Reports

New Technique for Decorating Dislocations in Olivine

Abstract. *Oxidation of iron-rich olivine induced in the laboratory causes preferential precipitation on lattice dislocations. This simple dislocation decoration technique greatly reduces the cost and time involved in surveying the dislocation structures of deformed olivine crystals and opens the way to a more thorough understanding of the deformation of this important geologic material.*

The high-temperature mechanical behavior of olivine, the primary (~ 75 percent) mineral in the earth's upper mantle, is a topic of particular importance to geophysicists. Convective flow in the mantle, which to a first approximation can be considered to be flow of olivine, is coupled to the large-scale motion of the overlying lithospheric plates and is manifested as continental drift. Models of the convective flow field in the mantle are highly dependent on the creep properties of olivine. Laboratory measurements of the relationship between the macroscopic creep parameters—stress, strain rate, and temperature—have been made by several research groups in the past 6 years. More recently, the defect microstructure generated during creep experiments on olivine and olivine-rich rocks have been investigated in some detail. Confident extrapolation of creep data obtained in the laboratory on a time scale of hours (10^{-4} year) to problems involving geologic times of millions of years (10^6 years) requires the establishment of a one-to-one correspondence between the mechanisms governing plastic flow in these two diverse conditions. For this reason, there has been particular interest in understanding the relationship between the imposed macroscopic conditions and the resulting dislocation microstructures. Extensive observations of the dislocation microstructures of naturally and experimentally deformed olivines have been reported (*1–4*). We report here a refinement of an experimentally simple technique for decorating dislocations in olivine to permit their study in the transmission optical microscope (Figs. 1 and 2).

For the deformation conditions experienced in the mantle, plastic flow proceeds by the glide and climb motion of dislocations within individual olivine grains. Direct observations of the resulting dislocation structures have been made primarily by transmission electron microscopy (TEM), although a few studies of dislocation distributions have been accomplished by x-ray topography (*3*), chemical etching of polished surfaces (*1, 5*), and decoration by the heterogeneous precipitation of Mn added to the olivine before deformation (*1, 6*). The oxidation decoration technique described here provides information on the dislocation structure of olivine which is quite different from and complementary to that obtained by TEM. In addition, unlike the Mn decoration scheme, the oxidation technique does not alter the location or distribution of dislocations.

To decorate the dislocations in olivine, a sample with one polished face is heated in air for 1 hour at 900°C. A standard 30-μm petrographic thin section is then prepared with the previously polished face in contact with the glass slide. For most crystallographic directions, dislocation lines as far as 50 μm from the polished face are decorated. A minimum decoration depth of 5 μm is observed for a grain thinned parallel to the (010) plane.

Decorated thin sections of olivine have a reddish color. X-ray and TEM studies by ourselves (*7*) and others (*8*) have shown that decoration results from the precipitation of platelets of a silica phase and of either magnetite or hematite normal to the dislocation lines. The platelets are approximately 0.01 μm thick and 0.5 μm across. In addition, globular enstatite regions 0.2 μm in extent exist near the dislocation lines. A study of the stability field to oxidation and reduction of iron-bearing olivines has recently been published (*9*). The precipitates in natural iddingsite likewise decorate the dislocation structure and most likely occurred through the same oxidation reaction, with later alteration of the precipitates to low-temperature hydrates.

The feature of the oxidation technique which makes it particularly valuable for the study of deformation-produced dislocation structures is that the decoration is accomplished under conditions of temperature and time for which the dislocations are practically immobile. For free dislocation densities of the order of 10^8 cm^{-2}, no observable rearrangement of dislocation occurs after annealing at 1000°C for 1 hour. At higher temperatures, the dislocation mobility increases and for the same annealing time the interaction stresses of neighboring dislocations cause ordering of the dislocations into low-angle boundaries (*4*).

Contrasted with TEM samples, decorated specimens have significantly larger volumes which can be observed. The decoration can easily extend over an area of 10^8 μm^2 and to a depth of 10 μm, compared to 10^4 μm^2 and 1 μm for 1-Mev TEM. As a result, dislocation studies are enhanced in three distinct ways in a decorated thin section.

