ishikawa et al. 2005; Arai et al. 2006). The heat from the ophiolite mantle section caused thermal metamorphism of altered oceanic crust up to amphibolite facies (Lippard et al. 1986; Hacker & Mosenfelder...
An H₂O-rich fluid released from the metamorphic sole infiltrated the mantle section (Ishikawa et al. 2005). Flux melting of residual harzburgites produced high-Mg andesitic or boninitic melt associated with highly refractory harzburgitic residue (spinel Cr# > 70) (Ishikawa et al. 2002; Arai et al. 2006; Tamura & Arai (2006); Dare et al. 2009). This implies that the fluid flux must have been abundant in the HRH zone in the northern Fizh mantle section. We adopted the intra-oceanic thrusting model in the above discussion because it represents an incipient stage in the formation of a subduction zone. A recent model of subduction initiation by subsidence and arc–trench rollback is an alternative to explain our observations in terms of the change in tectonic setting from spreading initiation by subsidence and arc–trench rollback is an alternative to explain our observations in terms of the change in tectonic setting from spreading to suprasubduction zone (Dilek & Furnes 2009). This implies that the fluid flux must have been abundant in the HRH zone in the northern Fizh mantle section. We adopted the intra-oceanic thrusting model in the above discussion because it represents an incipient stage in the formation of a subduction zone. A recent model of subduction initiation by subsidence and arc–trench rollback is an alternative to explain our observations in terms of the change in tectonic setting from spreading to suprasubduction zone (Dilek & Furnes 2009).

Previous studies of the northern Oman Ophiolite have proposed that palaeo-ridge segment boundary regions were located in the northern part of the Fizh Block, such as at Wadi Fizh north (Adachi & Miyashita 2003; Miyashita et al. 2003) and at Wadi Rayy (Le Méé et al. 2004; Monnier et al. 2006). The HRH zone extends from Wadi Rayy to Wadi Zabin, located in the north of Wadi Fizh (Fig. 7). We therefore infer that the HRH zone developed in the ridge segment boundary region during intra-oceanic thrusting. The NW–SE orientation of the HRH zone may be taken to imply that shear deformation in the segment boundary region enhanced fluid infiltration. Kelemen & Dick (1995) demonstrated that melt flow in the shallow mantle was focused along actively deforming ductile shear zones in the Josephine peridotite in SW Oregon. The intergranular flow of ascending liquid dissolved pyroxene and precipitated olivine, forming zones of dunite replacing harzburgite. Thick dunite bands (tens of metres thick) are abundant in the HRH zone in the northern Fizh mantle section. This field observation is consistent with fluid being focused in the HRH zone.

The highly refractory harzburgites (spinel Cr# > 0.7) are commonly isolated and are surrounded by less refractory harzburgites (spinel Cr# < 0.5) (Fig. 7). This means that transformation of anhydrous residue to flux-assisted residue was not pervasive and that the fluid and/or melt flow was rather focused in the high-porosity channels. In detail, this focused melting has been common in the western part (slightly deeper mantle) of the HRH zone, whereas it was more pervasive in the eastern part (the shallower section of the HRH zone). This spatial contrast is also related to the microstructural domain, whereby fluid and/or melt focusing was common in the porphyroclastic domain in which ductile shear deformation promoted the focusing of melt/fluid into channels; more-pervasive intergranular flow was however dominant in the coarse granular domain (Fig. 7a). Clinopyroxenes with high Na₂O content (>0.15 wt%) are more commonly observed in the coarse granular domain than in the porphyroclastic domain (Fig. 7b). Such high-Na₂O clinopyroxenes might have been crystallized from a trapped residual liquid as a consequence of pervasive intergranular flow in the coarse granular domain.

