Contrasting dilatant behaviors of mafic and ultramafic rocks based on triaxial deformation experiments

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We performed triaxial deformation experiments on cylindrical specimens of mafic and ultramafic rocks to quantify their dilatant behaviors. Experiments were performed using an intra-vessel deformation and fluid flow apparatus at room temperature, a constant strain rate of $10^{-6}$ s$^{-1}$, and a confining pressure of 20 MPa. Axial and radial strains were monitored using strain gauges glued to the specimens. The onset of dilatancy of mafic rocks ranged from 41 to 64% of the maximum differential stress, and the inelastic volumetric strain reached $7 \times 10^{-3}$ at the maximum differential stress. These results are generally typical of crystalline rocks. Microstructural observation of recovered samples after deformation indicates that the dilatancy of mafic rocks were caused by opening of axial microcracks. In contrast, the onset of dilatancy of ultramafic rocks occurred at >77% of the maximum differential stress, and the inelastic volumetric strain at the maximum differential stress was less than $2.7 \times 10^{-3}$. These contrasting behaviors of dilatancy could be related to different crack modes developed during deformation, where shear microcracks along grain boundary were dominated in ultramafic rocks as is evident from a nearly random crack orientation along grain boundary. As dilatancy is related to the opening of microcracks, these contrasting dilatant behaviors of mafic and ultramafic rocks can lead to different modification of the physical and transport properties during brittle deformation.

Keywords: Dilatancy, Microcrack, Ultramafic rocks, Mafic rocks, Triaxial deformation

INTRODUCTION

The opening of microcracks during deformation causes increases in inelastic volumetric strain (i.e., dilatancy), and most crystalline rocks exhibit dilatancy prior to brittle failure (e.g., Brace et al., 1966). Dilatancy influences a rock’s physical and transport properties, including seismic wave velocity, electrical conductivity, and permeability (e.g., Paterson and Wong, 2005); consequently, understanding dilatancy provides significant insight into the geological processes in crust such as earthquake generation, volcanic eruption, and subsurface fluid flow (e.g., Scholz et al., 1973; Zoback and Byerlee, 1975; Fortin et al., 2011). Although the dilatant behaviors of granite and sedimentary rocks have been studied extensively (e.g., Brace et al. 1966; Scholz, 1968; Lockner et al., 1977; Wu et al., 2000; Lin et al., 2002; Takemura and Oda, 2005; Mitchell and Faulkner, 2008; Nicolas et al., 2016), few experiments have been conducted on mafic and ultramafic rocks (e.g., Rao and Ramana, 1974; Shimada et al., 1983). Dunite samples used by Rao and Ramana (1974) were partially serpentinized, which could have modified their deformation behavior, because serpentine is markedly weaker than olivine and deformation can be localized within serpentinized layers (Escartín et al., 2001). Shimada et al. (1983) performed triaxial deformation experiments and monitored acoustic emissions from various rock types, including dunite, gabbro, and eclogite, but the volumetric strain measurements during their high-pressure experiments had large uncertainties. In this study, we performed a series of triaxial deformation experiments of mafic and ultramafic rocks and compared those results to understand their contrasting behaviors during brittle deformation. Our results are thus particularly relevant to the influence of dilatancy on the oceanic lithosphere.
EXPERIMENTAL DETAILS

Samples

We used mafic granulite (YA-13) and diabase (BG-4) as mafic rock samples and two peridotites (YA-01 and YA-04) as ultramafic rock samples for deformation experiments. The mineral assemblage, grain size, bulk density, and apparent porosity of these samples are listed in Table 1. Mafic granulite (YA-13) was collected from the Horoman Complex, Japan, and diabase (BG-4) was collected from the Belfast Complex, South Africa. These samples consist mainly of clinopyroxene and plagioclase, with minor amounts of olivine, and chromian spinel. The mafic granulite has a weak macroscopic foliation and a mosaic equigranular texture, indicating solid-state plastic deformation and grain boundary migration (Takazawa et al., 1999). For the mafic granulite sample, blocks were cored subparallel to the foliation. The Belfast diabase has an ophitic texture that is commonly observed in diabase. Peridotite samples (YA-01 and YA-04) were collected from the Horoman Complex, Japan. Peridotite samples are composed mainly of olivine with orthopyroxene porphyroclasts, without serpentine minerals. These samples were cored and prepared as a cylindrical specimen 20 mm in diameter and 40 mm in length, with flat end surfaces were ground parallel to within 0.01 mm. All specimens were dried in an oven at 70 °C for at least 24 h prior to the deformation experiments, and experiments were performed under dry conditions.

