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Natural type-C olivine fabrics in garnet peridotites in North Qaidam UHP collision belt, NW China

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Water is known to change the lattice-preferred orientation (LPO) of olivine, which significantly affects seismic anisotropy in the Earth’s upper mantle. Research into the LPO of olivine in the deep interior of the Earth has been limited due to inadequate specimens. We report both the water-induced LPOs of olivine and the presence of large quantities of water inside olivine, enstatite, and garnet in garnet peridotites from the North Qaidam ultrahigh-pressure (UHP) collision belt in NW China. We show that the [001] axis of olivine is aligned subparallel to the lineation and that the [100] axis is strongly aligned subnormal to the foliation. This alignment is a known feature of type-C LPO of olivine formed experimentally under water-rich conditions (>700 ppm H/Si) at high pressure and temperature. Enstatite possessed an LPO with the [001] axis aligned parallel to the lineation and the [100] axis aligned normal to the foliation. FTIR analysis of this specimen revealed that olivine contained concentrations of water up to 1130 ± 50 ppm H/Si in clean areas, whereas olivine, enstatite, and garnet contained considerably more water, i.e., 2600 ± 100 ppm H/Si, 5000 ± 100 ppm H/Si, and 21,000 ± 200 ppm H/Si, respectively, when exsolved inclusions were visible. Confocal micro-Raman spectroscopy of these exsolved inclusions revealed that they were composed of hornblende and amphiboles. Straight dislocations were also commonly observed in olivine and are characteristic of olivine that had been experimentally deformed under hydrous conditions. These observations suggest that the type-C LPO of olivine in the North Qaidam UHP belt formed under water-rich conditions.

1. Introduction

Water significantly affects the physical properties of mantle materials (Bell and Rossman, 1992; Karato, 2003). Experimental studies conducted under high pressure and temperature conditions have shown that water lowers the melting temperature of peridotite (Gaetani and Grove, 1998; Hirose and Kawamoto, 1995), reduces the flow strength of mantle rocks (Blacic, 1972; Karato and Jung, 2003; Karato et al., 1986; Mackwell et al., 1985; Mei and Kohlstedt, 2000), reduces both the bulk and shear moduli of olivine (Jacobsen et al., 2008), enhances the electrical conductivity of olivine (Wang et al., 2006; Yoshino et al., 2006), and changes the dominant slip system of olivine (Karato, 1995; Mackwell et al., 1985), which causes fabric transitions (Jung and Karato, 2001a; Jung et al., 2006; Katayama et al., 2004). Given that olivine is a dominant mineral in the upper mantle, a change in its lattice-preferred orientation (LPO) due to water has significant implications for interpreting seismic anisotropy in the upper mantle (Jung, 2009; Jung and Karato, 2001a; Jung et al., 2006; Karato et al., 2008; Kneller et al., 2005; Long and Silver, 2008; Mainprice, 2007; Mizukami et al., 2004; Nakajima and Hasegawa, 2004; Park and Levin, 2002; Skemer et al., 2006, 2012; Tasaka et al., 2008).

Natural rocks, which are first deformed and then exhumed from the deep upper mantle, are found in the ultrahigh-pressure (UHP) belt of several regions and can provide important information on the deformation conditions and water content deep within the Earth’s interior. Previous studies showed that olivine with a C-type LPO was observed in samples obtained from the UHP terranes in the Alpe Arami of Switzerland (Möckel, 1969), Cima di Gagnone in the Central Alps of Switzerland (Frese et al., 2003), Otroy in Norway (Katayama et al., 2005; Wang et al., 2013), and Zhimafang garnet peridotites in Eastern China (Xu et al., 2006). However, the water content for olivine in these studies was less than approximately 700 ppm H/Si (Katayama et al., 2005; Xu et al., 2006), which indicates that the olivine LPO might not have formed because of water (Xu et al., 2006; Wang et al., 2013). In this study, we analyzed the LPO and water content of olivine within garnet peridotites obtained from the North Qaidam UHP belt in China. We report the novel discovery of C-type LPOs in olivine containing considerable larger quantities of water than obtained in previous studies, which suggests that the C-type LPO formed because of water, and a large amount of water go down subduction zone.
2. Geological setting and sample characteristics

