Microstructural evolution of the Yugu peridotites in the Gyeonggi Massif, Korea: Implications for olivine fabric transition in mantle shear zones

Munjae Park, Haemyeong Jung *

Article history:
Received 19 October 2016
Accepted in revised form 13 April 2017
Available online 28 April 2017

Keywords:
Olivine fabric transition
Mantle shear zone
Deformation mechanism
Water
Yuga peridotite

Abstract

Large-scale emplaced peridotite bodies may provide insights into plastic deformation process and tectonic evolution in the mantle shear zone. Due to the complexity of deformation microstructures and processes in natural mantle rocks, the evolution of pre-existing olivine fabrics is still not well understood. In this study, we examine well-preserved transitional characteristics of microstructures and olivine fabrics developed in a mantle shear zone from the Yugu peridotite body, the Gyeonggi Massif, Korean Peninsula. The Yugu peridotite body predominantly comprises spinel harzburgite together with minor lherzolite, dunite, and clinopyroxenite. We classified highly deformed peridotites into four textural types based on their microstructural characteristics: proto-mylonite; proto-mylonite to mylonite transition; mylonite; and ultra-mylonite. Olivine fabrics changed as occurring under hydrous conditions at low temperature and high strain, because of characteristics such as Ti-clinohumite defects (and serpentine) and fluid inclusion trails in olivine, and a hydrous mineral (pargasite) in the matrix, especially in the ultra-mylonitic peridotites. Even though the ultra-mylonitic peridotites contained extremely small (24–30 μm) olivine neoblasts, the olivine fabrics showed a distinct (E-type) pattern rather than a random one. Analysis of the lattice preferred orientation strength, dislocation microstructures, recrystallized grain-size, and deformation mechanism maps of olivine suggest that the proto-mylonitic, mylonitic, and ultra-mylonitic peridotites were deformed by dislocation creep (A-type), dislocation-accommodated grain-boundary sliding (D-type), and combination of dislocation and diffusion creep (E-type), respectively.

1. Introduction

Compared to small-scale mantle xenoliths, large-scale emplaced peridotite bodies (massifs) provide greater insights into petrological, geochemical, geophysical and tectonic evolution in the mantle (e.g., partial melting, melt–rock reaction, and plastic deformation) (Bodinier and Godard, 2003). Peridotite massifs often display ductile shear zones which preserved various deformation microstructures related to deformation conditions. As mantle shear zones play a crucial role in large-scale tectonic evolution, and even plate tectonics, understanding the factors that control the initiation and development of shear localization is crucial.

Over the past decade, a large number of studies have been conducted to understand the development of natural mantle shear zones (Handy, 1989; Drury et al., 1991; Furusho and Kanagawa, 1999; Dijkstra et al., 2002; Michibayashi and Mainprice, 2004; Precigout et al., 2007; Skemer et al., 2010; Kaczmarek and Tommasi, 2011; Linckens et al., 2011; Hidas et al., 2013; Jung et al., 2014; Herwegh et al., 2016). In general, shear localization has been attributed to grain size reduction promoted by the fluxing of a reactive melt (Dijkstra et al., 2002), metamorphic reactions (Newman et al., 1999), deformation-induced dynamic recrystallization (Drury et al., 1991), and cataclasis (Vissers et al., 1997). However, details of microphysical processes that generate localized deformations are still poorly understood.

Information on mechanical properties of the lithosphere and the relative strength of the crust and upper mantle is essential in order to understand geodynamic processes. Lithosphere rheology varies significantly, depending on a range of physicochemical parameters, such as temperature, pressure, mineral assemblage, grain size, melt/ fluid content and composition, and differential stress conditions (Bürgmann and Dresen, 2008). Incorporation of water in minerals and the presence of melt can dramatically reduce the strength of mantle rocks (Mackwell et al., 1985; Karato et al., 1986; Hirth and Kohlstedt, 1995; Mei et al., 2002; Karato and Jung, 2003; Zimmerman and Kohlstedt, 2004), and also influence deformation microstructures and processes (Dijkstra et al., 2004; Skemer et al., 2010; Soustelle et al., 2010; Kaczmarek and Tommasi, 2011; Jung et al., 2014; Linckens et al., 2011; Hidas et al., 2013; Jung et al., 2014; Herwegh et al., 2016).
al., 2015). Previous experimental studies have shown that olivine fabric is controlled by stress, temperature, and water content (Jung and Karato, 2001a; Katayama et al., 2004; Jung et al., 2006; Katayama and Karato, 2006), and the basic relationships between olivine fabrics and deformation kinematics are well known. However, a continuous evolution of pre-existing olivine fabrics in natural mantle shear zones is not

Fig. 1. (a) Simplified tectonic map of Northeast Asia showing location of the study area at Yugu in South Korea. NM (Nangrim Massif), IB (Imjingang Belt), GM (Gyeonggi Massif), TB (Taebaeksan Basin), OB (Okcheon Belt), and YM (Yeongnam Massif). (b) Geologic map of the Yugu peridotite in the southwestern Gyeonggi Massif, South Korea. Modified after 1:50,000 geological map from the Korea Institute of Geoscience and Mineral Resources (KIGAM). (c) Simplified cross-section of the study area showing the textural types of Yugu peridotites. (d, e) Representative peridotites from the study area shown in (c).
well understood. The Yugu peridotites have well-preserved transitional characteristics of deformation microstructures which can provide important information on the continuous evolution of pre-existing olivine fabrics. However, there was no study on detailed deformation microstructures of the Yugu peridotites. In this study, we conducted a detailed analysis of microstructures and petrofabrics of the Yugu peridotites from the Gyeonggi Massif (Korean Peninsula) in order to understand the continuous evolution of olivine fabrics and deformation conditions in a natural mantle shear zone.

