Rheology of omphacite at high temperature and pressure and significance of its lattice preferred orientations

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Received 14 January 2006; received in revised form 4 April 2006; accepted 4 April 2006
Available online 2 June 2006
Editor: R.W. Carlson

Abstract

We have investigated the rheology of hot-pressed polycrystalline omphacite (Di58Jd42, space group C2/c) at strain rates of 10−4–10−5/s, temperatures of 1300–1500K and a pressure of 3GPa, using a 5GPa Griggs-type deformation apparatus. The rheological constitutive equation of omphacite is determined with a stress exponent of 3.5±0.2 and an activation energy of 310±50kJ/mol. Our study shows that: (1) the creep strength of omphacite falls between those of diopside and jadeite; (2) experimental omphacite microfabrics are indistinguishable from natural ones: S-type fabric and its mesoscopic foliation develop under conditions of axially symmetric shortening, whereas L-type fabric and its mesoscopic lineation develop under conditions of general strain, with L parallel to the greatest elongation; (3) as in naturally deformed omphacite, the deformation substructure is characterized by the dominant slip systems {110}1/2〈110〉, {110}[001] and (100)[001]. We conclude that both S- and L-type omphacite fabrics are produced by these slip systems; fabric differences arise solely from variation of the geometry and orientation of the finite strain ellipsoid. We also confirm the previous suggestion that Na-bearing pyroxenes are significantly weaker than Na-free pyroxenes.

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Keywords: omphacite; rheology; fabric; slip system

1. Introduction

Omphacite is a Na–Al-rich high-pressure clinopyroxene existing as a major mineral of eclogite. Natural eclogites commonly have compositions approximately midway between diopside (CaMgSi2O6) and Jadeite (NaAlSi2O6). Natural eclogites also in many cases show clear evidence of extensive deformation; a clear foliation and lineation defined by strong lattice and shape preferred orientations of omphacite crystals and other minerals are common [1,2]. Garnet, the other major mineral of eclogite, rarely has a strong shape fabric and behaves mostly as a rigid body during plastic deformation of eclogite (e.g. [3,4]). These microstructures suggest that omphacite may dominate the flow properties and seismic anisotropy of eclogite [5,6]. Investigation of the rheology of omphacite is of great importance for a better understanding of geodynamic problems associated with eclogite in subducted oceanic and continental crusts.

