LETTER

Crustal diopsidites from the northern Oman ophiolite: Evidence for hydrothermal circulation through suboceanic Moho

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This paper details a new discovery of anorthite-bearing diopsidites (= anorthite diopsidites) from the lowermost crust along Wadi Fizh in the northern Oman ophiolite. The anorthite diopsidites occur as networks within layered gabbros 50 m above the gabbro/peridotite boundary, and are mainly composed of high-Mg diopsidic clinopyroxenes and anorthites with various amounts of uvarovite. They are intermediate in mineral chemical characteristics between the crustal gabbros and the diopsidites, and interpreted as an interaction product between high-temperature Ca-rich hydrothermal fluids and peridotites within the mantle section. The anorthite diopsidites were probably formed by interaction between the fluids involved in diopsidization within the mantle section and the layered gabbro. The fluids responsible for the formation of the anorthite diopsidite were also Ca-rich and carried Cr to form uvarovite from the underlying mantle section. High-temperature hydrothermal circulation plays an important role in the transportation of elements, e.g., Ca and Cr, from the upper mantle to the lower crust across the Moho in the ocean floor.

Keywords: Diopsidite, Anorthite diopsidite, Hydrothermal fluids, Upper mantle, Lower-crust gabbro, Oman ophiolite

INTRODUCTION

Although hydrothermal circulation is one of important ways of chemical transfer in the oceanic lithosphere, the depth and extent of hydrothermal fluids within this zone remain controversial. The Oman ophiolite offers unparalleled information on this topic because it exposes an entire sequence from the upper crust to the upper mantle. It is widely accepted that seawater reached the base of the sheeted dike complex (Nehlig and Juteau, 1988; Yoshihata et al., 2009) and penetrated further down to the layered gabbros (Kawahata et al., 2001; Abily et al., 2011) in the Oman ophiolite. The seawater penetration through the lowermost crust to the uppermost mantle is expected, but the hydrothermal network in rocks becomes less dense with increasing depth (e.g., Nehlig, 1993; Bosch et al., 2004). Consequently, it is inevitably difficult to find traces of seawater circulation within these sections.

Diopsidites, mainly composed of diopsides, have been discovered as dikes within the mantle section in the Oman ophiolite (Python et al., 2007a). These diopsidites were formed by reactions between Ca-rich hydrothermal fluids and peridotites at various temperatures, from approximately 600 °C to higher than 900 °C (Python et al., 2011). Their presence indicates that the fluids probably passed through the entire crust to the mantle section, and could have reversed their flow back to the crust.

We discovered anorthite-bearing diopsidites in the lowermost crust of the Oman ophiolite. The anorthite-bearing diopsidites are similar to gabbros in terms of the plagioclase/clinopyroxene ratio, but resemble the diopsidites defined by Python et al. (2011) in diopsidic nature of clinopyroxenes. We call them as anorthite diopsidites in this paper and discuss their petrogenesis by making a comparison with mantle diopsidites (Python et al., 2007a) from the northern Oman ophiolite to understand the activity of high-temperature hydrothermal fluids from the suboceanic uppermost mantle to the lowermost crust.

GEOLOGICAL BACKGROUND

The northern Oman ophiolite provides an excellent opportunity to observe a crust-mantle section of a kind of oceanic lithosphere formed at a fast-spreading center (e.g., Lippard et al., 1986; Nicolas, 1989). The exposure of rocks in this ophiolite is the most extensive in the world, and the rocks preserve considerable information on the hydrothermal alteration prior to the obduction of the oceanic lithosphere.

The northern Oman ophiolite exposes effusive rocks...
to mantle peridotites in good condition (Fig. 1). We can observe sharp gabbro/peridotite transition along Wadi Fizh in the northern Oman ophiolite (e.g., Uesugi et al., 2003; Akizawa and Arai, 2009), which reveals excellent exposures of crust-mantle rocks formed at a segment margin of a spreading ridge (Miyashita et al., 2003).