2. Geologic setting

The Korean Peninsula consists of three major Precambrian massifs (the Nangrim, Gyeonggi, and Yeongnam) juxtaposed along two Neoproterozoic–Paleozoic fold-thrust belts, the Imjingang and Ogcheon (Cho et al., 2013) (Fig. 1a). Ultramafic bodies are sparsely distributed in the southwestern part of the Gyeonggi Massif. The Gyeonggi Massif has been considered as a possible eastward extension area of the Chinese collision belt (Qinling–Dabie–Sulu HP/UHP terrane) between the Sino-Korean (North China) and Yangtze (South China) blocks (Oh et al., 2005; Kim et al., 2006; Oh and Kusky, 2007; Kwon et al., 2009), but this is still debated (Lee et al., 1996; Chough et al., 2000; Cho et al., 2007; Cho et al., 2013; Choi, 2014).

The Gyeonggi Massif consists mainly of Precambrian metamorphic rocks and Mesozoic granitoids (Lee et al., 2003), with two peridotite-dominated areas in the southwestern part of the massif at Hongseong and Yugu. In the Hongseong area, isolated and lenticular-shaped small ultramafic bodies (<1 km) occur as highly serpentinitized dunite and harzburgite (Oh et al., 2012), which are generally distributed in a NNE trend, parallel to the main NNE fault orientation (Seo et al., 2013). The Yugu peridotite body (2 × 4 km) (Fig. 1a and b) is considered as an orogenic massif and is one of the largest ultramafic bodies in Korea (Cho and Kim, 2005). The body is emplaced into the Precambrian Yugu granitic gneiss (Fig. 1b), and the gneiss consists of biotite, amphibole, garnet, sillimanite, muscovite, plagioclase, and quartz (Kim et al., 2003).

The age of Yugu granitic gneiss was reported as 1863 ± 9 Ma, based on sensitive high mass-resolution ion microprobe (SHRIMP) zircon analysis (Song et al., 2003; Lee et al., 2005). This is consistent with the age of the Nangrim Orogen (Ar40/Ar39 system ages) of 1864 ± 11 Ma (Lee et al., 2005). The Yugu massif is considered to represent the transition from upper mantle to crustal conditions.

3. Field observations and sampling

Field observation shows that the strike (dip) of basement rock varied between N80E and N30W (70NW and 60NE). The peridotite body is normally overlain by granitic gneiss with foliation sub-parallel to the contact in the South (Fig. 1b), but in the North and East the foliation is not sub-parallel to the contact. The contact areas are often reactivated by small brittle faults accompanied by strong serpentinitization and alteration. The relatively fresh part of peridotite body shows lateral and vertical extension of several meters. The Yugu peridotite body is somewhat unclear due to serpentinitization and lack of exposures. Peridotites from the SSE area show proto-mylonitic and mylonitic textures (Fig. 1c and e), whereas those from the NNW area display mylonitic and ultra-mylonitic textures (Fig. 1c and d). Ultra-mylonitic peridotites in NNW area are narrow distributed close to the serpentinite and adjacent migmatitic gneiss (basement rock) (Fig. 1c). There is a continuous increase of deformation (decrease in grain size of matrix) from proto-mylonitic peridotites in the SSE to ultra-mylonitic peridotites in the NNW. Even though most of peridotites show well-developed foliation with compositional layering, pyroxenite layers are much more common in the NNW area (Fig. 1d). Compositional layers are generally parallel (or sub-parallel) to the foliations. Orthopyroxene and spinel porphyroclasts are strongly elongated in the NNW area, and generally show flattening structures.

4. Microstructures

High-quality thin sections, oriented perpendicular to the foliation and parallel to the lineation (i.e., XZ plane), were taken for microstructural observation and analysis. Foliation was determined by alignment of spinel, elongation of pyroxene porphyroclasts, and compositional layering of pyroxenite. Lineation was determined by using shape preferred orientation (SPO) of olivine, pyroxene, and spinel in the foliation.

The samples are all spinel peridotites consisting of olivine, orthopyroxene, clinopyroxene, spinel, and amphibole (Table 1). Based on microstructural characteristics of highly deformed peridotites (especially olivine grain size), we classified them into four textural types: proto-mylonite (Fig. 2a); proto-mylonite to mylonite transition (Fig. 2b); mylonite (Fig. 2c); and ultra-mylonite (Fig. 2d). Clinopyroxene content is generally increased from the proto-mylonite

Table 1
Sample descriptions and results of the studied Yugu peridotites.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock</th>
<th>Texture</th>
<th>Modal composition (%)</th>
<th>Ol</th>
<th>Opx</th>
<th>Cpx</th>
<th>Sp</th>
<th>Amp</th>
<th>Ol LPO type</th>
<th>Fabric strength</th>
<th>Max. aspect ratio (Opx x &lt;2&gt;</th>
<th>Ol grain-size (μm)²</th>
<th>Stress (MPa)</th>
<th>Van der Wal et al. (1993)</th>
<th>J &amp; K (2001b) wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>YG-4</td>
<td>Sp-Hzb</td>
<td>PM</td>
<td>83 13 1 3 tr A</td>
<td>0.19</td>
<td>4.50</td>
<td>5:1</td>
<td>621</td>
<td>9</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YG-7P</td>
<td>Sp-Hzb</td>
<td>PM</td>
<td>85 12 0 3 tr A</td>
<td>0.10</td>
<td>2.75</td>
<td>50:1</td>
<td>30</td>
<td>116 108</td>
<td>280</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YG-7M</td>
<td>Sp-Hzb</td>
<td>M</td>
<td>75 17 2 4 2 D</td>
<td>0.06</td>
<td>2.34</td>
<td>10:1</td>
<td>322</td>
<td>15</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YG-8</td>
<td>Sp-Hzb</td>
<td>M</td>
<td>77 15 2 4 2 D</td>
<td>0.07</td>
<td>2.64</td>
<td>281</td>
<td>17</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YG-9</td>
<td>Sp-Lhz</td>
<td>UM</td>
<td>69 18 6 3 4 E</td>
<td>0.05</td>
<td>2.08</td>
<td>50:1</td>
<td>30</td>
<td>116 108</td>
<td>280</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YG-10</td>
<td>Sp-Lhz</td>
<td>UM</td>
<td>67 17 7 4 5 E</td>
<td>0.02</td>
<td>1.60</td>
<td>141</td>
<td>127</td>
<td>310</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


b: Mean grain-size (3D) of olivine in the matrix.
(harzburgite) via mylonite (harzburgite) to ultra-mylonite (lherzolite), and also from the SSE area to the NNW (Table 1).