It is common to observe lattice preferred orientations (LPOs) of clinopyroxene in both natural samples and
experimental samples with the c-axis, [001], parallel to the lineation (L) and the b-axis, [010], normal to the foliation plane (S) (e.g., [1,2,7–14]). Helmstaedt et al. [7] classified two principal types of LPO in natural eclogites (Fig. 1a and b). The L-type LPO is characterized by a point maximum of [001] parallel to the lineation, while [010] forms a girdle perpendicular to the lineation. The S-type LPO is featured by a point maximum of [010] normal to the foliation, while [001] forms a girdle corresponding to the foliation plane. However, it is more common to observe intermediate LPOs with a point maximum of [001] axes parallel to the lineation and a point maximum of [010] axes normal to the foliation plane reported from low-temperature eclogites, pyroxenites and cpx-amphibolites [15,16]. They have annealed microstructures likely resultant from concomitant grain growth. The deformation processes associated with these fabrics are currently not fully understood. The strong preferred orientations of omphacite have most often been attributed to dislocation creep during plastic deformation. The crystallographic plane and direction of slip approach the foliation and lineation respectively during dislocation glide on a single slip system. Therefore, both S-type and L-type preferred orientations would suggest ‘easy glide’ along (010) [001]. However, previous TEM studies revealed that (100)[001] is the easiest slip system at low and intermediate temperature [17,18], while {110}1/2 〈110〉 and {110}[001] are dominant glide systems in clinopyroxene at high temperature [1,17–19]. Because the (010)[001] slip system has never been reported as a significant slip system in clinopyroxene, the observed omphacite fabrics cannot be explained by ‘easy glide’ on this slip system. This has led to a debate over whether omphacite fabrics are formed by a single slip system or multiple slip systems [2,6,11,19–21]. Other mechanisms, such as diffusion creep with concomitant anisotropic growth and dissolution, have also been proposed [7,10]. The intermediate type fabric of omphacite represents a combination of L-type fabric with S-type fabric. The correlation between crystallographic fabric and shape fabric suggests that the variation may be associated with deformation geometry (shearing or flattening) [2,7,10,22]. On the other hand, a temperature-dependent switch in dominant slip system due to space group transformation has also been proposed to cause this variation [11]. All of these questions remain to be further elaborated by careful experimental work. Deformation experiments are required to resolve such ambiguities in the correlation of rheology and deformation mechanisms of minerals or rocks under various $P$–$T$–$\varepsilon$ conditions. Unlike other clinopyroxenes, omphacite is only stable at pressures in excess of approximately 1.2 GPa. At temperatures sufficient for mineral reactions to proceed on a reasonable laboratory timescale and to establish ductility of the constituent minerals (garnet and pyroxene), pressures in excess of 2 GPa are required, pressures beyond the capacity of most conventional machinery designed to induce deformation and measure stresses (such as the Paterson apparatus and conventional Griggs deformation apparatus). As a consequence, no quantitative deformation experiments have been conducted on omphacite except our recent initial study on eclogite at high pressure that provides only a cursory look at these problems [4]. Otherwise, understanding of omphacite rheology and deformation mechanisms has been limited to inferences from microstructural observations and analogue experimental studies on diopside single crystals [18,23–25] or polycrystalline

![Fig. 1. Classification of omphacite LPOs.](image)

(a) S-type: [001] axes form a girdle in the foliation plane, while [010] axes are normal to the foliation; (b) L-type: [001] axes are concentrated parallel to lineation, while [010] axes form a girdle in the plane normal to the lineation; (c) SL-type: both [001] axes and [010] axes develop a point maximum concentration—[001] parallel to lineation and [010] normal to foliation.
aggregates [9,26–28]. These experiments show: (1) diopside deforms by mechanical twinning on (100) and (001) planes at low temperature and high strain rates; (2) dislocation creep and/or diffusion creep dominates flow at high temperature depending on grain size and flow stresses; (3) the observed slip systems in diopside are similar to those in omphacite. However, the LPO of experimentally deformed diopside specimens is not well documented. Only a recent study reported an S-type fabric of diopside from axial compression experiments and an oblique S-type fabric from torsion experiments [9]. On the other hand, all those experiments suggest an unreasonably high stress required to deform clinopyroxene-rich rocks by dislocation creep under lower crustal or upper mantle conditions. This is inconsistent with natural observations that indicate that omphacite deforms by dislocation creep at temperatures as low as 450°C [29]. The preliminary experimental data on the deformation of sodic-clinopyroxene (jadeite and omphacite) indicates a lower flow strength than that of diopside-hedenbergite clinopyroxenes [4,30]. These latter studies have questioned the previously inferred high strength of eclogite.

In order to determine the rheology and deformation mechanisms of omphacite that produce the observed LPOs in natural samples, we conducted deformation experiments on hot-pressed polycrystalline omphacite at strain rates of $10^{-4} – 10^{-5}$/s, temperatures of 1300–1500 K and a pressure of 3 GPa.