Alternatively, even although the fluid flux was initially uniformly supplied into the base of the mantle section, due to compositional heterogeneity in the mantle section the HRH zone might have been developed by a positive feedback mechanism between fluid focusing and flux melting. Based on the presence of significantly low spinel Cr#, Le Méé et al. (2004) and Monnier et al. (2006) inferred a first-order ridge segment (Macdonald et al. 1991) in the northern part of the Fizh Block. Generally speaking, more fertile peridotite has the potential to produce a larger amount of melt than more depleted peridotite. An increase of porosity by flux melting of fertile peridotite further promotes the infiltration of fluid (Aharonov et al. 1995; Kelemen et al. 1995a). As a result, it could have increased the amount of flux flowing into the high-porosity channels that were developed in the boundary region of the ridge segment, thereby forming highly refractory peridotites by flux melting of harzburgite. A similar phenomenon has been discussed with respect to the formation of dunite by a reaction between basaltic melt and harzburgite in the Oman peridotites (Kelemen et al. 1995b). Dissolution of orthopyroxene and precipitation of olivine transforms harzburgite into dunite; the high permeability of dunite promotes further flow of melt into it, resulting in the growth of dunite channels by positive feedback (Kelemen et al. 1995b). In the case of the northern Fizh mantle section, we also consider that dunite channels were responsible for fluid infiltration from the base of the ophiolite. The dunites near the basal thrust tend to be characterized by spinel Cr# greater than 0.7 (Suetsake & Takazawa 2012; Takazawa 2012; Takazawa et al. 2012). Fluid infiltration through dunite channels might have promoted the flux melting of wallrock harzburgite. Large volumes of dunite (tens of metres thick) crop out in the HRH zone, and further research is needed to clarify the role of dunite in the formation of the HRH zone in the northern Oman Ophiolite.

Summary and conclusions

(1) Whole-rock compositions of the harzburgites in the northern Fizh mantle section (northern part of the Oman Ophiolite) define residual
trends with either linear or curved arrays in diagrams of oxides versus spinel Cr#. The partial melting reaction inferred from the modal variation of harzburgite in the northern Fizh mantle section is 0.79 opx + 0.35 cpx = melt + 0.13 olivine + 0.01 spinel. This is in close agreement with the partial melting reaction of clinopyroxene-free harzburgite at 1.0–1.5 GPa if the clinopyroxene present formed by exsolution from orthopyroxene.

(2) The spatial variation of mineral composition (i.e. the Al2O3 content of orthopyroxene and the Cr# of spinel) in the less-refractory harzburgites with spinel Cr# < 0.6 indicates that the degree of partial melting gradually increases from the basal part toward the palaeo-Moho in the northern Fizh mantle section. The peridotites with spinel Cr# < 0.6 preserve compositional variations expected for a residual column that formed beneath a mid-ocean ridge.

(3) In the northern Fizh mantle section, some harzburgites contain high-Cr# spinels exceeding the upper limit of the range for abyssal peridotites; that is, Cr# > 0.6. This indicates that the degree of melt extraction from these highly refractory harzburgites was greater than from the abyssal peridotites. The harzburgites with spinel Cr# greater than 0.7 are distributed as a 3-km-wide band extending from the basal thrust to the palaeo-Moho on the western side of the shear zone in the northern Fizh mantle section.

(4) The northern Fizh mantle section has evolved through a two-stage process. In the first stage, the partial melting of asthenospheric mantle beneath a mid-ocean ridge produced oceanic lithospheric mantle that was more refractory towards the top because of the increase in the degree of melt extraction. In the second stage, during detachment and intra-oceanic thrusting of oceanic lithosphere, an H2O-rich fluid was released from the metamorphic sole due to thermal metamorphism of altered oceanic crust. The fluid infiltrated the mantle section, mainly along the shear zone, through deformation-induced positive feedback and induced flux melting of residual harzburgites by a reduction of solidus temperature, resulting in the formation of highly refractory harzburgites (Cr# > 0.7). Alternatively, an increase of porosity by flux melting of fertile peridotites (herzolite), which are common in the segment boundary region, further promoted the infiltration of fluid. This further increased the amount of fluid flowing into the high-porosity channels, thereby forming highly refractory harzburgites by flux melting.

We thank the Ministry of Commerce and Industry, Directorate General of Minerals in Oman, for facilitating our fieldwork in the Oman Ophiolite. We are grateful to S. Miyashita, S. Arai, S. Umino, Y. Adachi, K. Michibayashi and T. Ishikawa for fruitful discussions and for their support during our fieldwork. Reviews by S. Arai, an anonymous reviewer and H. Rollinson (as Volume Editor) greatly improved the manuscript. We thank S. Miyashita and T. Shimura for assistance in microprobe analysis and H. Ishimoto for XRF analysis. We benefited from discussions with E. Hellebrand, H. Kagami, K. Shuto and T. Shimura. This study was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education of Japan (09041101) and from JSPS (11681121, 16540413, 19540478).

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