Dark brown chlorite rocks were formed in isotropic gabbros, which are located just below the sheeted dike complex along Wadi Bani Umar in the Fizh block of the northern Oman ophiolite (Yoshitake et al., 2009). Complete chloritization occurred on isotropic gabbros and dolerites as a result of hydrothermal alteration (Yoshitake et al., 2009). In addition, Kawahata et al. (2001) reported that the entire sequence of oceanic crust along Wadi Fizh underwent hydrothermal alteration. However, the diopsidites, which are a product of hydrothermal alteration of peridotite, have not yet been reported from the Fizh block (cf. Python et al., 2007a).

FIELD RELATIONSHIPS AND PETROGRAPHY

Field relationships

We examined an anorthite diopsidite network cutting a layered gabbro in the lowermost crust about 50 m above the layered gabbro/peridotite boundary at Wadi Fizh in the northern Oman ophiolite (see Akizawa and Arai, 2009) (Figs. 1 and 2a). The thickness of individual veins varies from a few centimeters to a few tens of centimeters. Boundaries between unaltered layered gabbros and anorthite diopsidites are gradual, and the transitional zones between them are a few centimeters in thickness (Fig. 2a).

Petrography

The layered gabbros are mainly composed of anhedral grains of clinopyroxene and plagioclase, and their modal proportions vary across the layers (e.g., approximately 60 vol% and 40 vol% plagioclase in the lighter and darker layers, respectively). Each layer contains only a small amount of olivine (<few vol%). They are adcumulates in texture, as classically observed in the lower crustal gabbros (Nicolas and Ildefonse, 1996).

The anorthite diopsidites are mainly composed of diopsidic clinopyroxenes and Ca-rich plagioclases with textural and chemical properties that clearly contradict a magmatic origin. The diopside grains are quite heterogeneous in appearance: some of them show irregular patchy chemical zonation (left-hand side of Fig. 2b), and others showing somewhat concentric zoning (right-hand sides of Figs. 2b and 2c). The anorthite diopsidites exhibit a “pseudo-porphyritic” texture, composed of coarse grains of diopside and anorthite contain a fine-grained matrix of anorthite (Fig. 2b). The coarser grains, with diameters of several hundreds of microns, show ambiguous outlines (Figs. 2c and 2d). The contact between diopside and anorthite grains is sharp and clear (Figs. 2b and 2c).

The transitional zone between unaltered gabbros and anorthite diopsidites contains chemically heterogeneous clinopyroxenes (Fig. 2e), which differ significantly in texture from diopsides in the anorthite diopsidites (Figs. 2b–2d). Igneous clinopyroxenes are replaced by lamellar tremolites along cleavages and irregular diopside veinlets (Fig. 2e). Rocks of the transitional zone are also composed of coarse clinopyroxene and plagioclase veinlets, and a fine-grained matrix of diopside and anorthite (Fig. 2f).

The anorthite diopsidites described here differ from ordinary rodingites in that they are free from zoisite and grossular, although uvarovite occurs frequently. They are instead similar to diopsidites and anorthite diopsidites described from the mantle section of the Oman ophiolite (Python et al., 2007a, 2011).

MINERAL CHEMISTRY

Major elements

Microprobe analysis was performed for clinopyroxenes and plagioclases with a JEOL-8800 microprobe on selected grains at Kanazawa University. Analytical conditions were an accelerating voltage of 20 kV, a probe current of 20 nA, and a 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 was assumed to be Fe2+ in silicates. Mg# and An content were Mg/(Mg + Fe2+) and 100Ca/(Ca + Na + K) atomic ratios, respectively. Major-element compositions...
Origin of crustal diopsidites from Oman ophiolite of clinopyroxenes and plagioclases are listed in Table 1 (available online http://joi.jlc.jst.go.jp/JST.JSTAGE/jmps/110621b).