2. Rheological experiments

2.1. Starting materials and methods

The experimental starting materials were prepared from fresh, coarse-grained, coesite-bearing eclogite of the Bixiling garnet peridotite-eclogite complex, Dabie Mountains, central China. The $P–T$ conditions estimated by thermobarometery are 2.8–4 GPa and 700–900°C [31], but recent discovery of pigeonite exsolution in diopside suggests much greater

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Fig. 2. Pressure assembly and experimentally deformed specimens. (a) High-pressure assembly, viewed in cross section. The specimen is welded in a platinum capsule (9 mm long × 3 mm diameter). The capsule sits on a 2.5-mm Al$_2$O$_3$ piston in a thick nickel sleeve (Ni) filled with CsCl. Salt also surrounds the upper Al$_2$O$_3$ deformation piston. Two Pt$_{64}$Rh$_{36}$–Pt$_{70}$Rh$_{30}$ thermocouples in mullite tubes, one at either end of the specimen, directly measure the temperature gradient during the experiment. (b) Specimen from an axial compression experiment (GB196). A 1.4-mm Al$_2$O$_3$ piston was placed on top to protect specimen during capsule welding. (c) Specimen from a shear experiment (GB321). A thin specimen (≈300 μm) was placed between the two halves of a 9-mm Al$_2$O$_3$ piston cut at 45° in the middle.
maximum pressures [32]. The natural eclogite was gently ground to disaggregate it into individual crystals. Omphacite crystals were separated and ground to a grain size ∼45–75 μm, and then hot-pressed in a modified 5GPa Griggs apparatus using the same technique we used previously for hot-pressing eclogite [4]. A small amount of quartz (5–10 vol.%, originally existing as inclusions in omphacite) could not be completely separated from the omphacite fine powder but the small volume fraction of this contaminant should have a negligible effect on the rheology of omphacite. Fourier-transform infrared spectroscopy (FTIR) showed that these omphacite powders contain structurally bound hydroxyl on the order of 100–200ppm using Bell et al.’s calibration method [33], whereas quartz has a hydroxyl concentration below the resolution of the IR spectrometer. Specimens were prepared by loading powders into 3-mm diameter cylindrical Pt capsules with a 25-μm foil of Ni placed above and below the powder to buffer the oxygen fugacity at Ni/NiO. A 1.4-mm long cylinder of fully dense polycrystalline Al2O3 was placed on top of the upper Ni foil within the capsule. The capsule, approximately 9mm long, was then welded shut and assembled into the standard high-pressure assembly for our 5GPa modified Griggs apparatus, using CsCl as confining medium (Fig. 2a). Specimens were pressurized to 3.0GPa over 15h at T=573K, hot-pressed at 1000–1300K for 12h and then deformed at temperatures of 1300–1500K (Fig. 2b and c). The experimental temperature was monitored by two Pt/Rh type B thermocouples included in each experiment, one located near the top of the specimen and the other near the bottom. No correction was made for the pressure effect on the thermocouple emf.

After hot-pressing, the samples showed well-equilibrated microstructures with dominant grain size of ∼50μm (Fig. 3a). A weak foliation defined by slightly flattened quartz and omphacite perpendicular to the cylinder axis was often observed, indicating a small axial deformation during hot-pressing. The omphacite has a composition close to a mixture of Di58Jd42 (estimated with the energy dispersive X-ray spectra) and a mineral structure of space group C2/c (confirmed by electron back-scattered diffraction).

2.2. Experimental results

At high temperatures and for relatively large grain sizes (>∼10μm at laboratory strain rates and >∼100μm at natural strain rates), plastic deformation of many materials occurs by dislocation creep (power law creep). The constitutive relation for this mechanism is well described by an empirical equation of form:

\[ \dot{\varepsilon} = A \dot{\gamma} \exp \left( \frac{-Q}{RT} \right) \]  

where A is a pre-exponential factor that varies with material, n is the stress exponent that varies with deformation mechanism, \( \dot{\varepsilon} \) the strain rate, \( \sigma \) the steady-state flow stress, R the gas constant, T the absolute temperature and Q the activation Gibbs free energy.

