Petrologic profile of peridotite layers under a possible Moho in the northern Oman ophiolite: an example from Wadi Fizh

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We examined vertical variations of the petrological characteristics of a 33-m-thick peridotite section under the layered gabbro section along Wadi Fizh of the northern Oman ophiolite to understand the formation mechanism of the Mohorovicic discontinuity (Moho) beneath a spreading center. Here, we refer to the base of the layered gabbro section as “L-Moho” for the sake of simplicity. Network-like gabbro sills in peridotites increase in frequency upward to the L-Moho. The L-Moho is underlain by a 1-m-thick wehrlite layer, under which exists a 10-m-thick dunite layer, overlying a harzburgite layer where total pyroxenes slightly increase downward. Wehrlite is also found as screens between gabbro layers above the L-Moho. The mineral chemistry indicates systematic variations toward the L-Moho within the peridotite section; the Fo content (91 to 85) and NiO (0.4 to 0.2 wt%) of olivine decrease; the TiO₂ content of clinopyroxene (0.1 to 0.6 wt%) and spinel (nil to 1.4 wt%) and atomic ratios of Cr/(Cr + Al) (0.5 to 0.6) and Fe³⁺/(Cr + Al + Fe³⁺) (0.05 to >0.1) in spinel increase upsection from the base (harzburgite) to the around L-Moho wehrlite via dunite. These variations are essentially similar to those observed in harzburgite/MORB reaction products from Hess Deep, East Pacific Rise, and possibly indicate that the lithological and mineral chemical variations within the examined peridotite layer resulted from the reaction between a harzburgite and a melt that produced the layered gabbros.

Keywords: Moho, Dunite, Wehrlite, Harzburgite, Peridotite/melt reaction, Wadi Fizh, Oman ophiolite

INTRODUCTION

The petrological nature of the sub-oceanic Mohorovicic discontinuity (hereafter referred to as Moho) has long been a subject of debate. Hess (1962) suggested that the Moho is an isothermal serpentinization front within peridotites. Clague and Straley (1977) suggested that the Moho is a boundary between partially serpentinized peridotite and fresh peridotite on the basis of experimental data and observations of ophiolites. In the Oman ophiolite, however, no such serpentinization fronts have been observed in the lowermost ultramafic section (Arai and Abe, 2008), and it is generally agreed upon that the Moho is represented by the boundary between layered gabbros and underlying dunitic peridotites (hereafter referred to as Moho transition zone) (e.g., Boudier and Nicolas, 1995). No detailed petrological observations of the boundaries between the layered gabbro and the underlying peridotite section from the Oman ophiolite have been carried out. In this study, we present, for the first time, detailed petrological properties of the peridotite section immediately beneath the layered gabbro at Wadi Fizh in the northern Oman ophiolite in order to clarify the genesis of the gabbro/peridotite transition. As stated below, the gabbro/peridotite transition obtained at Wadi Fizh is the simplest among all that we have observed in the northern Oman ophiolite. Therefore, this location is ideal for examining the gabbro/peridotite transition. Information about the nature of this transition will be indispensable for the success of the Mohole, a project in which a hole will be drilled through the Moho.

GEOLOGICAL BACKGROUND

The northern Oman ophiolite provides a good opportunity to observe a crust-mantle section of a type of oceanic lithosphere formed at a fast-spreading center (e.g., Lippard et al., 1986; Nicolas, 1989). It is characterized, however, by arc-type rocks, e.g., boninites and high-Cr plutonic rocks, that cut or intrude MORB-related rocks (e.g., Ishikawa et al., 2002; Ahmed and Arai, 2002; Tamura and Arai, 2006). Pearce et al. (1984) suggested a back-arc basin origin for the Oman ophiolite, whereas Arai et al.
N. Akizawa and S. Arai (2006) suggested multiple origins, namely, initial formation at a mid-ocean ridge followed by modification at a subduction zone immediately before obduction. The main part of the Oman ophiolite is representative of the oceanic lithosphere formed at a spreading center. In particular, the northern Oman ophiolite exposes effusive rocks to mantle peridotites downsection (Fig. 1). We can observe various types of gabbro/peridotite transitions in terms of sharpness in the northern Oman ophiolite. Wadi Fizh exhibits excellent exposure of crust-mantle rocks formed at a segment margin of a spreading ridge (Miyashita et al., 2003). This route provides us with one of the sharpest gabbro/peridotite boundaries in the Oman ophiolite (Arai, 2009). The Wadi Fizh gabbro/peridotite transition is also characterized by the apparent absence of late-intrusive wehrlite/dunite (Benn et al., 1988). Uesugi et al. (2003) provided detailed petrographical descriptions of the gabbro/peridotite transition.