Clinopyroxenes in the surrounding gabbros are augitic with relatively low Mg# (0.84 to 0.87) that gradually increases up to 0.98 across the transitional zone toward the anorthite diopsidite region, where it shows significant variation (Figs. 3a–3c). The diopsides in anorthite diopsidites show a wide difference in Cr2O3 content (almost nil to 0.6 wt%) as in the mantle diopsidite (Fig. 3a). In the clinopyroxene phases, the Al2O3 and TiO2 contents decrease from 2.8 wt% to almost nil and from 0.5 wt% to nil, respectively (Figs. 3c and 3d), whereas the CaO content increases from about 20 to 26 wt% from gabbros to anorthite diopsidites through the transitional zone (Fig. 3b). In the transitional zone, the coarse clinopyroxenes and veinlet diopsides are closer in chemistry to the gabbro clinopyroxenes and the diopsides in anorthite diopsidites, respectively (Fig. 3). The An content of plagioclase phases increases from about 82 to almost 100, with a decrease of FeO content from 0.5 wt% to almost nil (Fig. 4). In the transitional facies, the fine matrix anorthites are similar in chemistry to that in the anorthite diopsidites, and coarse plagioclases are closer in chemistry to the gabbro plagioclases (Fig. 4).

Trace elements

Trace-element (Ti, Sr, Y, Zr, Nb, and REE = rare earth elements) concentrations of clinopyroxene (Fig. 5a) and plagioclase phases (Fig. 5b) were determined with a laser ablation (193 nm ArF excimer: MicroLas GeoLas Q-plus) inductively coupled plasma mass spectrometer (Agilent 7500S; LA-ICP-MS) at Kanazawa University (Ishida et al., 2004; Morishita et al., 2005a, 2005b). Each analysis was performed by ablating 60 μm in diameter for diopside and clinopyroxene, and 100 μm in diameter for anorthite and plagioclase, at 6 Hz with energy density of 8 J/cm² per pulse. Signal integration intervals were 50 s for both gas background and ablation. The element concentration of NIST SRM 612 was selected from the preferred values of Pearce et al. (1997). Data reduction was facilitated using 29Si as the internal standard on the basis of SiO2 contents determined by microprobe, following a protocol essentially identical to that outlined by Longerich et al. (1996). The accuracy of measurements estimated from analyses of the reference material (NIST SRM 614) was better than 4% in relative standard deviation for all elements. Trace-element compositions of clinopyroxenes and plagioclases are listed in Table 2 (available online http://joi.jlc.jst.go.jp/JST.JSTAGE/jmps/110621b).

Diopsidic clinopyroxenes in anorthite diopsidites are highly variable in trace-element contents (Fig. 5a) as in major elements (Fig. 3). Augitic clinopyroxenes in the
surrounding gabbro are relatively high in incompatible trace elements (Fig. 5a) and almost in equilibrium with normal mid-oceanic ridge basalts (N-MORB; not shown), indicating that the gabbros are cumulates from N-MORB (e.g., Dick and Natland, 1996). Clinopyroxenes from the transitional facies are intermediate in trace-element abundances (Fig. 5a). We analyzed each part of the zoned diopsidites in the anorthite diopsidites: Di1 (the dark patch) and Di2 (in light surrounding part) of a patchy zoned grain (Fig. 2b), and Di3 (the core) and Di4 (the rim) of a concentrically zoned grain (Fig. 2c). The trace-element characteristics of Di1 and Di3 are similar to the augitic clinopyroxenes in the transitional facies, and Di2 and Di4 are similar to the diopside in the mantle diopsidites (Fig. 5a). Di4 differs slightly in trace-element characteristics from Di2 and other diopsides in the anorthite diopsidites (Fig. 5a), possibly because the dark and light parts (Fig. 2c) are mixed at Di4. Diopsides in the anorthite diopsidites show higher Ti levels and exhibit very weak or no positive Eu anomalies, as compared with the diopsides in the mantle diopsidites (Fig. 5a). All analyzed plagioclase phases show strong positive anomalies at Sr and Eu (Fig. 5b). Anorthites in the anorthite diopsidites are poorer in trace elements than plagioclases in the surrounding gabbro (Fig. 5b).

