Evidence of high water content in the deep upper mantle inferred from deformation microstructures

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ABSTRACT

Deep upper-mantle rocks from the Norwegian Caledonides show evidence for large strain deformation in both olivine and garnet under varying water contents. Using microstructural observations, including lattice-preferred orientation of olivine and subgrain boundaries of majoritic garnet, we infer the following deformation history. At depths exceeding ~150 km, large strain deformation occurred at low stress (~10 MPa) and modest temperature (~1300 K), involving high water content (>1000 H/10^6Si in olivine). This was followed by low strain deformation at lower water content (~200–1000 H/10^6Si) and modest stress (~40 MPa) in the shallower parts. These observations show that the deep upper mantle in this region had a considerably higher water content than the upper mantle near mid-ocean ridges.

Keywords: deformation microstructure, lattice-preferred orientation, water, majoritic garnet, olivine, Norwegian Caledonides.

INTRODUCTION

Water has marked effects on both physical and chemical properties of minerals and rocks, and hence the distribution of water is an important subject for geological studies (e.g., Williams and Hemley, 2001; Karato, 2003). Garnet peridotites carried from the deep upper mantle may provide a clue to the distribution of water in the deep mantle (Bell and Rossman, 1992). However, the high diffusivity of water in minerals (e.g., Kohlstedt and Mackwell, 1998) provides a challenge, because water can be lost or added easily during transport to the surface. It is therefore not clear if the measured water contents reflect in situ values in Earth's interior. One of the challenging issues here is to read the history of water contents from natural mantle samples.

Various deformation microstructures are known to be sensitive to water content as well as other physical parameters such as temperature and stress. The dominant slip systems in minerals such as olivine appear to depend on water content (Karato, 1995). This causes the change in lattice-preferred orientation (LPO) if an olivine-rich rock is deformed by large strain (Jung and Karato, 2001a; Katayama et al., 2004). Once formed, LPO is difficult to modify by subsequent annealing (Heilbronner and Tullis, 2002). In contrast, dislocation microstructures can be modified by small strain (~1%) deformation (Durham et al., 1977) and are subject to later-stage annealing (Karato and Ogawa, 1982). Therefore, LPO may record conditions for long-term, large strain deformation, whereas dislocation microstructures tend to reflect the conditions of the latest stage, short-term deformation (or annealing). In this report we attempt to read the history of deformation conditions of deep mantle peridotites using the analyses of deformation microstructures, which have different response times for time-varying physical and chemical environments.

SAMPLE CHARACTERISTICS

The garnet peridotite from Otrøy Island of the Western Gneiss Region in Norway has a unique texture of Si-rich precipitation in garnet, which is interpreted as a relict of former majoritic garnet (van Roermund and Drury, 1998; van Roermund et al., 2000, 2001). Such microstructure also has been reported in kimberlite xenoliths from South Africa (Haggerty and Sautter, 1990) and from the Sulu and Qaidam ultrahigh-pressure metamorphic terranes (Ye et al., 2000; Song et al., 2004). Structural transformation of pyroxene to garnet and solid-state dissolution of pyroxene into garnet (majorite substitution) require high pressure, >5 GPa. Therefore, these peridotites are considered to have been derived from the deep upper mantle or perhaps even the transition zone (Haggerty and Sautter, 1990). Based on the volume of the pyroxene exsolution in garnet, van Roermund and coworkers reported that the Otrøy garnet peridotites originated from pressure >6.4 GPa (>200 km depth) (van Roermund and Drury, 1998; van Roermund et al., 2000, 2001).

The Otrøy garnet peridotites occur as sporadically preserved layers or boudinage lenses within the high-grade crustal gneisses of the Western Gneiss Region, which formed by continental collision between the Baltic and Laurentia plates during the Caledonian orogeny (Brueckner and Medaris, 1998). These peridotites are composed mostly of olivine, garnet, and orthopyroxene, with minor clinopyroxene. Compositional layering is well defined, with variable amounts of garnet and Cr-diopside. Large porphyroclasts of garnet, olivine, and pyroxenes (centimeter scale) are extensively recrystallized to millimeter-scale grains, and the recrystallized garnet and pyroxene grains are elongated. The compositional banding is subparallel to the foliation, which is defined by elongated trails of garnet and pyroxenes. Secondary serpentines are well developed in these peridotites. Garnet neoblasts show exsolution microstructures (Fig. 1A), which are composed mainly of orthopyroxene and rutile along the garnet [111] direction. Olivine neoblasts contain ilmenite needles (Fig. 1B), which have also been reported in other Alpine-type garnet peridotites (Dobrzhinetskaya et al., 1996; Hacker et al., 1997; Risold et al., 2001).