To determine the rheological parameters for polycrystalline omphacite at high pressure, two groups of experiments were carried out at a confining pressure of 3GPa. The first group was performed at constant temperatures and strain rates of 4.6×10−5/s, 1.3×10−4/s and 4.6×10−4/s, respectively. According to Eq. (1), the stress exponent (n) can be determined with least squares criteria under conditions of constant pressure and temperature (Eq. (2), Fig. 4a), yielding a stress exponent, n=3.5±0.2.

\[ n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma}_{P,T} \]  

The second group of experiments was carried out at constant strain rate and different temperatures. A semi-log plot of strain rate vs. inverse temperature is shown in Fig. 4b. From these experiments, the creep activation energy (Q) can be determined with least squares criteria under conditions of constant pressure and strain rate (Eq. (3), Fig. 4b), yielding an activation energy, Q=310±50kJ/mol.

\[ Q = n \cdot R \cdot \left[ \frac{\partial \ln \sigma}{\partial (1/T)} \right]_{P,\dot{\varepsilon}} \]  

In summary, omphacite rheology over the range of conditions explored here can be described by the following constituitive equation:

\[ \dot{\varepsilon} = 10^{-2.0} \sigma^{3.5} \exp(-310000/RT). \]  

2.3. Deformation microstructures

Optical microstructures of deformed omphacite specimens show a pronounced foliation and/or
lineation defined by obviously flattened or elongated omphacite grains (Fig. 3b and c). Undulatory extinction and subgrain boundaries are common, indicating a strong intracrystalline deformation. After 20–25% strain, omphacite crystals are up to 50–100 μm long and form tabular-shaped crystals with characteristic aspect ratio of 1:2 to 1:3. The long axes of omphacite grains of specimens deformed in axial compression are generally perpendicular to the shortening direction and define the foliation (Fig. 3b). In specimens with shear strain greater than 2, omphacite crystals are up to 200 μm long and form lenticular-shaped crystals. They lie in the foliation (S) and are elongated parallel to the lineation (L) (Fig. 3c).

3. Electron back-scattered diffraction analysis

3.1. Methods

The LPOs of experimentally deformed omphacite were measured using the SEM-based Electron Back-Scattered Diffraction (EBSD) technique. This technique enables rapid automatic determination of crystallographic orientation of mineral grains on the surface of a polished sample with a spatial resolution of about 1 μm and an absolute angular resolution of 1–2° (e.g. [34]). We prepared doubly polished thin sections from oriented samples cut parallel to the maximum compression direction. The section surface was polished with 0.06-μm colloidal silica permanent
suspension and then lightly carbon coated. EBSD patterns were collected using a Philips XL30 scanning electron microscope, using 20-kV accelerating voltage and 15-mm working distance with 70° tilting of thin sections. HKL Channel 5 software was used to index electron back-scattered patterns (EBSP). The reference coordinates (XYZ) were determined according to the coordinate system (X=Normal to specimen axis in plane of thin section, Y=normal to thin section, Z=parallel to specimen axis). Pole figures were projected with equal area and lower hemisphere and contoured with a half width of 20° and a cluster size of 5°. Orientations of each identified crystal were collected and confirmed manually to ensure precision of measurements.

3.2. Results

We have analyzed the LPO of omphacite in most of our axially deformed samples, covering a temperature range of 1300–1500K and strain rates of 10⁻³–10⁻⁴/s with strains of 10–25% shortening. Orientations of approximately 120–200 grains were collected to plot pole figures.

LPO of omphacite from a representative hot-pressed sample is plotted as fabric diagrams of poles to {110} as well as [100], [010] and [001] axes in Fig. 5a: weak maxima are distributed near-randomly in all diagrams, reflecting a fairly weak axial compression due to hot-pressing.

LPOs of omphacite from four representative experimental samples are plotted the same as the hot-pressed specimen in Fig. 5b–e. They all show S-type fabrics of varying strength. In particular, the axial symmetry of the deformation is visible in all diagrams except [100]. The causes of imperfections in these S-type fabrics can be attributed to slightly heterogeneous deformation and the relatively low accumulated strains. These results are indistinguishable from the S-type omphacite fabrics of natural eclogites as well as experimentally deformed diopside samples [2,7,9]. The fabrics appear not to be sensitive to temperature within the window of our experimental conditions.