Proto-mylonitic peridotite (harzburgite; YG-4) consists of olivine, orthopyroxene, spinel, and minor clinopyroxene and amphibole, and is characterized by relatively coarse grained olivine (300–500 μm) with rounded to flattened orthopyroxene porphyroclasts (~ 5 mm) (Fig. 2a). Exsolution of clinopyroxene is common in the core of the orthopyroxene porphyroclasts (Fig. 2a). The maximum aspect ratio (X:Z ratio) of flattened orthopyroxene porphyroclasts is approached 5:1, and they generally show undulose extinctions and kink bands. Olivine crystals are usually elongated parallel to the lineation, and the olivine-olivine grain boundary is normally straight. In olivine dominated

---

**Fig. 2.** Optical photomicrographs of large-scale and small-scale thin sections (XZ planes) showing deformation microstructures of samples. The long axes of the photomicrographs are parallel to the lineation (X) and the short axes are normal to the foliation (Z). (a) Proto-mylonitic peridotite (YG-4). (b) Well-preserved transitional texture from proto-mylonitic (upper part) to mylonitic (lower part) peridotite (YG-7). (c) Mylonitic peridotite (YG-8). (d) Ultra-mylonitic peridotite (YG-10). (e–h) Magnified view of representative microstructures from olivine dominated domains: (e, f) proto-mylonite; (g) mylonite; and (h) ultra-mylonite. (i) Fluid inclusion trails in an olivine porphyroclast in ultra-mylonite (YG-10). Opx (orthopyroxene), Sp (spinel), Ol (olivine), Cpx (clinopyroxene), Amp (amphibole), and FI (fluid inclusion). White arrow heads (e–h) represent sub-grain boundaries.
Minor olivine and clinopyroxene porphyroclasts are more commonly orthopyroxene (10\times170\mu m), with stretched orthopyroxene porphyroclasts (Fig. 2c) with maximum aspect ratio approaching 10:1. The clinopyroxene and amphibole content of the matrix is a little higher in the ultra-mylonitic peridotites (Fig. 4d) and white dots and lines in the BSE images (Fig. 4e and f). In general, the density of free dislocation olivine porphyroclasts is relatively higher in the ultra-mylonitic peridotites (Fig. 4b and d) than the proto-mylonitic and mylonitic peridotites (Fig. 4a and e), and the spacing between straight dislocation walls (i.e., sub-grain boundaries) is smaller (Fig. 4a and b). In the ultra-mylonitic peridotites, neoblasts showing more polygonal shapes with 120° triple junctions are generally lacking dislocations. However, neoblasts with SPO and elongated shapes (e.g., Fig. 2h) still have free dislocations and straight dislocation walls (i.e., sub-grain boundaries) (Fig. 4c and d).

5. Dislocation microstructures

XZ-oriented thin-chips were well-polished using 1\mu m diamond paste and decorated with oxygen in air at a temperature of 800 °C for 1 h (Karato, 1987), then mounted on glass slides. Dislocation microstructures were observed using both an optical microscope (transmitted light) and a scanning electron microscope (SEM). Back-scattered electron (BSE) images were obtained using a JEOl JSM-7100F field emission SEM under an acceleration voltage of 15 kV and working distance of 10 mm at the School of Earth and Environmental Sciences (SEES), Seoul National University (SNU).

Observations reveal numerous dislocations in olivines, shown as reddish dots and lines in the optical photomicrographs (Fig. 4a–d) and white dots and lines in the BSE images (Fig. 4e and f). In general, the distribution of dislocations is almost inhomogeneous both within and between olivine grains. Straight dislocation walls, indicating sub-grain boundaries, often display normal to the lineation (Fig. 4a and b). In general, the density of free dislocation olivine porphyroclasts is relatively higher in the ultra-mylonitic peridotites (Fig. 4b and d) than the proto-mylonitic and mylonitic peridotites (Fig. 4a and e), and the spacing between straight dislocation walls (i.e., sub-grain boundaries) is smaller (Fig. 4a and b). In the ultra-mylonitic peridotites, neoblasts showing more polygonal shapes with 120° triple junctions are generally lacking dislocations. However, neoblasts with SPO and elongated shapes (e.g., Fig. 2h) still have free dislocations and straight dislocation walls (i.e., sub-grain boundaries) (Fig. 4c and d).

6. Lattice preferred orientation (LPO) and fabric strength of olivine

The LPO of olivine was measured using the electron-backscattered diffraction (EBSD) system hosted at SEES, SNU. The EBSD analysis was conducted in a high vacuum environment with acceleration voltage of 20 kV, working distance of 15 mm, and spot size of 60. We acquired diffraction patterns of olivine in XZ thin section and manually indexed them for accurate solution using HKL CHANNEL 5.0 software. The M-index (Skemer et al., 2005) and J-index (Bunge, 1982) were used to determine olivine fabric (LPO) strength. The M-index delineates differences in uncorrelated misorientation angle distributions between the observed fabric and a theoretical random fabric, and ranges between zero (random fabric) and one (single crystal). The J-index is the volume-averaged integral of the squared orientation density, and ranges from one (random fabric) to infinity (single crystal). The M-index and J-index were calculated using the MTEX toolbox for MATLAB with a kernel half width of 10° (Bachmann et al., 2010).