MICROSTRUCTURAL OBSERVATIONS

We chose two peridotites from Otrøy Island for measurement of olivine LPO, using the electron backscatter diffraction (EBSD) technique. In the analysis, Kikuchi patterns were collected and indexed on each olivine grain at an accelerating voltage of 20 kV and a beam current of 2.4 nA. One sample, a massive peridotite, has a homogeneous distribution of garnet and pyroxenes, and the other, a layered peridotite, has a layering defined by the concentration of Cr-diopside and garnet, which suggests interaction with melts. The massive peridotite shows a maximum for the [001] axis subparallel to the stretching lineation and the (100) plane subparallel to the foliation (Fig. 2A). This pattern is similar to that found in olivine experimentally deformed at high water content and relatively low stress (C-type in Jung and Karato, 2001a).

Couvy et al. (2004) reported that the C-type fabric was formed in olivine when deformed at 11 GPa. They suggested that the dominant slip system in olivine might change with pressure even at the same water content. However, their interpretation is subject to large uncertainties because their samples had high water contents (a few thousand H/10^6Si) and the stress levels were high (>100 MPa). The dominance of the [001] slip at high stress level has been known since Carter and Avé Lallemant (1970), and a high water content will enhance [001] slip systems, as demonstrated

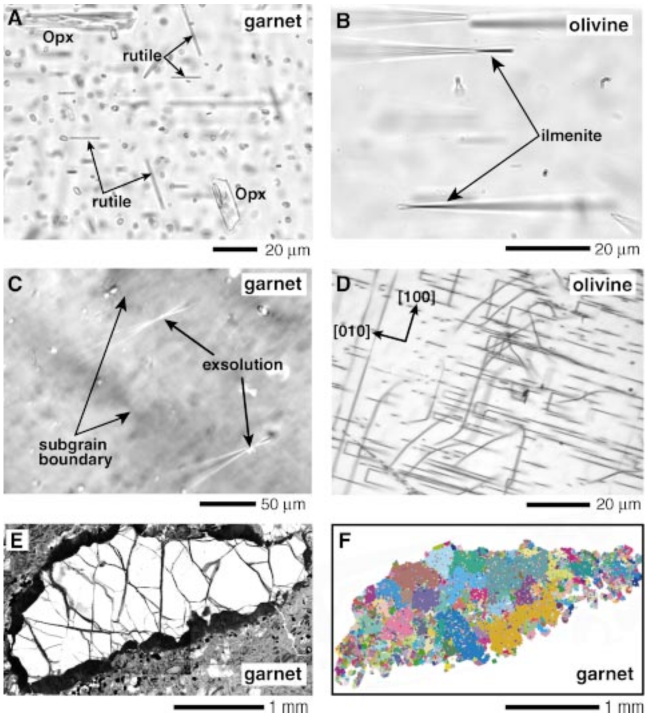

Figure 1. Microstructures of Otrøy garnet peridotites. A: Orthopyroxene (Opx) and rutile exsolutions in garnet. B: Ilmenite exsolutions in olivine. C: Exsolved minerals crosscutting deformation-induced subgrain boundaries in garnet. Boundaries are more clearly shown in electron backscatter diffraction (EBSD) mapping (F). D: Dislocation microstructures in olivine after decoration at 1173 K for 1 h, showing well-defined glide loops on (001) plane. E: Elongated garnet grain. F: Results of orientation mapping based on EBSD measurements at 1 μm step. Different colors represent different orientations with 1°–2° degree of misorientation angles.

by Jung and Karato (2001a). In addition, Jin (1995) found that an ultradeep mantle xenolith (deeper than ~300 km) has the [100] slip olivine fabric. Therefore we conclude that a case for pressure-induced fabric transformation is rather weak, and prefer a case for water-induced fabric transformation.