The Luliang Shan garnet peridotite massif in North Qaidam in NW China forms several large lensoid blocks within quartzofeldspathic gneisses and was exhumed during the Early Paleozoic continental collision between the North China craton and the Qaidam–Qilian block (Manning et al., 2001; Menold et al., 2001; Song et al., 2003, 2004, 2005a, 2005b, 2006; Yang et al., 2000; Yin et al., 2002, 2007; Zhang et al., 2005). A geologic map of the garnet peridotite massif is shown in Fig. 1. The garnet peridotite in the studied area possessed compositional layering that was largely defined by modal variations in major minerals such as olivine, orthopyroxene and clinopyroxene (Fig. 2 and figures in Song et al., 2007). We collected more than ten garnet lherzolites from the Luliangshan garnet peridotite massif in North Qaidam in NW China and investigated three of them which showed a well-defined foliation. The samples consisted of olivine (50–68%), enstatite (11–33%), diopside (10–17%) and minor garnet. Fig. 3A shows an example of the sample microstructures in cross-polarized light and demonstrates elongated clinopyroxene, enstatite, and olivine grains. Exsolution textures were observed in the garnet, olivine, and enstatite. Exsolutions in garnet consist of rutile, orthopyroxene, clinopyroxene, and amphibole (Fig. 3B, C, D, and G; see also Song et al., 2004, 2005a, 2009; Yang and Powell, 2008). Exsolutions in olivine include ilmenite needles, Cr-spinel, and amphibole (Fig. 3E, H, and J). Exsolutions in enstatite (i.e., amphibole) are also commonly found (Fig. 3F and I). The pyroxene exsolutions found in garnet (Fig. 3B, C, and D) suggest that the parental garnets originally possessed excess silicon and were, moreover, majoritic garnets that are only stable at depths in excess of approximately 150 km (Irifune, 1987; Ringwood and Major, 1971). Given the large amount of pyroxene exsolutions (up to 4.5 vol.%) and (Fe, Mg)TiO3 exsolution lamellae (0.53–0.69 wt.% TiO2) in olivine, the garnet peridotite body in North Qaidam, China, is believed to have originated at a mantle depth in excess of 200 km (Song et al., 2004, 2005a, 2007) and belongs to one of the UHP metamorphic belts, such as the Dabie–Sulu terrane in China (Yang et al., 1993; Ye et al., 2000; Zhang et al., 2000), Western Gneiss region in Norway (Van Roermund and Drury, 1998; Van Roermund et al., 2000), and Alpe Arami in Switzerland (Dobrzhinetskaya et al., 1996; Green et al., 1997). The application of an Al-in-Opx geothermobarometer (Brey and Köhler, 1990) and a Grt–Ol geothermobarometer (ONeill and Wood, 1979) to the matrix host minerals within the garnet peridotite yielded a pressure of P = 5.0–6.5 GPa and a temperature of T = 960–1040 °C (Song et al., 2004). Olivine shows a wide range of Fo values (Mg#, Mg/[Mg + Fe2+] = 0.83–0.91) (Song et al., 2007). Further details on the chemical composition of olivine, orthopyroxene, and garnet in our samples are available from previous studies (Song et al., 2004, 2007).