The results show a systematic relationship between olivine LPO pattern and rock texture. The LPO of olivine from proto-mylonitic peridotite (YG–4) shows alignment of the [100] axis sub-parallel to the lineation, and the [010] axis is strongly aligned subnormal to the foliation (Fig. 5a), which is known as A-type olivine fabric (Jung and Karato, 2001a), observed in ultra-mylonitic peridotite (Fig. 2d). The maximum aspect ratios of stretched orthopyroxene porphyroclasts approaches 50:1. Undulose extinctions and kink bands are commonly observed in orthopyroxene porphyroclasts. Recrystallized narrow zones are well-developed around orthopyroxene porphyroclasts (Figs. 2d and 3a), and are composed of relatively polygonal shaped orthopyroxene, olivine, clinopyroxene, and amphibole (pargasite) (Fig. 3b). Amphibole neoblasts in the recrystallized narrow zone around orthopyroxene are only present in the ultra-mylonitic peridotite. In the olivine dominated matrix, olivine crystals exhibit well-developed SPO and elongated shapes with undulose extinction and closely spaced sub-grains (Fig. 2h), but some of the finer olivine crystals have polygonal shapes with 120° triple junctions. The ultra-mylonitic peridotites have the highest matrix clinopyroxene and amphibole content (Table 1), and the only occurrence of fluid inclusion trails, which are common in olivine porphyroclasts (Fig. 2i).
representing the dominant slip system of (010)[100]. The LPO of olivine from a transitional peridotite (proto-mylonite to mylonite; YG-7) represents two different olivine fabrics. The LPO of olivine from the area with proto-mylonitic texture shows A-type olivine fabric (YG-7P) (Fig. 5b). Even though the [001] axis of olivine (Fig. 5b) is distributed as a girdle subparallel to the foliation, [100] axis shows a point maximum subparallel to the lineation, which can be also classified as A-type fabric. In contrast to the area with proto-mylonitic texture (YG-7P), the area with mylonitic texture is characterized by a strong alignment of [100] sub-parallel to the lineation and a weak girdle pattern of [010] and [001] subnormal to the lineation (YG-7M) (Fig. 5c), which is known as D-type olivine fabric. This LPO of olivine represents the activation of multiple slip systems of [0kl][100]. The LPO of olivine from the other sample with mylonitic texture (YG-8) (Fig. 5d) is similar to the petrofabric of sample YG-7M (Fig. 5c). However, the LPOs of olivine from the ultra-mylonites (YG-9 and YG-10) are different and characterized by an alignment of [100] axes sub-parallel to the lineation and [001] axes subnormal to the foliation (Fig. 5e and f), which is known as E-type olivine fabric. They represent the dominant slip system of (001)[100].

The LPO of olivine is changed from A-type (proto-mylonites) (Fig. 5a and b) via D-type (mylonites) (Fig. 5c and d) to E-type (ultra-mylonites) (Fig. 5e and f), depending on microstructures of the peridotites. The strength of olivine fabric (M-index and J-index) systematically decreases with decreasing olivine grain size from proto-mylonites via mylonites to ultra-mylonites (Fig. 5 and Table 1).

7. Olivine grain size and paleopiezometry

Olivine grain size was determined by the following method (e.g., Cao et al., 2015): (1) the outline of 200 olivine grains from olivine dominated areas was traced on photomicrographs and back-scattered electron images; (2) the diameter of circles of equivalent areas to measured grains was calculated, and weighted by the number of grains; (3) the number-weighted grain size was multiplied by a factor of 1.12 to convert it to grain size estimated by the linear-intercept method, based on the relationship established by Berger et al. (2011); (4) the 2D grain size was multiplied by a factor of 1.5 to convert it to 3D size. This was used to...
estimate stress based on the recrystallized grain size piezometers of Karato et al. (1980), Van der Wal et al. (1993), and Jung and Karato (2001b).

Mean 3D grain-sizes of olivine specimens are as follows: 621–530 μm (proto-mylonites); 322–281 μm (mylonites); and 30–24 μm (ultra-mylonites) (Table 1). Calculated stress based on dry

Fig. 5. Pole figures showing the lattice preferred orientation (LPO) of olivine. The east-west direction corresponds to stretching lineation (X), and the north-south direction (Z) is normal to foliation. Color-coding represents the density of data points. Equal-area and lower-hemisphere projection was used with a half scattering width of 30°. N represents the number of measured grains. Olivine fabric (LPO) strength is denoted as M (M-index) (Skemer et al., 2005) and J (J-index) (Bunge, 1982).
Paleopiezometers, Karato et al. (1980) and Van der Wal et al. (1993), is in the range of 9–10 MPa and 11–12 MPa (proto-mylonites), 15–17 MPa and 18–20 MPa (mylonites), 116–141 MPa and 108–127 MPa (ultra-mylonites), respectively. However, the stress calculated for ultra-mylonites using the wet paleopiezometer of olivine (Jung and Karato, 2001b) is higher (280–310 MPa).

8. Fourier transform infrared (FTIR) spectroscopy

The structural position of hydroxyl (OH) in nominally anhydrous minerals (olivine and pyroxene) was determined by FTIR spectroscopy using a Nicolet 6700 spectrometer with a Continuum IR Microscope at the Tectonophysics Laboratory, SNU. Prior to IR measurements, doubly polished thin-slices (150–250 μm thick) were placed in an acetone bath for 24 h to remove any residual glue, and then heated to 120 °C for at least 24 h to dispel any free water residing on the surface of the slice and in grain boundaries/cracks. FTIR measurements were performed using an unpolarized light source, a KBr beam splitter, and a mercury cadmium telluride detector cooled with liquid nitrogen, and dry and pure nitrogen gas was flushed into the system to avoid disturbance caused by moisture in the atmosphere. IR spectra were accumulated from an average of 128 scans with a resolution of 4 cm⁻¹.