In contrast to the massive peridotite, the layered peridotite shows a weaker fabric in which the [100] maximum is subparallel to the stretching lineation and the (010) plane is subparallel to the foliation (Fig. 2B). This is a typical olivine fabric from mantle xenoliths and ophiolite complexes (Ben Ismail and Mainprice, 1998). Laboratory experiments indicate that this fabric forms at low water content and low stress (Carter and Avé Lallemant, 1970; Zhang and Karato, 1995).

The water contents of olivines were measured by infrared spectroscopy and showed hydroxyl absorption bands between 3450 and 3650 cm^{-1} wave numbers. The water contents were estimated to be ~700–800 H/10^6Si from both massive and layered samples based on the Paterson (1982) calibration. If the recent calibration (Bell et al., 2003) is used, these values would be increased by a factor of ~3.5. The water contents, however, have almost certainly been modified at later stages, because these rocks have undergone extensive hydration and overprinting at amphibolite facies conditions during exhumation.

The deformation conditions associated with formation of the observed olivine LPO are inferred from the following microstructural observations. The garnet neoblasts show evidence for large strain deformation (shear strain, γ ~1, based on the aspect ratio of deformed grains, assuming simple shear) with undulatory extinction in polarized light under an optical microscope (Fig. 1C), and EBSD mapping reveals subgrain structure with misorientations of 1°–2° between the subgrains (Fig. 1F). Such microstructures suggest large strain deformation during high-temperature dislocation creep (Prior et al., 2000). Using the flow laws of garnet (Karato et al., 1995; Jin et al., 2001), we examined possible time-temperature paths needed to develop significant elongation of garnet and found that temperatures must be ~1300 K or larger to produce significant strains on a geological time scale (Fig. 3A). The exsolved orthopyroxene and rutile in the garnet crosscut the deformation-induced subgrain boundaries (Fig. 1C), which suggests that deformation of the garnets occurred while the garnets were in the majorite stability field, indicating pressures >5 GPa and depths >150 km (Fig. 4). The olivine neoblasts show different grain sizes between the two samples (1.35 mm for the massive peridotite, and 0.73 mm for the layered peridotite). We attribute this difference to differences in water content, as indicated by different olivine LPO, because high water contents cause large recrystallized grain size resulting from enhancement of grain-boundary migration (Jung and Karato, 2001b). The neoblast grain sizes correspond to the similar differential stresses at ~10 MPa. The deformation mechanism map for wet and dry olivine at 6 GPa and 1300 K shows that both olivines would have been deforming by dislocation creep (Fig. 3B), which is consistent with the development of the LPO.

The exsolution microstructures in garnet are, in some cases, truncated by fractures, which are occupied by pyroxene and spinel. This brittle deformation of the garnet occurs

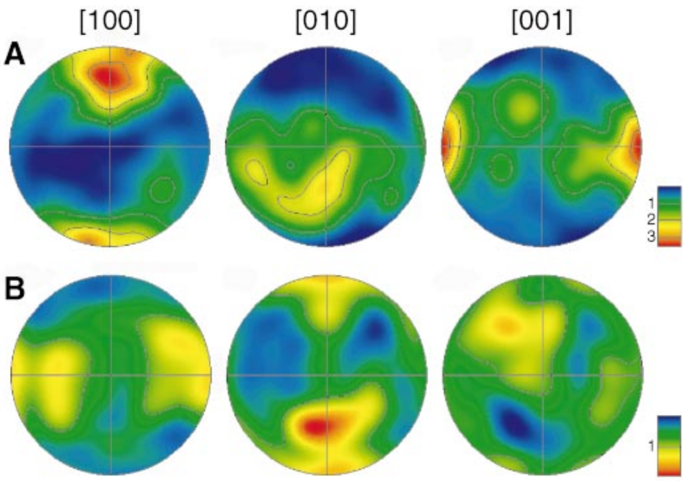

Figure 2. Pole figures of lattice-preferred orientation of olivines from massive peridotite (A) and layered peridotite (B). East-west direction corresponds to stretching lineation, and north-south direction corresponds to foliation normal. Equal-area lower-hemisphere projection was used with half scatter width of 30°. Orientations of ~200 grains were measured. Color coding refers to density of data points (numbers in legend correspond to multiples of uniform distribution). Massive peridotite shows [001] maximum subparallel to stretching lineation and (100) plane subparallel to foliation, which is similar to that found at high water content and low stress. Layered peridotite shows [100] maximum subparallel to lineation and (010) plane subparallel to foliation, which is typical olivine fabric at water-poor conditions and low stress.