3. Methods

3.1. Determination of the LPO in minerals and seismic anisotropy calculations

The foliation of each sample was determined by the compositional layering of olivine, pyroxene, and garnet, and the lineation of each
sample was determined from the grain elongation determined by grain shape analysis of digitized lines in the foliation (Panozzo, 1983, 1984). The samples were cut parallel to their lineation and perpendicular to their foliation for the microstructure analysis. The LPO of olivine and enstatite was measured for each sample by electron backscatter diffraction (EBSD) (Jung et al., 2006; Prior et al., 1999) using a scanning electron microscope (SEM JEOL 6380) at the School of Earth and Environmental Sciences (SEES), Seoul National University (SNU) in Korea, and the EBSD patterns were analyzed using HKL Channel 5 software and manually indexed to ensure the solution accuracy. The SEM operated at an accelerating voltage of 20 kV and a working distance of 15 mm. Approximately 150–250 individual olivine and enstatite grains were measured for each sample. The misorientation index (M-index) (Skemer et al., 2005) was calculated to estimate the fabric strength of the sample using the uncorrelated grain pairs determined from the EBSD data. The seismic velocity and seismic anisotropy were calculated from the orientation data for olivine, enstatite, diopside, and garnet using the elastic constants for olivine (Abramson et al., 1997), enstatite (Chai et al., 1997), diopside (Collins and Brown, 1998), garnet (Bass, 1989), and a software program (Mainprice, 1990).

3.2. Measurement of the mineral water content

The water content of olivine, enstatite, and garnet was measured using a Nicolet 6700 FTIR spectrometer with a Continuum IR microscope housed at the Tectonophysics Laboratory at the SEES in SNU, Korea. The FTIR spectrometer has a spectral range of 7800–350 cm\(^{-1}\), electronically temperature controlled Ever-Glo source, DLaTGS w/KBR Detector and Ge on KBR beamsplitter with OMNIC software. Each sample was sliced to a thickness of 300 μm, polished on both sides to a thickness of 210 μm, and dried at 120 °C for over 24 h prior to the FTIR analysis. Next, the sample chamber was purged with N\(_2\) gas during the FTIR measurements to exclude atmospheric moisture from our measurements. An IR beam with the dimensions of 50 × 50 μm was...
focused on a single crystal while avoiding cracks and grain boundaries using unpolarized transmitted light. The number of scans accumulated to obtain the FTIR spectrum was 128. The Paterson calibration (Paterson, 1982) was used to calculate the amount of water from infrared absorptions in the range of 3000–3750 cm\(^{-1}\), which is the region dominated by the O–H stretching vibrations. The background water content was determined in air immediately before measuring the specimen. Since the original paper discussing the effects of water on the LPO of olivine (Jung and Karato, 2001a) used the Paterson calibration and unpolarized light to determine the water content, we decided to report the mineral water contents using the Paterson calibration and unpolarized light.

3.3. Observation of dislocations

The samples were decorated with oxygen (Kohlstedt et al., 1976) for 1 h at 800 °C and polished using Syton (colloidal silica) to remove the thin oxide layer that formed on their surface. After this oxygen decoration, the dislocations in olivine were imaged using a scanning electron microscope (SEM JEOL 6380) (Jung and Karato, 2001b; Karato, 1987) at the SEES in SNU, Korea. A back-scattered electron (BSE) image was taken using a 15 kV acceleration voltage, 20 nA beam current, and 60 spot size.

3.4. Micro-Raman spectroscopy

A dispersive confocal DXR Raman microscope (Thermo Scientific) housed at the Tectonophysics Laboratory of the SEES in SNU, Korea was used to identify exsolved lamellae in garnet, olivine, and enstatite. The Raman microscope was equipped with a 532 nm laser (10 mW power) and an optical microscope (Olympus, 50× objective) with an automatic stage and had a resolution of 0.01 cm\(^{-1}\) over the wavenumber range of 50–3550 cm\(^{-1}\) with a beam size of 0.67 μm, which is small enough to analyze small inclusions. The Raman spectrum was mostly obtained at a depth of 10–50 μm below the specimen surface using a 32× exposure time.