The structural position of OH in olivines and orthopyroxenes is characterized using unpolarized FTIR spectroscopy (Fig. 6). The ultra-mylonitic peridotites show three IR peaks (3688, 3571, and 3562 cm⁻¹; Fig. 6c) relating to hydrous minerals found in olivine, whereas there is no IR peak in both the proto-mylonitic and mylonitic peridotites (Fig. 6a). The IR peak at 3688 cm⁻¹ is associated with serpentine inclusions (Kitamura et al., 1987; Khisina et al., 2001; Matsyuk and Langer, 2004; Jung, 2009), and the peaks at 3571 and 3562 cm⁻¹ are possibly related to Ti-clinohumite defects (Kitamura et al., 1987; Berry et al., 2005; Hermann et al., 2007; De Hoog et al., 2014). Small IR peaks of serpentine (3688 cm⁻¹; Fig. 6b) are rarely observed in orthopyroxenes from the proto-mylonitic and mylonitic peridotites. In contrast, stronger serpentine peaks are often observed in orthopyroxene from the ultra-mylonitic peridotites (Fig. 6d).

9. Mineral chemistry

The chemical composition of minerals was determined by electron microprobe analysis using a JEOL JXA-8100 wavelength-dispersive electron microprobe with ZAF matrix correction at the Gyeongsang National University in Jinju, South Korea. Operating conditions comprised 15 kV accelerating voltage, 10 nA beam current, 5 μm beam width, and 20 s counting time. Natural minerals were used as standards for Si, Ti, Al, Fe, Mn, Mg, Ca, Na, and K, with synthetic oxides for Cr and Ni. Representative microprobe analysis results are given in Table 2.

The electron microprobe analysis was performed on the cores of neoblasts in the olivine dominated area due to a lack of olivine porphyroclasts. The olivine Mg-number was 0.90–0.91 in harzburgites and 0.89 in lherzolites, and decreased from proto-mylonites (0.91) via mylonites (0.90) to ultra-mylonites (0.89). NiO content was in the range of 0.31–0.56 wt% for all peridotites, and there was no correlation between NiO content and lithology.

For spinel, there is a clear distinction in Al₂O₃ and Cr₂O₃ content between harzburgites and lherzolites. Spinel Cr-numbers, 0.216–0.293 in harzburgites and 0.118–0.130 in lherzolites, generally display a positive correlation with olivine Mg-numbers. The relationship between the olivine Mg-number (or Fo content) and spinel Cr-number in the olivine-spinel mantle array indicates that a petrogenetic setting of our specimen is abyssal peridotite (Fig. 7), and this is generally consistent with a previous geochemical study (e.g., Arai et al., 2008). They suggested that the Yugu peridotites had a similar petrogenetic setting as sub-arc or abyssal peridotites.
For orthopyroxene, all the analyzed grains are enstatite-rich with Mg-numbers ranging from 0.89 to 0.91. There is a distinct difference between orthopyroxene porphyroclast cores and rims, and the composition of orthopyroxene neoblasts is similar to the porphyroclastic rims. The Al$_2$O$_3$ content of orthopyroxene porphyroclasts decreases toward the rim in harzburgites (3.22 → 1.33 wt%) and lherzolites (4.60 → 2.93 wt%), whereas SiO$_2$ content increases in harzburgites (56.00 → 57.25 wt%) and lherzolites (54.61 → 55.96 wt%). The Cr$_2$O$_3$ content of orthopyroxene porphyroclasts decreases toward the rim (0.43 → 0.05 wt%), while MgO increases (32.03 → 33.83 wt%). Compared with orthopyroxene porphyroclasts cores, orthopyroxene neoblasts display lower levels of Al$_2$O$_3$ (1.06→1.77 wt%) and Cr$_2$O$_3$ (0.06→0.15 wt%), and higher levels of MgO (33.16→34.29 wt%).

For clinopyroxene, Mg-numbers ranged from 0.90 to 0.91, and there are clear compositional trends from core to rim of porphyroclasts. Both Al$_2$O$_3$ and Cr$_2$O$_3$ decreased (6.16 → 4.81 wt% and 0.15 → 0.05 wt%, respectively) from core to rim, whereas MgO slightly increases (14.36 → 14.83 wt%). CaO and SiO$_2$ increase toward the rim (22.35 → 23.30 wt% and 50.87 → 52.46 wt%, respectively) while Na$_2$O decreases (1.13 → 0.85 wt%).

Amphiboles are all pargasites and their Mg-numbers (0.88) are slightly lower than those for coexisting olivine and pyroxenes. The pargasites have low content of Na$_2$O (<0.70 wt%), TiO$_2$ (<1.45 wt%), and K$_2$O (<0.15 wt%).

### 10. Thermometry

Porphyroclast (PC) and neoblast (NB) equilibrium temperatures in this study were calculated based on the following formulations: (1) a thermometer based on coexisting orthopyroxene and clinopyroxene (T$_{Al,Cr-in-opx}$ WS91) for PC and NB; (2) orthopyroxene Al and Cr content (T$_{Al,Cr-in-opx}$ WS91) for PC and NB; (3) the Ca-in-opx thermometer (T$_{Ca-in-opx}$ B80) (Brey and Köhler, 1991).
high temperature (~1000 °C), low stress, and dry conditions, before having been preserved from the original fabric which was formed under A-type olivine fabric in the proto-mylonitic peridotites is thought to via D-type (mylonites) (Fig. 5c and d) to E-type (ultra-mylonites) (Fig. 5e and f). Proto-mylonitic peridotites show A-type olivine fabrics.