at lower temperature and pressure. Both samples show olivine neoblasts with similar dislocation microstructures (Fig. 1D). There is no systematic correlation between dislocation density and the distribution of exsolved ilmenite in olivine, suggesting that the exsolution occurred before formation of the preserved dislocation microstructure. Similar observations are also reported in Alpe Arami peridotites (Green et al., 1997). Many of the observed dislocations are linear with well-defined glide loops (Fig. 1D). These glide loops show that the dominant glide plane is (001), suggesting a dominant slip system of [100] (001). Our recent experiments showed that this slip system is dominant at modest water content ($200 < C_{OH} < 1000$ H/10^6Si) and low stress (Katayama et al., 2004). This slip system is distinct from the observed olivine LPO in both the massive and layered peridotites. Furthermore, the dislocation density in the olivines from the samples indicated differential stresses of ~40 MPa, which is much higher than those estimated using the neoblast grain size (~10 MPa). We interpret that the dislocation microstructures in these rocks reflect later stage (after ilmenite precipitation), small strain deformation at a higher stress level but with a moderate water content, and that the deformation at this stage has not significantly modified the preexisting LPO.

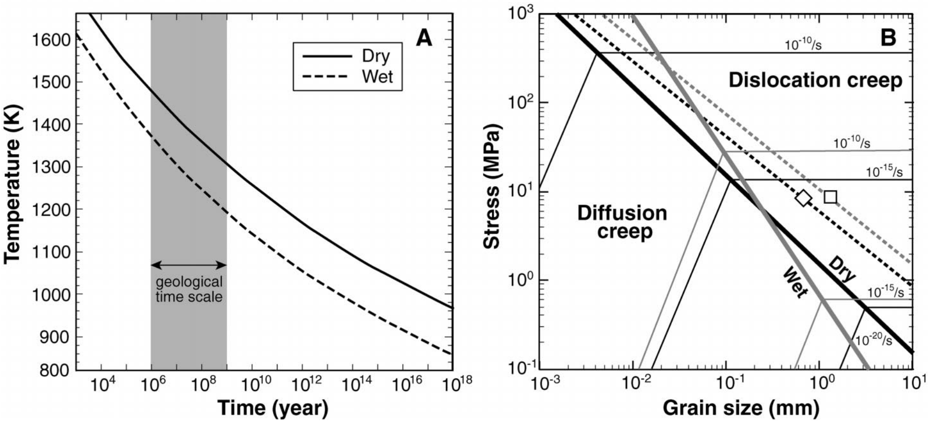

Figure 3. A: Time-temperature history during deformation, calculated from flow laws for dry garnet (Karato et al., 1995) and wet eclogite (Jin et al., 2001), assuming strain of $\gamma = 1$ and differential stress of 10 MPa at pressure of 6 GPa. Wet eclogite contains 40 vol% omphacite (Jin et al., 2001), so strain rate of wet garnet should be slower than that of eclogite. Temperature during deformation must have been ~1300 K to accomplish significant finite deformation over geologic time scale (millions to billions of years). B: Deformation mechanism map for olivine at 6 GPa and 1300 K. Deformation mechanism fields were calculated using method of Karato and Jung (2003) and are labeled by dominant mechanism. Thick black line defines field for dry olivine, and thick gray line defines field for wet olivine. Thin lines indicate strain-rate contours. Stress and grain-size relations are shown using dashed lines for dry (black) and wet (gray). Stresses were estimated using observed grain size in samples, as indicated by diamond for layered peridotite sample (dry fabric) and square for massive peridotite sample (wet fabric).

SUMMARY

We have shown that the olivine LPO from the Otrøy garnet peridotites includes one similar to that found by laboratory experiments at water-rich conditions (>1000 H/10^6Si). These peridotites were derived from a deep continental collision zone (van Roermund and Drury, 1998; van Roermund et al., 2000, 2001), and microstructural observations indicate that the large strain plastic deformation occurred at high temperatures and pressures (Fig. 4). The pressure-temperature conditions inferred from petrological observations are similar between these rocks, whereas the water contents at the time of the long-term deformation inferred from olivine LPO are distinct. We interpret that some localized water flux or localized interaction with melt in the deep portions (>150 km) results in highly variable water content at small scales in this region.