4. Results

4.1. LPO of olivine and enstatite

The LPOs for both olivine and enstatite are shown in the pole figure (Fig. 4). Samples 518 and 525 showed that the [001] axis of olivine was aligned subparallel to the lineation, whereas the [100] axis was strongly aligned subnormal to the foliation; this alignment is characteristic of the C-type LPO in olivine (Jung and Karato, 2001a; Jung et al., 2006). Sample 524 showed similar C-type LPO patterns for olivine in both the [100] and [001] axes; however, the [010] axis had a tendency to align subparallel to the lineation. There was an insufficient amount of EBSD data for the enstatites in samples 518 and 524 (see Supplementary Fig. S1), and the LPO of enstatite was only shown for sample 525 (Fig. 4D). The [001] axis of enstatite was strongly aligned parallel to the lineation, and the [100] axis was aligned subnormal to the foliation; such alignment is characteristic of the C-type LPO of enstatite (Jung et al., 2010). LPOs of other minor minerals such as diopside and garnet are shown in Supplementary Fig. S1. Combined pole figure of each mineral for all three samples is shown in Supplementary Fig. S3. It was also observed by EBSD that the linate rods in olivine were aligned parallel to the [010] axis of olivine.

4.2. Water content of olivine, enstatite, and garnet

We observed a large amount of water in olivine, enstatite, and garnet, and representative FTIR spectra (sample 525) are shown in Fig. 5. IR peaks were observed at the following wave numbers: 3689, 3676, 3668, 3649, 3630, 3613, 3598, 3588, 3568, 3564, 3536, and 3522 cm\(^{-1}\) in olivine (Fig. 5C–E); 3689, 3682, 3676, 3649, 3630, 3618, 3588, 3567, 3529, 3524, 3516, and 3424 cm\(^{-1}\) in enstatite (Fig. 5A & F); and 3678, 3675, 3670, 3649, 3629, 3620, 3598, 3576, and 3546 cm\(^{-1}\) in garnet (Fig. 5B). Other samples showed similar IR peaks. The IR peaks at approximately 3689, 3687, and 3685 cm\(^{-1}\) can be attributed to serpentine (Jung, 2009; Khisina et al., 2001; Milleni et al., 2002; Miller et al., 1987; Post and Rober, 2000); the peaks at approximately 3676 and 3660 cm\(^{-1}\) can be associated to amphibole (Skogby and Rosman, 1991) or talc (Khisina et al., 2001); while those at approximately 3613, 3598, 3571, 3567, and 3525 cm\(^{-1}\) represent structurally bound water in olivine (Kohlstedt et al., 1996; Mei and Kohlstedt, 2000). Olivine, enstatite, and garnet contained a large amount of water, i.e., 2600 ± 100 ppm H/Si, 5000 ± 100 ppm H/Si, and 21,000 ± 200 ppm H/Si, respectively; however, it should be noted that exsolved hydrous inclusions were present in olivine, enstatite, and garnet (Fig. 5A–C). The obtained values indicate an average water content of 10–14 grains. We also analyzed the water content of olivine without visible hydrous inclusions under transmitted light in an optical microscope. The water content in the clean olivine was 930 ± 50 ppm H/Si in average for 11 olivine grains. We didn’t observe any difference in water content between large and small olivine. A water content of 1130 ± 50 ppm H/Si in clean olivine in this study is the largest amount of water found in natural olivine with type-C LPO in the world. A sample FTIR spectrum of the clean olivine is shown in Fig. 5E; the water content in this olivine was 1130 ± 50 ppm H/Si. The varying water content of clean olivines indicates hydrogen diffusion from the olivine during uplift. The water content reported here would be approximately 3 times more than that estimated in this study using the alternate calibration (Bell et al., 2003).