![Figure 1. Locality of the study area on a geological sketch map along Wadi Fizh in the northern Oman ophiolite. The rock names indicate the dominant lithologies distributed in this area. Modified from Takazawa et al. (2003).](image)

LITHOLOGICAL VARIATION WITHIN PERIDOTITE SECTION UNDER LAYERED GABBRO

Field relations

We examined the peridotite section to a depth of approximately 33 m directly beneath the layered gabbro section at Wadi Fizh (Figs. 1-3). The profile was obtained from a route along a steep creek. The base of the layered gabbros is called “L-Moho” (= local or lithological Moho) for the sake of simplicity (Fig. 2a). Both the layering in the gabbros and the foliation plane are apparently parallel to the L-Moho (Figs. 2 and 3). Their attitude is approximately N70°W and 40°E. “Interval 1” corresponds to a set of wehrlite screens above the L-Moho (Figs. 2 and 3); “Interval 2,” a harzburgitic dunite layer immediately under the L-Moho (Figs. 2 and 3); and “Interval 3,” a harzburgite-dominant layer at the base of the examined section.

Uesugi et al. (2003) described a transition from the lowest part of the layered gabbros to the horizontally elongated network of gabbro sills within the wehrlite layer (Fig. 2a). The wehrlitic layer is less than 1 m thick and it changes downward to an approximately 8 m-thick dunite (partly harzburgitic) layer (Fig. 2b) (Interval 2) (Fig. 3). Harzburgite appears approximately 10 m below the L-Moho (Fig. 3). The boundaries between the dunite and the harzburgite and those between the dunite and the wehrlite are gradual and irregular (not planar), and some of the dunite bands are sinuous or partly network-like within harzburgite layer (Fig. 2c). The gabbro sills with or without dunitic to wehrlitic aureole (Fig. 2d) decrease in frequency downsection within the dunite layer and harzburgite layer. Dunite bands are occasionally observed in the harzburgite layer (Fig. 3). The gabbro sills and dunite bands are almost parallel to the layering of the gabbros (Fig. 2). Some of the peridotites exhibit prominent foliation expressed by flattened pyroxenes (Fig. 2b) and spinels, which are also comparable to the attitude of the gabbro sills and layers. The peridotites were sampled at intervals of 2 to 3 m to represent the lithology on the relevant part of the outcrops.

Petrography

Peridotites suffer from severe serpentinization, although the primary textures and minerals can be recognized in typical cases. Variations of the modal amounts of primary minerals (olivine and pyroxenes) are shown in Figure 3.

The harzburgite sharply changes to dunite, with less than 10 vol% of pyroxenes, 10 m beneath the L-Moho (Fig. 3). The harzburgite tends to decrease in the total pyroxene amount upward toward the dunite layer below the L-Moho, especially in Interval 3 of the harzburgite layer, despite frequent dunite intervention and significant modal fluctuation (Fig. 3).

The harzburgite exhibits weakly to strongly porphyroclastic textures with orthopyroxene porphyroclasts that are rarely kinked and contain very few exsolution lamel-
Figure 2. Photographs of outcrops of typical lithologies of peridotite under the layered gabbro. (a) Layered gabbros (G), overlying wehrlite (W), and dunite (D). The lower end of the layered gabbro is called L-Moho in this paper. Note the horizontally elongated network of gabbro around the wehrlite (cf., Uesugi et al., 2003). Small black lenses in the layered gabbro are wehrlite screens. (b) Harzburgitic dunite (D) in Interval 2 (Fig. 3). Note the flattened orthopyroxene porphyroclasts (small black lenses in rectangle) representing the foliation. Vertical veins are related to late-stage serpentinization and alteration. (c) Sinuous and partly network-like dunite band within harzburgite in Interval 3. It is sub-parallel to the foliation of the harzburgite. (d) Gabbro sill with wehrlitic aureole in harzburgite in Interval 3. It is parallel to the foliation of the harzburgite. Note that (a) gabbro layering, (b) foliation of peridotites, (c) bands of dunite, and (d) gabbro are all parallel or subparallel to each other. (b)-(d) The pen, which is set so as to be parallel to the lineament of the harzburgite foliation on the outcrop surface, is approximately 14 cm in length.

