Shock-induced deformation features in terrestrial peridotite and lunar dunite

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ABSTRACT—Single crystals of terrestrial olivine (Fo85) were experimentally shock-loaded (8000 g) to peak pressures of 340, 330, and 440 kbar and the resulting deformation features were compared to those present in olivine from lunar dunite 72415. Recovered fragments were examined on the Universal stage to determine the orientation of the plane fractures. With increasing pressure the percentage of pinacoids (1100), (1000), and (0011) and prisms (1400), (1001), and (0011), decreased 0 to 20%, whereas the percentage of pyramidal (a 31) increased 20-50%. The complexity of the dislocation of pyramidal (a 31) increases with increasing pressure. Other shock-induced deformation features, including varying degrees of orientation, are found in dunite and dunite of similar orientation, as observed by others. Lunar dunite 72415 was examined and found to contain olivine with well-developed shock-deformation features. The relative proportion of pinacoids, prism, and pyramidal (a 31) structures measured for olivine from 72415 indicates that this rock appears to have undergone shock pressure in the range 330-460 kbar. It displays a predominate pyramidal (a 31) alignment along (2 k + 1) planes which have not previously been reported in laboratory or naturally shocked specimens.

If this dunite was brought to the surface of the moon as a result of ejection of an asteroid event-sized impact crater, the shock pressure range experienced by the sample and the results of cratering calculations suggest that it would have originated no deeper than 90-150 km.

1. INTRODUCTION

In order to understand the effects in olivine caused by shock-loading, it is useful to compare deformation features in specimens shocked in well-defined laboratory experiments with deformation features displayed in olivine which is naturally shocked. Previously, Carter et al. (1968) shocked dunite, harzburgite, and single crystals of fayalite in the peak-pressure range 0.15-5.0 mbar. They observed: (1) a well-developed fracture and local undulatory extinction at 0.15-0.2 mbar, (2) a pervasive mosaic structure at 0.25 to 0.5 mbar, and (3) abundant recrystallization at 1.0 mbar with all gradations between. This scheme was then used to quantify the shock pressures necessary to cause the deformation features exhibited in olivine from twenty-five chondrites.

Müller and Harnann (1969) also shocked olivine crystals and a single-polycrystalline specimen from an olivine nodule and reported "planar deformation structures parallel to (100), (110), (001), (130), and (161) (bipyramids) together with irregular fractures, undulatory extinction, and mosaicite. They also observed that the crystallographic orientation of the bipyramids was dependent upon the shock-wave propagation direction. Planar structures parallel to (130) and..."
(bd) are considered by Müller and Hartmann to be characteristic of shock. They observed these orientations in olivines from ten chondrites (L-group) which are thus inferred to have undergone shock deformation. However, Levi (1973) has reported pinacoidal, prismatic, and bipyramidal cleavages may be induced in olivine by repeated and severe thermal cycling.

Sclar (1969), on the other hand, shock-honed crushed fractions (0.1-0.3 mm) of single-crystal olivine at about 200-400 kbar. He reported planar features (fractures that broke each olivine grain into a mosaic of slightly misoriented blocks) parallel to pinacoids (001), (001), and (010) and rarely parallel to domes (010) or (010) and prisms (001). Sclar and Moretti (1971) have reported shock-induced features in the Chassigny meteorite.

Short (1969) and James (1969) have examined the deformation features resulting in olivine in an olivine trachybasalt shock metamorphosed by the nuclear explosion. Danny Boy, Short (1969) established the dependence of deformation features on the degree of shock and observed features similar to those discussed above.

In addition, James (1969) distinguished five degrees of progressive shock metamorphism ranging from “weak” to “intense.” In weakly to moderately strongly shocked rocks, olivine exhibits undulatory extinction and deformation lamellae. Moderately strongly and strongly metamorphosed rocks contain olivine with “mosaic extinction and unique lamellar structures.” These lamellae commonly develop near [001], in the region of the twins [112], [122], and [111], and in a region broadly centering on [131].

With the relatively recent availability of lunar samples, another natural material is being examined for shock-deformation features. Engelhardt et al. (1976), Sclar (1970), Short (1970), and Short (1970), and others have described shock-deformation features in olivine in lunar basalts, breccias, and fines.

In this report, we present some additional results of shock-loading experiments on olivine. We have shocked single-crystal olivine to peak pressures 280, 330, and 440 kbar for the purpose of using the orientation of planar fractures, as defined by Stöffler (1972), as an indicator of the peak shock pressure experienced by an olivine-hearing natural sample. We have also examined the planar fractures of Juba dunite, 72415.

2. Experimental Methods

Single crystals (6 × 6 × 1 mm) of olivine (pale yellow from Arizona, about 40%) were implanted with tungsten projectiles that were launched with a high-performance propellant gun. Shock was propagated by shock waves (0.1) of the olivine crystals that were individually embedded in NaNO3 that was then mounted in a large block of NaCl and backed up by an aluminum plate. The assembly was encased in a steel jacket.