4.3. Micro-Raman analysis of hydrous inclusions

Several hydrous inclusions were found in olivine, enstatite, and garnet. These inclusions were analyzed using a confocal DXR micro-Raman microscope. The micro-Raman analysis of specimen (525) revealed that the exsolved olivine, enstatite, and garnet inclusions were amphiboles (Fig. 6). Hornblende and tremolite were both found in garnet (Fig. 6A), crocidolite was observed in enstatite (Fig. 6B), and anthophyllite was found in olivine (Fig. 6C, D). A Raman shift at 673 cm\(^{-1}\) for the exsolved inclusion in garnet (Fig. 6A: Tre) indicates the presence of tremolite (Bard et al., 1997; Blaha and Rosasco, 1978; Lewis et al., 1996). The Raman shifts at 664, 581, and 248 cm\(^{-1}\) appeared in the exsolved garnet inclusions (Fig. 6A: Hb) and indicate the presence of hornblende, which was confirmed by the chemical composition of the mineral determined using a JEOL JXA-8900R electron probe microanalyzer (EPMA) at SNU, Korea. The Raman shifts at 581 and 775 cm\(^{-1}\) for the exsolved inclusion in enstatite (Fig. 6B: Cro) indicate the presence of crocidolite (Bard et al., 1997; Lewis et al., 1996; Petry et al., 2006). The Raman shifts at 675, 670, 538, 429, 337, and 190 cm\(^{-1}\) for the exsolved olivine inclusions (Fig. 6C, D: Anth) indicate the presence of anthophyllite (Bard et al., 1997; Rinaudo et al., 2004).

4.4. Dislocation microstructures of olivine

Dislocation microstructures were observed in olivine using backscattered electron (BSE) images (Fig. 7) in a scanning electron microscope after the oxygen decoration of the specimens. These dislocations are primarily straight in olivine, which is consistent with the observation of straight dislocations in olivine with C-type LPO in previous experimental study at high pressure and temperature (Jung and Karato, 2001a).

4.5. Stress estimation of sample

Further deformation conditions associated with the formation of C-type LPO in olivine from North Qaidam were inferred from the following microstructural observations. A recrystallized grain-size piezometer
can be used to estimate the differential stress of a sample (Jung and Karato, 2001b; Karato et al., 1980; van der Wal et al., 1993). Average recrystallized grain-sizes in olivine samples 518 and 525 of 435 μm and 530 μm, respectively, were measured using the linear intercept method (Gifkins, 1970; Russ and Dehoff, 2000) and indicate differential stresses of 41 ± 15 MPa and 36 MPa ± 15 MPa, respectively, for the samples under wet conditions (Jung and Karato, 2001b). Moreover, the dislocation density ($\rho$) of olivine can be used to independently estimate the differential stress of each sample (Jung and Karato, 2001b; Karato and Jung, 2003), and $\rho$ can also be estimated by dividing the total dislocation length by the total grain volume (Jung and Karato, 2001b). The distribution of dislocation densities for 30 grains (sample 518) is shown in Fig. 8 and was determined from backscattered electron images. The mean density was calculated to be $\rho = 3.25 \times 10^{11}$/m$^2$ and $\rho = 2.19 \times 10^{11}$/m$^2$ for samples 518 and 525, respectively. Furthermore, the stresses ($\sigma = 55 \pm 20$ MPa and $\sigma = 40 \pm 20$ MPa) from the dislocation density in samples 518 and 525 were calculated using the relationship between the stress and the dislocation density (Jung and Karato, 2001b). The differential stress for two samples was estimated from the dislocation density and was in good agreement with those estimated from the recrystallized grain-size piezometer.