Deformation experiments

Triaxial compression tests were performed using an intra-vessel deformation and fluid flow apparatus (Fig. 1) at Hiroshima University, Japan; for apparatus details, see Tanikawa and Shimamoto (2009). Axial and radial strains were measured with two pairs of strain gauges (FCA-10–11, Tokyo Sokki) glued directly on the centers of the specimens opposite to each other. Strain data were monitored with a data recorder (EDX-100A Universal Recorder, KYOWA) at a sampling rate of 1 Hz. The specimens were jacketed in three layers of polyolefin (0.4 mm in thick) to separate them from the oil confining medium in the pressure vessel. All experiments were performed at a constant displacement rate of ~ 0.003 mm/min (corresponding to a strain rate of ~ 10^-6 s^-1) at room temperature and a constant confining pressure of 20 MPa. Confining pressure was controlled by a servo-system to compensate for the advanced piston volume during deformation. Differential stress was accurate to ~ 0.5 MPa because of the electrical noise in recording. Due to the lack of a high-resolution feedback system in our apparatus, we focus on the evolution of strain approaching the maximum differential stress, but not during the post-failure process.

Strain Analysis

We measured axial (ε_a) and radial (ε_r) strain during the triaxial deformation experiments. Volumetric strain (ε_v)
was calculated as
\[ \varepsilon_v = \varepsilon_a + 2\varepsilon_e. \]

In the experiments, compressive strain was taken as positive, and extensional strain as negative. All strain values were averaged from two strain gauges to minimize the heterogeneity within the specimens. Stress–strain curves were constructed up to the maximum differential stress \( \sigma \).

From the volumetric strain curve, elastic compaction is observed until a critical stress \( \sigma' \), beyond which volumetric strain deviates from a linear relationship. The onset of dilatancy commonly occurs at approximately half of the maximum stress (Paterson and Wong, 2005). Therefore, we calculated the linear relationships for each stress–strain curve between 15 and 35% of the maximum differential stress. The difference between the volumetric strain and the extrapolated elastic strain was defined as \( D \), which represents an inelastic volumetric strain corresponding to the amounts of dilatancy. \( \sigma' \) is defined as the stress at which the inelastic volumetric strain exceeds \( 0.05 \times 10^{-3} \), similar to previous experiments (e.g., Sawayama and Katayama, 2016). Young’s modulus \( (E) \) and Poisson’s ratio \( (\nu) \) were calculated from the linear elastic portions of the axial and radial strain curves.

**Microstructural observations**

Recovered samples after deformation experiments were first impregnated with epoxy and cut along parallel to the loading axis to prepare polished thin sections for observation with optical and scanning electronic microscope (SEM). The stereological measurements were performed for both undeformed and deformed samples. The number of crack intersections with test lines spaced at 0.1 mm was counted in the areas close to fault plane, according to the previous analyses by Underwood (1970). The selected areas were observed by SEM (JXA–8200, JEOL) with a voltage of 15 kV. Measurements were made in directions at angles with 15° step from the perpendicular to \( \sigma_1 \) (Nemati and Stroeven, 2001). At each angle \( \theta \) the linear intercept density \( P_L(\theta) \) (number of crack intersections per unit length) was calculated. The anisotropy factor of crack distribution \( \Omega_{23} \) was calculated as follow:

\[ \Omega_{23} = \frac{P_L(90^\circ) - P_L(0^\circ)}{P_L(90^\circ) + (4/\pi - 1)P_L(0^\circ)}, \]

which represents ratio between the surface area of cracks aligned parallel to \( \sigma_1 \) and the total crack surface area (Wong, 1985).