In general, A-type olivine fabric has been observed at high temperature, low water content, and low stress conditions in previous experimental studies (Zhang and Karato, 1995; Zhang et al., 2000; Jung and Karato, 2011; Park et al., 2014). Although the equilibrium temperature estimations at low temperature (700–760 °C) and high stress (moderate shear strain) conditions relative to proto-mylonites (A-type olivine fabric) is low, in the range of 700–760 °C, it does not necessarily mean that the LPO of olivine varied with textural type for the Yugu peridotites, from A-type (proto-mylonites) (Fig. 5a and b) via D-type (mylonites) (Fig. 5c and d) to E-type (ultra-mylonites) (Fig. 5e and f). Proto-mylonitic peridotites show A-type olivine fabrics. In general, A-type olivine fabric has been observed at high temperature, low water content, and low stress conditions in previous experimental studies (Zhang and Karato, 1995; Zhang et al., 2000; Jung and Karato, 2001a; Demouchy et al., 2012; Hansen et al., 2012) and in natural samples (Michibayashi and Maínprice, 2004; Jung et al., 2009; Falus et al., 2011; Park et al., 2014). Although the equilibrium temperature estimated from orthopyroxene rim neoblasts in the proto-mylonitic peridotites is low, in the range of 700–760 °C, it does not necessarily mean that the LPO was formed at low temperature. The olivine dominated area of proto-mylonitic peridotites consists of porphyroclastic olivines with few polygonal neoblasts (Fig. 2e and f), whereas that of the mylonitic peridotites consists of porphyroclastic olivines with ultra-mylonitic peridotites consists of predominantly small polygonal neoblasts (Fig. 2g and h). Moreover, there is no hydrous mineral IR peak in olivine from the proto-mylonitic peridotites (Fig. 6a). Therefore, A-type olivine fabric in the proto-mylonitic peridotites is thought to have been preserved from the original fabric which was formed under high temperature (~1000 °C), low stress, and dry conditions, before shear localization related deformation. However, the presence of polygonal shaped neoblasts indicate the high temperature A-type fabric was relatively weakened by dynamic recrystallization at a lower temperature (Fig. 2e).

In the mylonitic peridotites, olivine LPOs show D-type fabric, which is relatively common in lithospheric shear zones (ophiolites at low temperature and high stress) (e.g., Warren et al., 2008; Skemer et al., 2010; Linckens et al., 2011; Michibayashi and Oohara, 2013; Kaczmarek et al., 2015). Possible mechanisms for formation of D-type olivine fabric include: (1) activation of multiple {010}[100] slip systems at higher stress conditions than A-type olivine fabrics (Bystricky et al., 2000; Zhang et al., 2000; Jung et al., 2006); (2) activation of only the {010}[100] slip system under transtensional deformation regimes (Tommasi et al., 1999); (3) activation of dominant {010}[100] and {001}[100] slip systems at high temperature and low stress conditions, with strain compatibility constraints relaxed by grain-to-grain interactions (Tommasi et al., 2000), or (4) dislocation accommodated grain boundary sliding (DisGBS) (Warren et al., 2008; Hansen et al., 2012) under moderate transient strain conditions (Hansen et al., 2014).

As discussed above, olivines from our mylonitic peridotites are mostly recrystallized and had polygonal and equigranular textures, whereas olivines from the proto-mylonitic peridotites are generally characterized by a relatively coarse texture with porphyroclasts (porphyroclastic texture). This change of texture suggests that mylonitic peridotites were affected by deformation during shear localization at low temperature (700–760 °C) and high stress (moderate strain) conditions relative to proto-mylonites (A-type olivine fabric). Moreover, the Yugu mylonitic peridotites also display olivine fabrics of a transitional character (Fig. 5c and d), between high temperature A-type (proto-mylonite) and low temperature E-type (ultra-mylonite). The D-type olivine fabric, found in the mylonitic peridotites in this study, is considered to represent a mixture of {010}[100] and {001}[100] slip systems (a transition LPO between A-type and E-type), resulting from the change in deformation conditions (e.g., Sawaguchi, 2004; Kamei et al., 2010) to hydrous conditions, as indicated by the presence of a hydrous mineral (i.e., amphibole), but at smaller strains than the ultra-mylonite (Fig. 8). On the other hand, Hansen et al. (2014) carried out torsion experiments (DisGBS regime) under anhydrous conditions and found that the [100] axes form a strong point maxima and both the [010] and [001] axes are strongly distributed as a girdle (D-type) at moderate shear strains (γ: 3–5). Therefore, the
transition from A-type to D-type olivine fabric can also be affected by
the change of olivine deformation processes related to DisGBS at moder-
ate strains (Hansen et al., 2012; Hansen et al., 2014). If this scenario is
correct, a small amount of amphibole must have originated by retro-
grade or metasomatic processes after the shear localization process.
More detailed geochemical research on the relationship between defor-
mation and metasomatism of mylonitic peridotite is needed.

In ultra-mylonitic peridotites, olivine LPOs represent the E-type fab-
ric. This type of fabric is considered to be widespread in the astheno-
sphere (Karato et al., 2008). The E-type fabrics were reported in
collision zones (Sawaguchi, 2004; Jung, 2009; Jung et al., 2014), island
oceanic arc environments (Mehl et al., 2003), extensional settings
such as shear zones within oceanic lithosphere (Michibayashi and
Mainprice, 2004; Skemer et al., 2010; Linckens et al., 2011; Michibayashi and Oohara, 2013), and rifting environments (Palasse et
al., 2012; Kaczmarek and Reddy, 2013). The formation context of E-
type olivine fabric has been suggested by previous studies as wet condi-
tions (Katayama et al., 2004; Jung et al., 2006; Jung, 2009; Skemer et al.,
2010; Michibayashi and Oohara, 2013), low temperatures (Carter and
Ave’Lallement, 1970; Kamei et al., 2010; Linckens et al., 2011), and at
a high temperature with high melt content (Tommasi et al., 2006).