Figure 3. Petrographical and mineral chemical profile for the uppermost part of the peridotite section under the layered gabbro from Wadi Fizh, northern Oman ophiolite. L-Moho denotes the lowest end of the layered gabbro section. Depths from the L-Moho are indicated on the vertical axes. Mineral chemical characteristics almost systematically change upward to the L-Moho. Modal compositions fluctuate in the harzburgite layer, but pyroxenes appear to decrease upward in the upper half of Interval 3.
The foliation of the harzburgite becomes more prominent upward with orthopyroxene porphyroclasts apparently decreasing in size and abundance. The orthopyroxene porphyroclast is frequently poly-grained, and it is replaced with olivine at its rims in the harzburgite, especially in the upper part of the harzburgite layer (Interval 3). Chromian spinel in the harzburgite is deep brown in color in the thin section, and varies in shape from anhedral to subhedral.

The dunite is partly harzburgitic (Figs. 2c and 3) and in particular, severely altered, and no orthopyroxene grains are preserved. Chromian spinel is mostly subhedral and deep brown to black in color in dunite and wehrlite. Clinopyroxene is subhedral to anhedral and contains interstitial to olivine grains in dunite and wehrlite. Completely saussuritized plagioclase is found in small amounts in wehrlite and dunite.

Gabbros are composed of slightly to moderately elongated grains of clinopyroxene, plagioclase, and olivine. They are aligned roughly parallel to the attitude of sills and layers or bands. Primary amphiboles, orthopyroxene, and oxides are not found. Clinopyroxene and plagioclase are anhedral, and olivine is fine in grain size, subhedral to anhedral, and interstitial to clinopyroxene and plagioclase. Some of the gabbros, especially those forming network-like sills and bands (Figs. 2b and 2d), are severely altered to form saussurite and chlorite.

**MINERAL CHEMISTRY**

Microprobe analysis of selected grains of olivine, pyroxenes, and chromian spinel was carried out using a JEOL-8800 microprobe at Kanazawa University. We analyzed only the cores of the mineral grains because no significant intra-grain chemical heterogeneity was recognized. The analytical conditions were an accelerating voltage of 20 kV, probe current of 20 nA, and probe diameter of 3 µm. Natural and synthetic minerals were used as standards, and the ZAF online correction program was used for data reduction. All Fe is assumed as Fe$^{3+}$ in silicates, and Fe$^{2+}$ and Fe$^{3+}$ were calculated for spinel assuming stoichiometry. Mg# and Cr# denote Mg/(Mg + Fe$^{2+}$) and Cr/(Cr + Al) atomic ratios, respectively. Y$_{Fe}$ denotes the Fe$^{3+}/(Cr + Al + Fe^{3+})$ atomic ratio in spinel.

The basal harzburgite of the section examined here (Interval 3) exhibits chemical characteristics of ordinary mantle harzburgite; the olivine, Fo$_{89}$ and 0.4 wt% NiO; and the chromian spinel, 0.5–0.6 Cr#, low Y$_{Fe}$ (0.05 on average), and TiO$_2$ (almost nil) (Figs. 3 and 4). The Fo and NiO contents of olivine in harzburgite from Interval 3 (harzburgite layer) are around 90 and <0.4 wt%, respectively (Fig. 3). The dunite (Interval 2) and wehrlite (Interval 1) exhibit lower Fo (89 to 85) and NiO (0.2–0.3 wt%) contents of olivine than harzburgite (Figs. 3 and 4f). The Cr# is slightly lower than 0.6 and the TiO$_2$ content is up to 1.4 wt% in chromian spinels from dunite and wehrlite (Figs. 3 and 4c). The Y$_{Fe}$ of spinel ranges from 0.05 to 0.24 in dunite and wehrlite (Fig. 4e). In the clinopyroxene, the TiO$_2$ content increases from 0.1 to 0.6 wt% whereas the Cr$_2$O$_3$ content decreases from approximately 1.2 to 0.5 wt% from harzburgite (Interval 3) to dunite (Interval 2) and wehrlite (Interval 1) (Figs. 4a and 4b). The Fo content of olivine decreases, on average, from harzburgite at the base of Interval 3 to wehrlite (Interval 1) through dunite (Interval 2), with a very slight increase in Cr# of spinel, being gradually deviated from the olivine-spinel mantle array (a residual spinel peridotite trend) in the Fo (olivine)–Cr# (spinel) space (Fig. 4f).