**RESULTS**

**Mechanical data**

Experimental results are summarized in Table 2, and stress-strain curves for each rock type are illustrated in Figure 2 and Figure S1 (Figure S1 is available online from https://doi.org/10.2465/jmps.181120). The maximum differential stress \( (C) \) varied among rock types, even at the same confining pressure. The mafic granulite from the Horoman complex and the Belfast diabase yielded similar maximum differential stresses that ranged from 574 to 620 MPa. The Horoman peridotites reached a maximum differential stress of up to 480 MPa. These results indicate that the mafic rocks are much stronger than the ultramafic rocks.

During elastic deformation, the slope of the axial strain curve and the ratio between axial and radial strains represent Young’s modulus and Poisson’s ratio, respectively. Mafic rocks in our experiments have Young’s modulus of 105–125 GPa. Ultramafic rocks yielded a steep stress-strain curve and have Young’s modulus of

<table>
<thead>
<tr>
<th>Rock type (Sample)</th>
<th>Run No.</th>
<th>( C ) (MPa)</th>
<th>( C'/C ), %</th>
<th>( D_{mx} \times 10^{-3} )</th>
<th>( E ), GPa</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diabase (BG-4)</td>
<td>IVA1472</td>
<td>618</td>
<td>41.1 ± 1.8</td>
<td>6.52 ± 0.08</td>
<td>105.1 ± 0.7</td>
<td>0.233 ± 0.010</td>
</tr>
<tr>
<td></td>
<td>IVA1486</td>
<td>620</td>
<td>62.3 ± 0.3</td>
<td>9.89 ± 0.01</td>
<td>110.2 ± 0.0</td>
<td>0.262 ± 0.002</td>
</tr>
<tr>
<td>Mafic granulite (YA-13)</td>
<td>IVA1493</td>
<td>611</td>
<td>63.9 ± 1.1</td>
<td>7.03 ± 0.01</td>
<td>125.2 ± 0.6</td>
<td>0.287 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>IVA1501</td>
<td>574</td>
<td>53.1 ± 3.4</td>
<td>6.67 ± 0.03</td>
<td>123.7 ± 0.3</td>
<td>0.266 ± 0.004</td>
</tr>
<tr>
<td>Peridotite (YA-01)</td>
<td>IVA1491</td>
<td>396</td>
<td>77.4 ± 2.3</td>
<td>2.69 ± 0.01</td>
<td>150.6 ± 0.2</td>
<td>0.262 ± 0.002</td>
</tr>
<tr>
<td></td>
<td>IVA1494</td>
<td>378</td>
<td>81.0 ± 4.8</td>
<td>1.19 ± 0.03</td>
<td>152.1 ± 1.1</td>
<td>0.266 ± 0.006</td>
</tr>
<tr>
<td>Peridotite (YA-04)</td>
<td>IVA1492</td>
<td>452</td>
<td>80.5 ± 5.0</td>
<td>2.37 ± 0.04</td>
<td>170.3 ± 1.2</td>
<td>0.263 ± 0.008</td>
</tr>
<tr>
<td></td>
<td>IVA1495</td>
<td>480</td>
<td>88.6 ± 1.4</td>
<td>1.54 ± 0.03</td>
<td>174.8 ± 1.0</td>
<td>0.272 ± 0.006</td>
</tr>
</tbody>
</table>

\( C \), maximum differential stress; \( C' \), stress at onset of dilatancy; \( D_{mx} \), maximum inelastic volumetric strain; \( E \), Young’s modulus; \( \nu \), Poisson’s ratio. The experimental errors were estimated from the calculation uncertainty of the linear relationship between stress and strain.
151–175 GPa, more than twice that of fine-grained granite under similar conditions (68.5–69.2 GPa; Sawayama and Katayama, 2016). The Poisson’s ratios of mafic and ultramafic rocks are similar to each other (0.233–0.287).