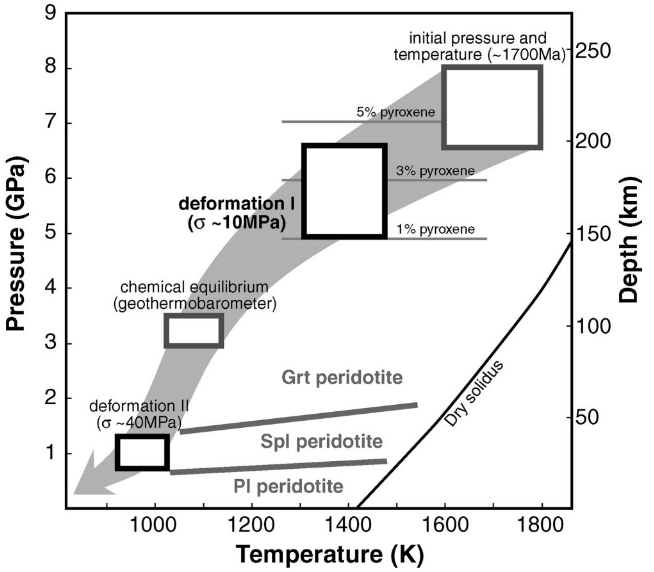

Figure 4. Recorded pressure-temperature-depth (*P*-*T*-D) path of Otrøy garnet peridotites, with decompression during Early Proterozoic (ca. 1700 Ma) from initial high pressure and temperature condition >6.4 GPa and 1600–1800 K (van Roermund and Drury, 1998; van Roermund et al., 2000, 2001). Rocks equilibrated within lithosphere at 3.2 GPa and ~1100 K, and then were exhumed at 425–400 Ma during Caledonian orogeny (Brueckner and Medaris, 1998). Deformation microstructures in our samples indicate large strain deformation associated with formation of olivine lattice-preferred orientation at pressures >5 GPa and temperatures >1300 K. Dislocation microstructures in olivine indicate modest stress (~40 MPa), and are inferred to have occurred at lower temperatures, while samples were in lithosphere. Mineral abbreviations: Grt, garnet; Spl, spinel; Pl, plagioclase.

Although most natural peridotites from ophiolite complexes and mantle xenoliths show dry olivine fabric (Ben Ismail and Mainprice, 1998), some Alpine-type peridotites have been reported to show olivine fabrics that developed under water-rich environments (Möckel, 1969; Frese et al., 2003; Mizukami et al., 2004). The Alpine-type peridotites occur in plate convergent regions where high water content is expected. This agrees with the evidence of water-rich fabrics in these mantle rocks. However, the depths of deformation in these rocks are not well constrained (for discussions see Green et al., 1997; Hacker et al., 1997; Risold et al., 2001; Bozhilov et al., 2003) and the lack of silica-rich precipitates in garnets in these rocks suggests that they have shallow origins ($<$150 km). Therefore, we consider that the wet olivine fabric from the Otrøy garnet peridotites gives the first direct evidence for the presence of high water content in the deep upper mantle ($>$150 km).

We suggest that regions with high water content may be widespread in the subduction-zone upper mantle or in the deep roots of continents that have not undergone depletion by partial melting. Unique olivine fabric such as the C-type, E-type, or B-type will be present in these regions that have unique signature in seismic anisotropy. In addition, the anomalies in seismic attenuation and velocity in the deep portion of wedge mantle beneath the Philippine Sea may be attributed to the presence of significant amounts of water (Shito and Shibutani, 2003). Exploration of these seismological signatures combined with experimental studies on rock fabrics and the studies of mantle rocks will provide important clues on the distribution of water in Earth's mantle.

ACKNOWLEDGMENTS

We thank P. Skemer for discussion and Z. Jiang for technical assistance. Comments from three anonymous reviewers helped to improve this paper. This study was supported by U.S. National Science Foundation grants (to Karato) and by a research fellowship by Japan Society for the Promotion of Science (to Katayama).

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Manuscript received 2 November 2004
Revised manuscript received 15 March 2005
Manuscript accepted 17 March 2005

Printed in USA