We employed the implosion match method (Walsh and Christiansen, 1955) utilizing the Hopkinson equations of state of tungsten (McQueen et al., 1970), the Twin Sister Plutus dunite (McQueen et al., 1970) and the measured projectile velocities. For the three rates, projectiles velocities were 1431 ± 0.02, 167 ± 0.02, and 214 ± 0.02 km/s with resultant shock pressures of 280 ± 5, 330 ± 6, and 440 ± 7 kbar, respectively.

After dissolving the halides, the olivine grains were retrieved, mounted in epoxy, hand-polished, and examined on a 4-mm Zeiss Universal stage to determine the orientation of laminate fractures.
3. Results

(a) Petrographic description

It has been well established that planar fractures are a definite effect of shock deformation in olivine. Planar fractures are defined to be open fissures occurring in parallel sets (Stöffler, 1972). In this study, however, some of the fractures may be singular but, by their planar nature and precise orientation, distinguishable from irregular fractures. Also, euhedral and subhedral (Horz, 1960) are combined as planar fractures, since grain mounts were used to examine the experimentally shocked olivine. Thus, inasmuch as the original grain boundaries of olivine in the lunar dunite are usually absent, any distinction between faults or cleavages is

Table 1 lists the planar fractures which have been produced by shock deformation (except perhaps some of the features parallel to [010] and less frequently [100] observed in the unshocked crystals). There is a distinct decrease in the percentage of prisms [010], [010], and [001] and of pyramids [101], [010], and [010] with increasing shock pressure whereas the percentage of bipyramids increases with increasing pressure.

Some examples of planar fractures formed during 280-kbar shock-loading are shown in Fig. 1. Irregular fractures, undulatory extinction, and some planar elements were observed, in addition to what were clearly planar fractures. There was no petrographic evidence of recrystallization. (The descriptive terms used are defined by Stöffler (1972).)

Figure 2 illustrates some planar fractures formed during 336-kbar shock-loading. In addition, irregular fractures, undulatory extinction, deformation bands, and planar elements were well developed. Distinct mica sheeting and recrystallization were minor features on a microscopic scale.

Figure 3 contains examples of deformation features observed after a 440-kbar shock. Besides the planar fractures, some grains recovered from the sample were completely recrystallized. Planar elements, irregular fractures, undulatory extinction, deformation bands, and possibly mosaicism were well developed. Recrystallized fragments, themselves, were often fractured.

Table 1. Shock-induced planar fractures in experimentally shock-loaded olivine crystals and in lunar dunite 73415.

<table>
<thead>
<tr>
<th>Shock pressure (kbar)</th>
<th>Number of fractures</th>
<th>Number of crystals</th>
<th>Planar fractures</th>
<th>Bipyramidal fractures</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>42.5</td>
</tr>
<tr>
<td>336</td>
<td>64</td>
<td>6</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>440</td>
<td>13</td>
<td>5</td>
<td>3</td>
<td>28</td>
</tr>
<tr>
<td>lunar dunite</td>
<td>10</td>
<td>4</td>
<td>2</td>
<td>29</td>
</tr>
</tbody>
</table>
Fig. 1. Photomicrographs in plane-polarized light of fractures resulting from 280-kbar shock pressure. Miller indices of fractures are indicated. (a) Sample No. 272-1-3, (b) Sample No. 272-2-1, (c) Left sample No. 272-1-1. Note the several well-developed fractures for (040) and (300).

Fig. 2. Planar fractures resulting from 380-kbar shock pressures. (Plane-polarized light.) (a) Sample No. 283-1-3, (b) Sample No. 283-1-1. (c20) planar fracture at high angle to the plane of the photomicrograph.
(b) Orientation of deformation features

The crystallographic orientations of the planar fractures observed in experimentally shock-loaded olivine (Fig. 4) are uncertain by at least 10° (due to undulatory extinction). This is strikingly exhibited by the scatter of the pinacoids.

Figure 4 (A-C) indicates that there is a tendency toward the development of bipyramids with increasing pressure. The majority of points in (A) are near the (111) planes. There are relatively few scattered points in (B). Figure 4 (B) shows a distinct increase of bipyramids with increasing pressure while the number of pinacoids decreases and prisms remain approximately the same as in (A). The majority of bipyramids lie near the h = k planes and the h = -k planes. Finally, (C) shows the significant increase of the percentage of bipyramids with increasing pressure while the percentage of pinacoids and prisms decrease.

(c) Shock-deformation features of lunar dunite 72415

Lunar dunite 72415 from Apollo 17, Station 2 in the lunar highlands, has been described by Albee et al. (1970). The dunite is described as "rounded clasts."
composed of large (to 50 mm) single crystals of pale-green, translucent olivine... enclosed in a granular, white matrix composed predominantly of olivine. The matrix formed simply by crushing without recrystallization and has the same composition (Forsterite) as the olivine clasts. Other minerals include plagioclase, Cr spinel, pyroxene, and Fe metal.

The large-olivine clasts exhibit many deformation features resulting from significant shock pressure. These features include trephine fractures, planar fractures, which occur singly and in sets, very well-developed deformation bands, planar elements, some isolated mosaicism, and a very few completely recrystallized grains (Fig. 5C).