At high differential stress, the volumetric strain deviates from the linear elastic relationship at a critical stress $C'$, which represents the onset of dilatancy. In the present study, the values of $C/C'$ for mafic rocks ranged between 41 and 64%, which are typical of intact rocks (Brace et al., 1966). In contrast, the onset of dilatancy was delayed in the ultramafic rock samples, which show >77%. At stresses above $C'$, the inelastic volumetric strain ($D$) increased as samples approached failure (Fig. 3). Mafic rocks reached maximum $D$ ($D_{\text{max}}$) ranging from $6.52 \times 10^{-3}$ to $9.89 \times 10^{-3}$, which is similar to that of granite under the same confining pressure ($8.3 \times 10^{-3}$–$9.0 \times 10^{-3}$; Sawayama and Katayama, 2016). On the other hand, ultramafic rocks had much lower inelastic volumetric strain of $1.19 \times 10^{-3}$ to $2.69 \times 10^{-3}$.

**Structural observation**

Samples recovered after deformation experiments show macroscopic fault planes, which develop at an angle of approximately 30° from the loading direction. Ultramafic rock samples show failure occurred along a single macroscopic fault; however, mafic rock samples are characterized by a conjugated fault planes. This likely reflects different damage zones during brittle deformation between...
in ultramafic rocks, microcracks could be formed and localized near the fault plane, whereas, in mafic rocks, microcracks could be developed pervasively in the specimens.

The stereological measurements were performed with backscattered electron images (Fig. 4). The mean and standard deviation values of the stereological parameters of deformed samples are summarized in Table 3 and rose diagrams of linear crack density at a given angle for each deformed and undeformed sample are shown in Figure 5. The linear crack density is markedly increased after deformation compared to that of starting material. Although the crack density of undeformed ultramafic rocks was initially higher than that of mafic rocks, the increasing crack density after deformation was relatively small in ultramafic rocks. In mafic rocks, microcracks were mainly developed subparallel to the loading axis (Figs. 5a and 5b). Crack density normal to the loading axis \( P_{L}(90^\circ) \) was significantly larger than that parallel to the loading axis \( P_{L}(0^\circ) \), resulting in high value of anisotropy factor \( \Omega_{23} \), which is similar to those of the other crystalline rocks reported by previous studies (e.g., Wong, 1985; Fortin et al., 2011). On the other hand, nearly random orientation of microcracks were observed in ultramafic rocks (Figs. 5c and 5d), and no clear difference between \( P_{L}(90^\circ) \) and \( P_{L}(0^\circ) \) was observed for deformed ultramafic rock samples, resulting in low \( \Omega_{23} \).
DISCUSSIONS

Different dilatant behavior between mafic and ultramafic rocks

In our experiments, ultramafic rocks showed the late onset of dilatancy close to failure ($C'/C > 77\%$) and the lack of significant volume increase ($D_{\text{max}} < 2.7 \times 10^{-3}$). This is contrasting to mafic rocks exhibited typical dilatant behavior, where the onset of dilatancy occurred at 41–64% and a marked volume increase prior to macroscopic failure ($D_{\text{max}} > 6.5 \times 10^{-3}$). A number of previous studies have shown that dilatancy is caused by the opening of axial (mode I) microcracks, which likely formed at the tips of pre-existing cracks due to the local tensile stress concentration (e.g., Brace and Bombolakis, 1963; Cotterell and Rice, 1980; Nicolas et al., 2016). However, Esclàrtín et al. (1997) found that, in serpentinites, the onset of dilatancy occurred immediately prior to failure, and no significant dilation occurred. They observed microcracks aligned subparallel to the (001) cleavage in serpentine, and the damage zone was localized near the fault in the recovered samples after deformation. These non-dilatant behaviors in serpentinites could be related to deformation mainly accommodated by shear sliding along the basal plane, which results in negligible volume increase.