4.6. Seismic anisotropy

The seismic P- and S-wave anisotropy (Vp and AVs) (Fig. 9) was calculated using the LPO of olivine and enstatite corresponding to the fabrics (Fig. 4). The P-wave (Vp) exhibited seismic anisotropy of olivine in the range of 2.7–5.9% for three samples. The Vp anisotropy of enstatite (sample 525) was 3.4%. The maximum anisotropy of the shear wave (AVs) in olivine was in the range of 2.44–5.02%. By combining the seismic anisotropy of both enstatite and olivine (sample 525), we found that both the P-wave and the S-wave anisotropies were reduced to 1.5% and 2.3%, respectively (Fig. 9E), which indicates that the LPO of enstatite reduced the overall seismic anisotropy of the sample (e.g., Mainprice and Silver, 1993). The polarization direction of the fast S-wave ($V_S$) in the two samples (518, 524) was normal to their lineation (E–W) as shown in Fig. 9A and B, whereas that of sample 525 was subnormal to the lineation. By combining the polarization anisotropy of enstatite (Fig. 9D) with that of olivine for sample 525, we found that the polarization direction of the fast S-wave shifted nearly 45° from the north at the center of the pole figure (Fig. 9E), which depicts the vertically propagating S-waves. This result indicates that the LPO of enstatite can modify the overall polarization direction of the fast S-waves. In addition, we calculated seismic properties of each sample considering all constituent minerals (olivine, enstatite, diopside, and grossular) (Supplementary Fig. S2). Elastic stiffness ($C_{ij}$) of representative olivine (518) and enstatite (525) is shown in Table 1. Elastic stiffnesses ($C_{ij}$) of combined LPOs of individual mineral for all three samples are shown in Supplementary Table S1.

![Fig. 4. Pole figures of olivine (A–C) and enstatite (D) presented in the upper hemisphere and equal area projection. L and S represent the lineation and foliation, respectively. Olivine shows a typical C-type LPO. The color coding represents the data point density. The contours correspond to multiples of the uniform distribution. A half width of 20° was used to draw the pole figures. N: number of grains analyzed. M: Misorientation-index (Skemer et al., 2005) to show the fabric strength. En: enstatite.](image-url)
5. Discussion and implications

5.1. LPO of olivine

We have reported the presence of C-type LPO in olivine within garnet lherzolites obtained from the North Qaidam UHP belt for the first time. Similar C-type LPO was found in olivine from other UHP terranes around the world, such as the Alpe Arami in Switzerland (Möckel, 1969), Cima di Gagnone in the Central Alps in Switzerland (Frese et al., 2003), Otroy in Norway (Katayama et al., 2005; Wang et al., 2013), and Zhimafang garnet peridotite in the Sulu UHP terrane in China (Xu et al., 2006). Because samples with a C-type LPO did not contain a considerable amount of water, Xu et al. (2006) proposed that the fabric was formed by high pressure and low temperature. In this case, water may have been diffused out of olivine after forming the C-type LPO because of the high hydrogen diffusivity of olivine (Kohlstedt and Mackwell, 1998). The C-type LPO of olivine was experimentally produced under low stress and water-rich conditions (≥700 ppm H/Si) (Jung and Karato, 2001a; Jung et al., 2006). In this study, we report olivine showing C-type LPO and containing a large amount of water, i.e., 1130 ± 50 ppm H/Si, for the first time when hydrous inclusions in olivine were not visible (Fig. 5E). Both this observation and a previous experimental study (Jung and Karato, 2001a) suggest that C-type LPO formed in olivine because of water.

5.2. Effect of pressure on the LPO of olivine

It has been suggested that pressure may affect the LPO of olivine (Couvè et al., 2004; Jung, 2012; Jung et al., 2009; Mainprice et al., 2005; Ohuchi et al., 2011). Couvè et al. (2004) performed relaxation experiments on Fe-free olivine (forsterite) at a pressure of 11 GPa and temperature of 1400 °C and reported that a C-type LPO formed due to the high pressure. As previously suggested (Jung et al., 2009; Karato et al., 2008; Katayama et al., 2005), these samples (Couvè et al., 2004) contained a large amount of water (approximately 850–2200 ppm H/Si) and experienced a differential stress of approximately 100–1500 MPa, which can induce [001] slipping in olivine (Carter and Avé Lallemant, 1970; Jung and Karato, 2001a). Therefore, the C-type LPO produced by Couvè et al. (2004) may have been produced by either water or high stress. Deforming a single crystal of Fe-free olivine (forsterite), Raterron et al.
showed that the [001] slip was easier than the [100] slip at pressures between 3 and 7 GPa. Moreover, recent experimental study of harzburgite (Jung et al., 2009) showed that olivine deformed at low stress and dry condition under pressures higher than 3 GPa did not produce C-type LPO, but B-type LPO. In addition, Ohuchi et al. (2011) also produced B-type LPO of olivine at high pressure of 7 GPa. These studies indicate that the C-type LPO of olivine was not produced by high pressure under dry conditions. To the best of our knowledge, there is no solid experimental evidence that C-type LPO in olivine forms from high pressure alone. In addition, natural C-type LPOs of olivine were found recently in the spinel peridotites which were originated from a depth of 40–60 km at Rio Grande rift, U.S.A. (Park et al., submitted for publication), suggesting that C-type LPO of olivine can be also formed at low pressure condition and high pressure is not a prerequisite to make C-type LPO.