The planar fracturing is very well developed in this section 72415.11. When this thin section was prepared, it was ground to ~0.005-0.01 mm (so that the olivine exhibits plagioclase interference colors). The result has been the very excellent expression of the shock-deformation features.

Examination of Fig. 4D and Table 1 illustrates that the planar fracture orientations place the shock pressure that affected lunar dunite 72415 between 930
and 440 kbar which is not dissimilar to the 400 ± 50-kbar pressure suggested by Albett et al. (1979). Many of the (hkl) pyramids, however, appear to occur along the (0, h = k) plane in 72415, which is not present in the experimentally shocked olivine. The recrystallization occurring along fractures depicted in Fig. 5C was not observed in laboratory-shocked olivine. This feature has not been described before.

4. DISCUSSION

In our laboratory experiments there is a distinct increase in the complexity of distribution of (hkl) pyramids from 380 to 440 kbar, while the percentage of pinacoids and prisms decreases. The increase of recrystallization features with pressure, i.e. none at 280 kbar, minor areas at 330 kbar, and some grains completely recrystallized at 440 kbar is also significant.

This increased complexity with pressure is reasonable in light of recent work by Heinrich et al. (1975). They calculated elastic stresses and self-energies of dislocations and found that increased energy is necessary to create dislocations along directions with more complex Miller indices. Presumably such lines of
dislocations could provide lines along which the observed planar elements develop during deformation. We infer that the orientation of planar fractures and the degree of recrystallization when combined with other shock-induced deformation features, which have been shown (Carter et al., 1968; Short, 1969; James, 1969) to vary with shock intensity, can be used to help establish the degree of shock experienced by olivine.

It must be noted that the predominance of prisms near (136) observed by Müller and Hornemann (1969) for planar features in experimentally shocked olivine and olivine in meteorites, and by Engelhardt et al. (1970) for olivine in lunar samples, was not observed in this experiment, but we have not examined olivine shocked in different orientations. Fractures near prisms in our experimentally shocked samples appear to be randomly distributed.

Recently, O'Keefe and Ahrens (1975) have carried out hypervelocity flow calculations which define the maximum depth to which a given shock pressure penetrates a lunar-type crust during a major basin-forming impact. By scaling from terrestrial explosion craters, estimates of meteors' kinetic energy for a crater of Imbrium dimension, range from $-1.4 \times 10^{17}$ to $-9 \times 10^{16}$ ergs. Scaling the calculated dynamic pressure distribution in gabbroic anorthosite to infer the maximum depth range for a shock pressure of $-330 \text{kbar}$ yields depths in the $50-150 \text{ km}$ range. By using the gabbroic anorthosite as a model for the average lunar crust, in the shock wave propagation calculation we are really assuming that the thickness of a hypothetical dunite body is much less than the inferred depth range. If dunite comprised a significant portion of the primordial lunar crust, qualitatively we would expect the present estimates of the maximum depths of origin to increase. Thus, if the present sample is an ejecta fragment from a "deep" estimate, as its homogeneity and large grain size suggest, that was excavated by such an event, we can infer that it could have come from a depth as great as $-50-150 \text{ km}$. Of course, a shallower position for the time when it was subjected to shock cannot be precluded.

5. Summary

The orientation of planar fractures and the degree of recrystallization of experimentally shock-loaded single crystals of olivine can be used as a standard against which shock deformation features shown by natural materials can be compared. Limitations exist, however, in the completeness of the present single-crystal data with regard to comparison with features exhibited by polycrystalline rocks. Nevertheless, the planar fractures exhibited by the olivine in lunar dunite, 724.5, when compared with planar fractures in single crystals shock-loaded along (010), indicate that the dunite was subjected to a $-330-440 \text{kbar}$ shock pressure on the basis of comparing the percentage of pinacoids, prisms, and pyramids to corresponding percentages in experimentally deformed olivine. Although recrystallization occurs in the dunite, it is not as well developed as it is in the olivine that was shocked to $440 \text{kbar}$ in the laboratory. If deformation bands, planar features, recrystallization and/or massifs in this dunite are compared to the Cutter et al. (1969) shock scheme, their shock-pressure criteria would place this dunite within
the heavy to very heavy pressure range (~0.25–0.50 mbar) in agreement with the present results.

It has been shown that the orientation of planar fractures within the 280–440-kbar shock-pressure range for 1010 oriented crystals is dependent upon shock pressure. With increasing shock pressure, the percentage of pinacoids and prisms decreases while the percentage of bipyranyds increases. In addition, the complexity of the crystallographic distribution of bipyranyds increases with shock pressure. The amount of recrystallization also increases with increasing pressure.

This relationship, plus the dependence of other shock-induced deformation features upon pressure, indicates that lunar dunites (72415) was probably subjected to shock pressures greater than 330 kbar but probably less than 440 kbar. Also, hypervelocity flow calculations infer a maximum depth of origin of ~50 to ~150 km if this sample was shocked and excavated by a major basalt-forming hypervelocity impact in a predominantly gabbroic anorthosite crust.

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REFERENCES


Short N. M. (1968) Shock metamorphism of basalt. Modern Geology 1, 81-95.