In this study, we observed anisotropic crack formation in mafic rocks, with a preferred orientation parallel to $\sigma_1$ (Figs. 5a and 5b), suggesting that dilatancy in mafic rocks was caused by opening of axial microcracks (mode I cracks) as well as the other crystalline rocks (e.g., Brace et al., 1966). In contrast, nearly random crack orientation and highly localized distribution close to fault plane (Figs. 5c and 5d) were observed in ultramafic rocks. These observations indicate that the brittle deformation of ultramafic rock is related to shear (mode II) microcracking, which attributed to a relatively minor amount of dilatancy. Shear microcracks in ultramafic rocks were observed mainly along grain boundaries of olivine, suggesting that shear microcracking along grain boundary is easier than axial microcracking in ultramafic rocks. Since the grain boundary sliding is frequently recognized in deformed olivine aggregates (e.g., Marquardt and Faul, 2018), elastic strain could be accommodated at grain corners or steps on grain boundaries rather than axial microcracking even in the brittle regime.

According to Esclàrtín et al. (1997), the mechanical response to the style of microcracking was related to the brittle and plastic deformation regimes by comparing onsets of dilatancy and yielding. Yielding stress ($\sigma_y$) is defined as a stress beyond which axial strain curve deviates from the linearity. Figure 6 shows the plot of $C'/C$ versus $\sigma_y/C$ for various rock types. Based on previous experimental data, deformation is mainly accommodated by axial microcracking at relatively low $C'/C$ and $\sigma_y/C$, whereas shear microcracking becomes dominant at higher $C'/C$ and $\sigma_y/C$. Our experimental results indicate that mafic rocks have relatively low $C'/C$ and $\sigma_y/C$ and were plotted at similar area to the other dilatant rocks. On the other hand, ultramafic rocks tend to have higher $C'/C$ and $\sigma_y/C$,
similar to serpentinites, which indicates that the brittle deformation of ultramafic rocks could be associated with shear microcracks (Fig. 6).

Possible influence on physical and transport properties

Physical and transport properties such as seismic wave velocity and permeability are strongly influenced by the opening of microcracks, because these properties are closely related to the pore microstructures in rocks (e.g., Guéguen and Palciauskas, 1994). Since the formation and growth of axial microcracks are characterized by dilatancy, differences in dilatant behavior between mafic and ultramafic rocks can result in the different evolutions of these physical and transport properties during deformation. In mafic rocks, marked dilation during deformation may cause a large decrease in seismic wave velocity and a large increase in permeability (e.g., Mitchell and Faulkner, 2008; Fortin et al., 2011; Zaima and Katayama, 2018). In contrast, the relatively small dilation of ultramafic rocks means that the physical and transport properties of an ultramafic rock layer is not significantly modified due to the small amounts of opening of axial microcracks until failure occurs. David et al. (2018) measured elastic wave velocity during triaxial deformation using antigorite serpentinite and found no significant decrease in elastic wave velocity even prior to failure due to the lack of dilatancy. Brace et al. (1966) performed high pressure experiments and reported dilatancy even at confining pressure up to 800 MPa. In such a case, brittle fracturing across the crust-mantle boundary might cause differences in the development of microcracks, resulting in marked contrasts in physical and transport properties at this lithological boundary.

CONCLUDING REMARKS

This study presents the experimental results that document the evolution of strain during triaxial deformation of mafic and ultramafic rocks. We found that dilatant behavior is remarkably different between mafic and ultramafic rocks. Mafic rocks had typical dilatant behavior in terms of both the onset of dilatancy ($C'/C = 41–64\%$) and the maximum amounts of dilation ($D_{\text{max}} = 6.52–9.89 \times 10^{-3}$). In contrast, ultramafic rocks displayed atypical dilatant behavior characterized by the later onset of dilatancy ($C'/C = 77–89\%$) and relatively small amounts of dilatancy ($D_{\text{max}} = 1.19–2.69 \times 10^{-3}$). This unique dilatant behavior of ultramafic rocks could be related to the shear microcracks along grain boundaries. Since dilatancy greatly influences physical and transport properties such as seismic wave velocity and permeability, the different dilatant behaviors between mafic and ultramafic rocks can lead to different modification of these properties during brittle fracturing.

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SUPPLEMENTAL MATERIAL

Supplementary Figure S1 is available online from https://doi.org/10.2465/jmps.181120.
REFERENCES


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