DISCUSSION

The anorthite diopsidites reported here, although exhibit-
rich in Ca, assuming iso-volume metasomatic change, appears that the fluids forming anorthite diopsidite were diopsidites than in precursor gabbros (Figs. 3b and 4). It diopsidites as for the mantle diopsidites (Python et al., possibly involved in the formation of the crustal anorthite ture hydrothermal fluids rich in silicate components were which is suggested by network-like replacements of the age between the two suites of diopsidites. High-tempera-

Figure 5. Chondrite-normalized trace-element patterns for clinopyroxenes (a) and plagioclases (b). Chondrite values are from Sun and McDonough (1989). The gray field in (a) is for diopside in the mantle diopsidites in the Oman ophiolite (Python et al., 2007b). The analytical points of diopsides (Di1 to Di4) are indicated in Figures. 2b, 2c, and 2g. The detection limit is shown in (b), and values under the detection limits are shown without symbols.

roxenes in the anorthite diopsidites can likely be attribut-
ed to irregular chemical modification. The lower crustal anorthite diopsidites share petrographical and mineral chemical characteristics with the mantle diopsidites reported by Python et al. (2007a), suggesting a genetic linkage between the two suites of diopsidites. High-tempera-
ture hydrothermal fluids rich in silicate components were possibly involved in the formation of the crustal anorthite diopsidites as for the mantle diopsidites (Python et al., 2007a).

The minerals are obviously richer in Ca in anorthite diopsidites than in precursor gabbros (Figs. 3b and 4). It appears that the fluids forming anorthite diopsidite were rich in Ca, assuming iso-volume metasomatic change, which is suggested by network-like replacements of the gabbro with the anorthite diopsidite. Ca-rich fluids, which gained Ca during circulation through the crustal section down to the mantle, are also responsible for the formation of the mantle diopsidites (cf., Python et al., 2011; Yoshitake et al., 2009). We consider that the fluids that had left diopsidites in the mantle section were involved in formation of the anorthite diopsidites in the lowermost crust. This is consistent with the occurrences of both the mantle diopsidites and crustal anorthite diopsidites around the layered gabbro/peridotite boundaries along Wadi Fizh (Python et al., 2007a). These fluids possibly carried Cr from the mantle upward to precipitate uvarovite garnets in the crustal diopsidites. Relatively high Sr contents were possible in the fluids responsible for the precipitation of the crustal diopsidites because diopsidites show slightly positive Sr anomalies in addition to the strong Sr anomalies of anorthites (Fig. 5). Precipitation of chlorites with strong negative Eu anomalies from downward hydrothermal fluids (Yoshitake et al., 2009) possibly resulted in the relatively high–Eu character of the fluids flowing from the lower crust to the upper mantle. The relatively high Ti content of diopside was inherited from augitic clinopyroxenes in the precursor gabbros (Fig. 5a). In contrast, the diopside in the mantle diopsidite (Python et al., 2007a) is depleted in Ti (Fig. 5a), in accordance with the low–Ti character of mantle peridotites (Godard et al., 2000).

The temperature of diopsidite formation was possibly higher than that of ordinary rodingitization of gabbros and could have exceeded 900 °C (Python et al., 2011), although the lack of critical mineral assemblages for gabbro/peridotite boundaries. Such high-temperature conditions around the level of the Moho (~ 0.2 GPa) is possibly available at the sub-oceanic spreading center, marked by the high-temperature asthenospheric mantle uprise (cf. Python et al., 2007a). These fluids possibly carried Cr and Si around the lower crust to the upper mantle through metasomatic formation of diopsidites, as suggested by Python et al. (2007a, 2011). Cr, which has been regarded as immobile in hydrothermal conditions, is possibly mobile through such high-temperature fluids rich in silicates.

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Tables 1 and 2 are available online http://joi.jlc.jst.go.jp/JSTJSTAGE/jmps/110621b.

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