In the Yugu peridotites, estimated neoblast temperatures are similar
for mylonite and ultra-mylonite, at 700–760 °C, which means that the
different olivine fabrics in the study area were not related to high tem-
perature conditions (with/without melt). Previous extensive experi-
ments on the formation of E-type LPO in olivine (Katayama et al.,
2004; Jung et al., 2006) have shown that the dominant (001)[100] slip
system can be formed under moderate water content (wet conditions).
Moreover, most previous studies of E-type olivine fabrics in natural
mantle shear zones (Sawaguchi, 2004; Skemer et al., 2010; Michibayashi and Oohara, 2013; Jung et al., 2014) have reported forma-
tion of the slip system under wet conditions. In our ultra-mylonitic pe-
ridotites with E-type olivine fabrics, we also found indicators of H2O
activity such as Ti-clinohumite defects (and serpentine) (Fig. 6c) and
fluid inclusion trails (Fig. 2i) in elongated olivine porphyroclasts, and
a hydrous mineral (pargasite) in the matrix (Table 1 and Fig. 3b). Hydrous

![Deformation mechanism maps (DMMs) of olivine as a function of stress and grain size.](image-url)
fluid/melt was probably supplied from the dehydration of the surrounding crustal rock due to shear localization (Sawaguchi, 2004), as our ultra-mylonitic peridotites are located in marginal areas of peridotites, adjacent to migmatitic gneisses (basement rock) (Fig. 1c). This scenario is also supported by a previous geochemical study by Arai et al. (2008) on U-shaped rare earth element (REE) patterns in clinopyroxenes and amphiboles from Yugu lherzolites. They concluded that hydration was associated with enrichment in light REE, resulting from either a fluid circulating in the crust or a slab-derived fluid. Recently, Tasaka et al. (2016) conducted torsion experiments of olivine aggregates under hydrous conditions (\(T = 1200\ ^\circ\text{C}\) and \(P = 300\ \text{MPa}\)) and observed (001)[100] and (100)[001] slip at high strain (\(\gamma \geq 3.4\)). However, Hansen et al. (2014) carried out similar torsion experiments under anhydrous conditions and found that the [100] axes form a strong point maxima and both the [010] and [001] axes are strongly distributed as a girdle (D-type) at similar shear strain (\(\gamma = 3-5\)), with a fabric transition to A-type fabric at high shear strains. These observations indicate that activation of the olivine (001)[100] slip system representing E-type fabric cannot be explained without the presence of water. Therefore, E-type olivine fabrics in the Yugu ultra-mylonitic peridotites are interpreted as forming under hydrous conditions at low temperature and high strain (Fig. 8). It is worth noting that water is a significant factor for enhancing shear strain, and can produce a transition from pre-existing fabric in the mantle shear zone. In order to reset the pre-existing LPO of olivine under dry conditions, high strains are required to reach a steady-state crystallographic fabric based on experimental and modeling observations: \(\gamma > 5\) (Hansen et al., 2014) and \(\gamma > 4\) (Boneh et al., 2015). According to these results, the shear strain of at least \(\gamma > 5\) (or \(\gamma > 4\)) is needed under dry conditions for the olivine fabric transition from A-type to E-type in our study. However, the Yugu ultra-mylonitic peridotites are considered to be deformed under hydrous conditions. Therefore, a study under wet conditions is needed to explore the role of specific strains on the olivine fabric transition in the future.

One further interesting point is that our E-type fabric is unique in terms of its relatively small olivine grain size (24–30 \(\mu\text{m}\) in 3D) for a mantle shear zone context. Most E-type fabrics previously described from natural mantle shear zones have coarser olivine grains, such as 257–646 \(\mu\text{m}\) (Michibayashi and Oohara, 2013), 250–500 \(\mu\text{m}\) (Skeber et al., 2010), and 110–350 \(\mu\text{m}\) (Lincens et al., 2015). E-type olivine fabric with very small grains, 10–20 \(\mu\text{m}\) in size, has been previously reported only from mylonitic and ultra-mylonitic xenoliths in the East African Rift (Kaczmarek and Reddy, 2013).

11.2. Deformation mechanisms of olivine in the mantle shear zone

The three main olivine deformation mechanisms are dislocation creep, diffusion creep, and dislocation accommodated grain boundary sliding (DisGBS). All three mechanisms can operate at the same time, but with one mechanism dominant. Based on microstructural observations of naturally and experimentally deformed specimens, the transitions from dislocation creep to DisGBS, and between dislocation creep and diffusion creep (Hirth and Kohlstedt, 1995), have been considered as major sources of strain localization in the Earth’s lithosphere (Warren and Hirth, 2006; Précigout and Gueydan, 2009; Hansen et al., 2011, 2012; Précigout and Hirth, 2014). Based on microstructural analyses of mylonite fabric in naturally deformed peridotites, Warren and Hirth (2006) suggested that an LPO is maintained during DisGBS when the easy slip component is dominant during deformation (grain size 10–100 \(\mu\text{m}\)), though rate limited by the GBS component. In addition, deformation experiments of olivine aggregates (Hansen et al., 2012) showed dislocations, sub-grain structures with SPO (grain size 7–27 \(\mu\text{m}\)), and the development of a strong LPO in the DisGBS regime.