For comparison, Fig. 5f–h shows LPOs from three high-strain shear experiments. A specimen subjected to a relatively small strain (γ=2.1) is characterized by a strong L-type fabric: [001] axes form a strong concentration parallel to the lineation but inclined at a moderate angle to the shear plane; [010] axes form a girdle in the plane normal to the lineation; [010] axes and poles to {110} show no discernible pattern; similarly [100] axes are widely spread (Fig. 5f). With increasing shear strain, the [001] axis maximum rotates progressively toward the shear direction; the [010] girdle breaks up and draws back into a high concentration approaching normal to the shear plane; poles to {110} concentrate increasingly at ~45° from the shear plane and normal to the lineation; [100] axes concentrate near the center of the plot (Fig. 5h). In short, by γ= ~5, the LPO becomes an increasingly well-defined pseudo single crystal.

4. Transmission electron microscopy (TEM) analysis

4.1. Methods

3-mm-diameter disks of experimental samples were mounted on copper grids and polished down...
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to 30μm thickness with 600-mesh sandpaper followed by “dimpling” down to 15μm in the center. Then the disk and the copper grid were removed from glass by soaking in acetone, mounted on a graphite holder and sputtered down to electron transparency in a Gatan 691 Precision Ion Polishing system. The thinned disks were coated with a very thin layer of carbon by vacuum evaporation prior to analysis in a Philips CM300 transmission electron microscope (TEM) with a 300-kV acceleration voltage. The dislocations were analyzed using standard centered dark field, weak beam and selected

Fig. 6. TEM micrographs of dislocations in omphacite. (a) [100] zone axis bright-field image of omphacite. Note that the dislocations are relatively heterogeneously distributed with high density along sub-grain and twist boundaries. Most of the dislocation lines are curved and are not confined in a specific slip plane. (b) Weak-beam image of dislocations tangled at sub-grain boundary; most of the dislocations in contrast have Burgers vector of 1/2 \langle110\rangle. (c) Weak-beam image of relatively straight dislocations with Burgers vector 1/2(110) not confined in a specific slip plane. (d) Weak-beam image of straight [001] screw dislocations arranged in \{110\}.

Fig. 5. Crystallographic preferred orientations of omphacite. Contoured pole figures (lower hemisphere equal area projections) of poles to \{110\} as well as \{100\}, \{010\} and \{001\} zone axes determined by EBSD with half width of 20° and cluster size of 5°. Arrows denote the maximum compression direction or shear plane in each sample. Panel a displays a near-random fabric in hot-pressed specimen despite slight axial compression during hot-pressing. Panels b–e show typical S-type fabrics from axial compression experiments. Panels f–h are fabrics from shear experiments; transition from L-type to SL-type is seen with increasing shear strain. Scale: pole densities (multiples of random distribution).
area electron diffraction (SAED) techniques. Burgers vectors of dislocations were identified using the $\mathbf{g} \cdot \mathbf{b} = 0$ and $\mathbf{g} \cdot \mathbf{b} \times \mathbf{u} = 0$ criteria.

4.2. Results

TEM images show high dislocation densities, $\sim 5 \times 10^{13} \text{m}^{-2}$ (Fig. 6). The dislocations are relatively heterogeneously distributed with high density along sub-grain and twist boundaries. Many dislocations are curved and not confined to a specific slip plane (Fig. 6b). There are some straight dislocations, usually with screw character and $\mathbf{b} = [001]$, which are confined into well-defined slip planes (Fig. 6d), whereas straight dislocations with $\mathbf{b} = \frac{1}{2} \langle 110 \rangle$ are not confined in their original slip planes (Fig. 6c). The majority of dislocations have Burgers vectors $\mathbf{b} = [001]$ and $\frac{1}{2} \langle 110 \rangle$. Straight dislocations with Burgers vector $\mathbf{b} = [001]$ lie mainly in $\{110\}$ slip planes and sometimes in $\{100\}$ planes, while dislocations with Burgers vector $\mathbf{b} = \frac{1}{2} \langle 110 \rangle$ are confined only in $\{110\}$ planes. Very few dislocations have Burgers vector $\mathbf{b} = [100]$.