**DISCUSSION**

The mineral chemical trend observed in the peridotite section below the L-Moho, a suite of harzburgite, dunite, and wehrlite, almost mimics that obtained from the harzburgite-dunite-troctolite-olivine gabbro assemblage from Hess Deep, East Pacific Rise (e.g., Arai and Matsukage, 1996) (Fig. 4). The dunite, troctolite, and olivine gabbro are interpreted as reaction products between the harzburgite and MORB (Arai and Matsukage, 1996; Dick and Natland, 1996). Essentially, the same mechanism, i.e., reaction between a harzburgite and some melt, can be expected to be involved in both suites of rocks, although the rock assemblage is different (cf., Kelemen et al., 1995; Koga et al., 2001).

We confirmed a reaction origin for individual rock types from their field relations. The reaction was associated with incongruent melting of orthopyroxene in harzburgite, as suggested by an upsection decrease in orthopyroxene both in size and in volume. Harzburgitic or orthopyroxene-bearing dunite (Fig. 2c) within the dunite layer is possibly a relic of the mantle harzburgite after incomplete digestion of orthopyroxene. Wehrlite was most probably formed by incomplete melt extraction from a reaction product (olivine + melt), where clinopyroxene and olivine were precipitated from the melt (cf., Arai and Take-moto, 2007). The base of the layered gabbro section (around the L-Moho) of the oceanic lithosphere represented by the northern Oman ophiolite was initially a reaction front of mantle harzburgite in contact with a melt (or melts), which formed the layered gabbro, i.e., the very base of the crustal sequence.

The essential difference between Hess Deep (East Pacific Rise) and Wadi Fizh (Oman ophiolite) rocks is the relative abundance of wehrlite and troctolite. Wehrlite has
Figure 4. Mineral chemical variations in peridotitic rocks obtained under the L-Moho. Minerals increase in incompatible elements roughly from Interval 1 to Interval 3 through Interval 2. The Cr content of chromian spinel is exceptional, increasing upward to the L-Moho. Trends for the rocks (from harzburgite/dunite through troctolite to olivine gabbro) from Hess Deep, East Pacific Rise (Arai and Matsukage, 1996), are roughly indicated by arrows. They are almost concordant with those in the Wadi Fizh, from harzburgite through dunite to wehrlite. (f) OSMA is the olivine-spinel mantle array, a residual spinel peridotite trend, as defined by Arai (1994).

been very rarely found (Arai and Takemoto, 2007); however, troctolites are very common in drill cores from Hess Deep (e.g., Arai and Matsukage, 1996). In contrast, troctolites are far less abundant than wehrlites around the L-Moho from Wadi Fizh (Figs. 2 and 3). Wehrlites are quite common as xenoliths from arc settings (e.g., Arai et al., 2000; Arai and Ishimaru, 2008). This contrast is possibly due to the difference in the order of crystallization of minerals in the melt involved in or resulting from the reaction; olivine was followed by plagioclase in Hess Deep, but by clinopyroxene in Wadi Fizh. This indicates that the melt involved in the formation of Moho transition zone rocks in the Oman ophiolite (Wadi Fizh) is different in chemistry from the ordinary MORB involved in the formation of a plutonic rock suite in Hess Deep (e.g., Dick and Natland, 1996; Arai and Matsukage, 1996; Arai, 2005). MORB is suggested to be involved in the formation of wehrlites and related rocks in the Moho transition zone of the southern Oman ophiolite (Koga et al., 2001). We consider a back-arc basin magma, which is MORB-like but has an arc-magma affinity, although a careful and more thorough examination is required.

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