5.3. Origin of garnet peridotite in the North Qaidam UHP belt

The origin of garnet peridotite in North Qaidam is still controversial. Yang and Powell (2008) argued that the Luliangshan garnet peridotites probably formed via the dehydration of oceanic serpentinized peridotites during the subduction of the oceanic slab. Based on Re–Os data and bulk-rock geochemistry, Shi et al. (2010) suggested that the Shenglikou (Luliangshan) dunites are derived from the Archean (>2.6 Ga) subcontinental lithospheric mantle (SCLM), and garnet lherzolites were produced through the refertilization of these dunites by mafic melts (now pyroxenites) during the Paleoproterozoic era (ca. 2.2 Ga). Based on zircon Hf isotopic data, Xiong et al. (2011) recently suggested that the Shenglikou (Luliangshan) garnet peridotite massif is a fragment of metasomatized Archean SCLM from the Qilian block. However, petrological and geochemical data do not seem to support the peridotite massif being a suboceanic or subcontinental lithospheric mantle fragment. The large compositional variation of the primary rock-forming minerals, the documented major and trace element systematics, and the magmatic zircon cores strongly suggest that the Luliangshan garnet peridotite ultramafic complex crystallized from high-Mg melts in an arc environment before UHP metamorphism (Song et al., 2007). It was previously suggested that corner flow of the mantle wedge during continental subduction lowered the garnet peridotites to depths of approximately 150–200 km after approximately 420 Ma and exhumed the garnet peridotites during subsequent continental collision (approximately 400 Ma) (Song et al., 2005b; Song et al., 2007). Based on the study of thermomechanical modeling, Yin et al. (2007) suggested that the development of UHP metamorphism and subsequent exhumation of the UHP metamorphic rocks in the North Qaidam area are related to diapiric flows during oceanic subduction.

5.4. Stress estimation of sample

Stress of specimen was estimated by two methods in this study: recrystallized grain-size piezometer and dislocation density. Stress estimation from dislocation density needs to be cautious because dislocation density of olivine can be affected by annealing or later deformation processes. In our study, stress estimated from recrystallized grain-size of olivine was similar to the one estimated from dislocation density, indicating that dislocation density of specimen was not much affected by later deformation processes.

5.5. Evidence of large amount of water in peridotites

A large amount of water was found to be present in olivine in garnet lherzolite from the orogenic UHP belt in North Qaidam. We detected water contents of up to 1130 ± 50 ppm H/Si in clean olivine with an average value of 2600 ± 100 ppm H/Si in areas containing exsolved amphibole. Experiments on the solubility of water in olivine (Jung et al., 2006; Kohlstedt et al., 1996) indicate that it increases with increasing pressure. The water content of garnet (21,000 ppm H/Si, which is equivalent to 1460 ppm H2O) corresponds to the solubility of water above approximately 5 GPa (Withers et al., 1998). We found amphibole lamellae in olivine, enstatite, and garnet (Figs. 3, 5, and 6). Sodic amphiboles in garnet from the same locality were reported previously (Song et al., 2005a, 2005b, 2007; Yang and Powell, 2008), and amphibole lamellae in olivine have also been reported (Yang and Powell, 2008). Song et al. (2005a, 2005b) found a topotaxial relationship between the lamellae and host garnet via TEM observation, which suggests that these amphibole lamellae formed during decompression-induced exsolution from a parental garnet. The presence of amphiboles in olivine, enstatite, and garnet implied that the olivine, enstatite, and garnet precursors were OH-bearing minerals that were stable at the mantle depth during a continental collision in the early Paleozoic (approximately 423 Ma by SHRIMP dating of zircon) (Song et al., 2005b). The results from our FTIR study indicated that olivine, enstatite, and garnet from orogenic garnet peridotite in the cold subduction zones may contain a considerably larger number of hydroxyls than those obtained from orogenic garnet peridotite in the hot subcontinental mantle (Dixon et al., 2002).