5. Discussion and conclusions

5.1. Omphacite rheology

Microstructural observations (flattened crystals, strong foliation, undulatory extinction, etc.) in the optical microscope and the measured stress exponent of $n = 3.5$ indicate that the omphacite was deformed in the dislocation creep regime. This is consistent with the pronounced LPOs as well as the dislocation microstructures. The high dislocation density in experimental samples is generally attributed to the high stress level and fast strain rate applied during experiments (e.g. [35]).

If we extrapolate our flow law of omphacite to a natural strain rate of $10^{-14} \text{s}^{-1}$ and compare with other clinopyroxenites and eclogite, our data suggest that, under comparable conditions, omphacite has a creep strength significantly weaker than those of dry polycrystalline diopside, eclogite and wet clinopyroxenite [4,26,27], but stronger than that of polycrystalline jadeite (pure sodic clinopyroxene) [30] (Fig. 7). The result that the creep strength of omphacite falls between those of diopside and jadeite is probably a simple manifestation of their chemistry (omphacite is a solid solution between diopside and jadeite). These results support the earlier suggestion of Stöckhert and Renner [30] based on their preliminary data on polycrystalline jadeite.

5.2. Deformation mechanism

The origin of omphacite fabrics has been under extensive discussion for more than 20 yr. The deformation mechanisms of omphacite proposed to explain observations of natural rocks include twinning at low temperature [1,15] and dislocation creep or diffusion creep with orientated growth at high temperature [2,10,11]. Depending on different assumptions, either of the latter is capable of producing pronounced fabrics in omphacite, although the last involves ad hoc assumptions to predict observed patterns. Our omphacite experiments provide a resolution of this uncertainty because the deformation fabrics and dislocation microstructures produced in the laboratory are indistinguishable from those found in natural eclogites, indicating that they have the same deformation mechanisms even though laboratory deformation is as much as 10 orders of magnitude faster than in nature. Straightforward interpretation of the mechanical data, microstructures and microfabrics leads to an internally consistent explanation of the deformation mechanisms without any fundamental assumptions.

As our results and previous studies of dislocation microstructure in naturally deformed omphacite have shown, the dominant glide systems in omphacite are $\{110\}[001]$, $\{110\}1/2\langle 110 \rangle$ and $(100)[001]$. The $(010)$
[001] slip system has never been reported as a dominant slip system in naturally or experimentally deformed omphacite. Therefore, neither the S-type nor L-type omphacite fabric can be explained by ‘easy glide’ on the (010)[001] slip system. This has led to the debate whether omphacite fabrics are formed by multiple slip systems \[2,6,11,19–21\] or diffusion creep with preferred growth and dissolution \[7,10\]. The latter requires extensive recrystallization and growth of omphacite crystals, which is not observed in our experimental samples. Diffusion creep is also not consistent with our mechanical data nor the observed high dislocation densities produced in our experiments and commonly observed in natural omphacite. Therefore, we conclude that omphacite is deformed by the combined slip systems of \{110\}[001], \{110\}1/2(110) and (100)[001], which have been shown by computer simulation to be capable of producing the observed fabrics \[12\].