In order to compare a dominant deformation mechanism of olivine with the textural types of the Yugu peridotites (e.g., Précigout and Hirth, 2014), we created deformation mechanism maps (DMMs) of olivine (Fig. 9) using olivine flow laws (Hirth and Kohlstedt, 2003; Hansen et al., 2011). The DMMs of olivine for the mylonite (M) and proto-mylonite (PM) were calculated for dry conditions at a pressure of 0.5 GPa and a temperature of 800 °C (Arai et al., 2008) (Fig. 9a and b). Based on the flow law of Hirth and Kohlstedt (2003), the dominant deformation mechanisms of olivine are varied with textural types for the Yugu peridotites, from PM (dislocation creep) to M (both dislocation creep and DisGBS) (Fig. 9a). In contrast, based on the flow law of Hansen et al. (2011), the deformation mechanism of olivine for both PM and M belongs to the DisGBS regime (Fig. 9b). Proto-mylonitic peridotites in the Yugu peridotite body showed strong olivine LPOs (Fig. 5a and b) which were interpreted as the result of deformation at high temperature (A-type olivine fabric). Those strong LPOs and numerous dislocations in olivine (Fig. 4a) indicate that proto-mylonitic peridotites were deformed by dislocation creep, which is consistent with the deformation mechanism of olivine in the DMM (Fig. 9a). Mylonitic peridotites had weaker olivine LPOs (D-type olivine fabric) than the proto-mylonitic peridotites and fabric strength (M- and J-index) sharply decreased (Fig. 5c and d), with grain size reduction, while polygonal shaped olivines increased in number (Fig. 2g). However, some olivines still contained dislocations (Fig. 4e). These microstructure characteristics indicate a transition in the deformation mechanism from dislocation creep to DisGBS, which is consistent with the deformation mechanisms of olivine in the DMMs (Fig. 9a and b).

For the ultra-mylonite (UM), the DMMs of olivine were calculated by using the flow law of Hirth and Kohlstedt (2003) at a pressure of 0.5 GPa under wet conditions (500 ppm H/Si for E-type LPO) depending on specific strain rates of \(10^{-12} \text{s}^{-1}\) and \(10^{-13} \text{s}^{-1}\) (Fig. 9c and d). For the DMMs of olivine under wet conditions, the DisGBS was not considered in the calculation because of the lack of accommodation by GBS at hydrous conditions due to the fast climb of dislocations at hydrous conditions (Hirth and Kohlstedt, 2003; Warren and Hirth, 2006; Hansen et al., 2011). At the strain rate of \(10^{-13} \text{s}^{-1}\), the dominant deformation mechanism of UM belongs to both dislocation creep and diffusion creep regime (Fig. 9c) whereas, at the higher strain rate of \(10^{-12} \text{s}^{-1}\), it is expanded to the dislocation creep regime (Fig. 9d). In the ultra-mylonitic peridotites, E-type olivine LPOs were developed with extreme grain size reduction (24–30 \(\mu\text{m}\)) and fabric strength was lower (Fig. 5e and f) than that of the mylonitic peridotites. Neoblast dislocation microstructures in the ultra-mylonitic peridotites showed two characteristics: (1) elongated grains with straight dislocation walls; and (2) polygonal grains lacking dislocations. The dominant deformation mechanisms of both dislocation and diffusion creep (Fig. 5c and d) are generally consistent with those microstructural observations and temperatures of neoblasts for the strain rate of \(10^{-12} \text{s}^{-1}\) (Fig. 9d) which is relatively higher strain rate than geological strain rates of \(10^{-15} \text{s}^{-1}\) to \(10^{-13} \text{s}^{-1}\) (Pfiiffer and Ramsay, 1982; Précigout and Gueydan, 2009). Therefore, we infer that the ultra-mylonitic peridotites were deformed by the combination of dislocation and diffusion creep.

12. Conclusions

We reported on well-preserved transitional characteristics of olivine microstructures and LPOs found in the mantle shear zone of the Yugu peridotite body in the Gyeonggi Massif, Korea. The Yugu peridotite body predominantly comprises spinel harzburgite together with minor lherzolite, dunite, and clinopyroxenite. We classified highly deformed peridotites into four textural types, based on their microstructural characteristics (especially olivine grain size): proto-mylonite; proto-mylonite to mylonite transition; mylonite; and ultra-mylonite. The proportion of clinopyroxene and amphibole increased toward ultra-mylonitic peridotites. Olivine LPO varied with textural type of specimens, from A-type (proto-mylonites) via D-type (mylonites) to E-type (ultra-mylonites). The olivine fabric transition from A-type to E-type is interpreted to have occurred under hydrous conditions at low temperature (700–760 °C) and high strain, based on characteristics such as Ti-clinohumite defects (and serpentine) and fluid inclusion.
trails in olivine, and a hydrous mineral [paragase] in the matrix, especially from the ultra-mylonitic peridotites. Olivine fabric strength (M- and J-index) systematically decreased with decreasing olivine grain size from proto-mylonite via mylonite to ultra-mylonite. Even though the grain size of neoblasts in the ultra-mylonitic peridotites was extremely small (24–30 μm), olivine fabrics showed a clear E-type pattern rather than random fabric. Analysis of the LPO strength, dislocation microstructures, recrystallized grain-size, and DMMs of olivine suggest that the proto-mylonitic, mylonitic, and ultra-mylonitic peridotites were deformed by dislocation creep (A-type), DisGBS (D-type), and the combination of dislocation and diffusion creep (E-type), respectively.

Acknowledgements

The authors would like to thank Dr. Jong Ok Jeong (Gyeongsang National University) for the EPMA analyses. The authors acknowledge the thorough and constructive reviews by two anonymous reviewers, as well as the careful editorial work by Philippe Agard, which substantially improved the paper. This work was supported by the Korea Metrological Administration Research and Development Program under Grant, KMIPA2017-9020 (H.J.) and the Fellowship for Fundamental Academic Fields in Seoul National University to Munjae Park.

References


Klein, H., 2006. Phanerozoic high-pressure eclogite and intermediate-pressure granulite facies metamorphism in the Gyegonggi Massif, South Korea: implications