5.6. Possible origin of water in the specimen

Song et al. (2007, 2009) suggested three stages of evolution for Luliangshan garnet peridotite. Stage I: cooling of Mg-rich melts led to the formation of cumulate ultramafic assemblage in a sub-arc lithospheric mantle overlaying a paleo-subduction zone; Stage II: oceanic lithosphere subduction induced asthenospheric corner flow which transported the cumulate peridotite body deep into the mantle in the subduction zone; and Stage III: the subducted continental crust seized the peridotite body and carried it to depths in excess of 200 km. It is unlikely that large quantities of water dissolved in its original cumulative rocks. Therefore, the source of water preserved in the anhydrous minerals was probably originated from the cold and hydrous subducted oceanic lithosphere at Stage II. The olivine C-type LPO and estimated stress of 40–50 MPa suggest that the deformation temperature is supposed to be higher than 750–850 °C (Katayama and Karato, 2006). The calculated P–T conditions of garnet lherzolite (P = 5.0–6.5 GPa, T = 960–1040 °C) and garnet-bearing dunite (P = 4.6–5.3 GPa, T = 980–1130 °C) (Song et al., 2009) are consistent with required temperature to form C-type LPO. In addition,
this minimum temperatures (750–850 °C) forming C-type LPO is more or less coincident with the initial temperature (~700–800 °C) (corresponding to ~3 GPa) of exhumation of UHP metamorphic rocks (e.g., Yin et al., 2007). Therefore, we can infer that the deformation probably occurred during the subduction of continental crust above 3 GPa (Stage III). Because the solubility of water in olivine increases with increasing pressure (Kohlstedt et al., 1996), the water uptaken in Stage II can be well preserved at high pressure and secure the

Fig. 9. Seismic anisotropy calculated for the fabrics shown in Fig. 4. Seismic anisotropies are shown in the upper hemisphere and equal area projection. The E–W directions correspond to the lineation (L), and the horizontal line represents the foliation. Both the compressional-wave velocity (Vp) and shear-wave anisotropy (AVs) are shown. Vs1 is a plot of the polarization direction of fast S-waves along different propagation orientations. The center of the stereonet corresponds to a vertical propagation. For the vertical propagation of S-waves in olivine (A–C), the polarization direction is nearly perpendicular to the flow direction (lineation). Small black square and white circle represent maximum and minimum anisotropy, respectively. Ol: olivine, En: enstatite.

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<th>Vp Contours (km/s)</th>
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<td>Anisotropy = 2.7 %</td>
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deformation to occur in a wet condition. However, origin of water in the peridotites in North Qaidam UHP belt is not yet clear. We need a further study to understand that where, when, and how rocks became hydrated.

6. Conclusions

The C-type LPO of olivine—a fabric reflecting the [100][001] slip system—was found in garnet lherzolites obtained from the North Qaidam UHP collision belt. An FTIR study of the samples yielded data on water contents for olivine, enstatite, and garnet of 2600, 5000, and 21,000 ± 200 ppm H/Si, respectively, when exsolved hydrous inclusions to be amphiboles from the decompression stage of project. We thank A. Yin and anonymous reviewers for their constructive comments.

Acknowledgments

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References


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Density 3.355 g/cm³

Enstatite Sample 525

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Density 3.306 g/cm³

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Density 3.306 g/cm³