The conclusion that omphacite favors multiple slip systems on \{110\} instead of a single slip system on (010) is easily explained by pyroxene crystallography which exhibits chains of SiO$_4$ tetrahedra parallel to [001] (Fig. 8). Forming dislocation glide planes on (100) would require either breaking of many strong bonds between the cations (M1) that connect to the apical oxygens of the tetrahedral chains or breaking fewer such bonds but at the same time development of severe corrugations in the glide planes, consisting of offsets along \{110\} planes. Slip on (010) planes would require less-severe corrugations in the glide planes but also would have to break many bonds between M1 cations and silicon-oxygen chains. In contrast, glide on \{110\} can be achieved by breaking primarily the much weaker bonding between the basal surfaces of SiO$_4$ tetrahedra and M2 cations (Na and Ca in omphacite). As a consequence, \{110\} slip will significantly lower the stress required for deformation. The orientation with the (010) plane parallel to the foliation is preferred because higher resolved shear stress on \{110\} planes are achieved with such orientation in omphacite \[12\]. The result, we believe, is that slip occurs dominantly on \{110\} planes and \{110\} planes are always under the tendency to rotate toward the higher shear strain orientations. Therefore, orientation of \{110\} planes with acute angles to the shear plane is preferred. Because (010) planes are bisectors of the acute angles between the two equivalent \{110\} planes in omphacite, (010) planes oriented parallel to foliation are achieved if the slip on (110) and (−110) is equal. Thus, such rotations also deflect [100] away from high shear stress orientations. This rationale is consistent with our observation of [100] maxima parallel to the intermediate principle strain in strongly rotational deformations (Fig. 5g,h). As a consequence, equal amounts of glide on (110) and (−110) parallel to [001] are equivalent to glide on (010)[001]. Indeed, such equal slip on those two planes is equivalent to slip on the hypothetical corrugated (010) plane, but provides greatly facilitated opportunities for dislocation cross slip and climb. The simpler and shorter slip geometry parallel to [001] rather than (110) explains why it is energetically more efficient for dislocations on \{110\} planes to have \textbf{b}=[001] than any other direction.

5.3. Variation between S-type and L-type fabrics

It has been well documented in deformed natural eclogites that there are two principle types of

Fig. 8. Omphacite slip systems. (a) Schematic projection of clinopyroxene structure. The TOT strips (shaded parts) represent the strong bonding and define the potential dominant dislocation glide planes. (b) Observed dominant slip systems in omphacite.
deformation fabrics in omphacite: S-type and L-type fabrics. The intermediate type fabric represents a combination of L-type fabric with S-type fabric (Fig. 1). This observation is often interpreted to reflect changes in deformation regime from compression to constriction [2,7]. However, a new hypothesis has been formulated recently, suggesting that this variation can also be produced by a temperature-dependent change in Burgers vectors related to an ordering of cations [11]. This new hypothesis involves the space group transformation from C2/c to P2/n in omphacite at temperatures around 750°C [36,37].

We have demonstrated here that a typical S-type omphacite fabric is produced in foliated samples under axial compression, whereas a typical L-type omphacite fabric is produced in lineated samples undergoing shear deformation (Fig. 5). This strong correlation between crystallographic fabric and shape fabric is consistent with previous observations in naturally deformed eclogite samples [2,7,10]. Because omphacite space group transformation is not involved during our experiments, we conclude that the variation between S-type and L-type omphacite fabric seen in our experimentally deformed omphacite is associated with the geometry of finite strain rather than omphacite space group transformation. The control of fabric by strain and rotation rather than stress or crystallography is clearly demonstrated by the simultaneous rotation of the L-maximum and the lineation defined by crystal elongation toward the shear plane with progressive strain in shear experiments. Strain and rotation control is also consistent with the prediction of computer simulation studies and observations of high-temperature mantle eclogite xenoliths [6,12,22].

In conclusion, the experimental results remarkably capture the essence of natural deformation textures and fabrics in omphacite. The much lower flow strength of omphacite than Ca,Mg clinopyroxenes also explains the large strains implicit in mesoscopic structures in deformed eclogites in deeply subducted basaltic rocks.

Acknowledgements

We thank Haemyeong Jung, Larissa Dobrzhinetskaya and Zhenmin Jin for constructive discussions of experimental procedures, and Frank Forgit for machining of parts for the sample assemblies, preparation and welding of the platinum capsules, and apparatus maintenance. Reviews and comments by D. Mainprice and H.L.M. Van Roermund are greatly appreciated.

This work was sponsored by US National Science Foundation (Grant no. EAR#0003631 to H.W. Green).

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