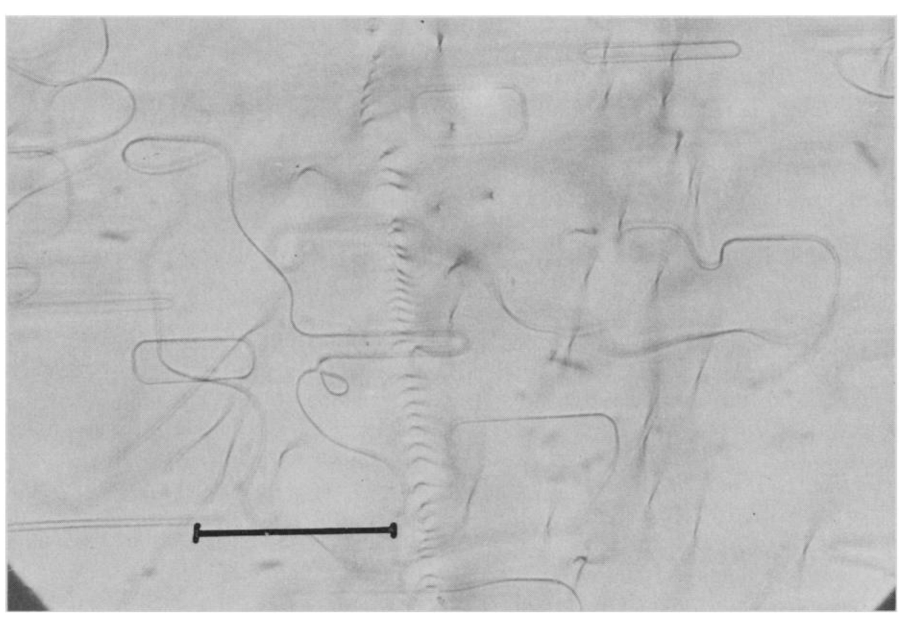

Fig. 1. Low density of decorated dislocations in an olivine-rich xenolith from Kilbourne Hole, Texas. Note the low-density, north-south trending tilt boundary piercing the field of focus. Scale bar, 50 μm.

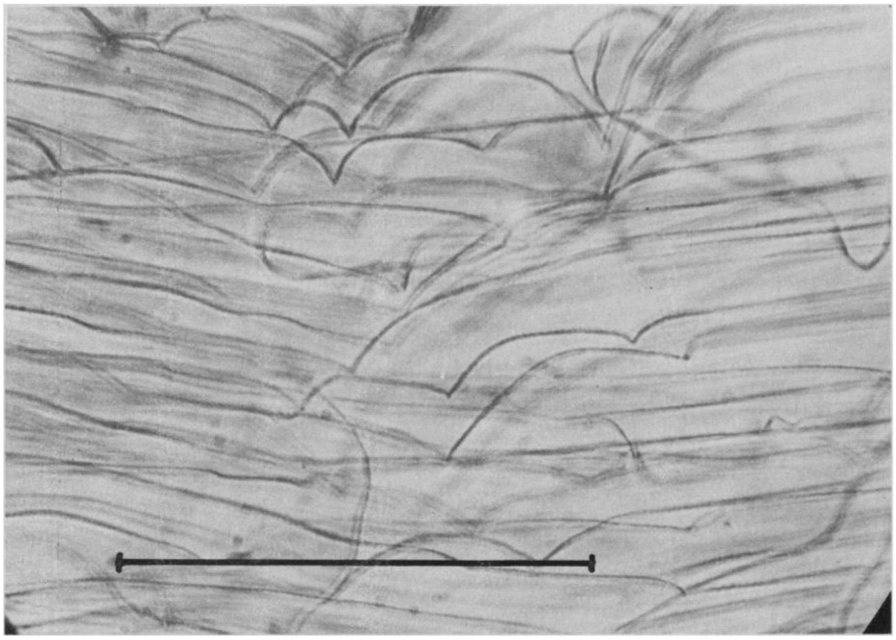

Fig. 2. Network of bowed-out screw dislocations in an olivine-rich xenolith from Salt Lake Crater, Hawaii. Scale bar, 50 μm.

1) The great depth of decoration provides an excellent impression of the three-dimensional aspects of the dislocation structure. With the depth of field of the petrographic microscope reduced to a few micrometers, small changes in the focusing level allow a vertical tour through the thin section. A similar effect is obtained by TEM or x-ray topography only through stereophotography and serial sectioning.

2) The large lateral extent of a decorated thin section permits a study of the variation of the dislocation structure within a grain and from grain to grain in a polycrystalline aggregate. Dislocation structures resulting from partial recrystallization and from small thermal strains imposed near grain corners and the distribution and statistics of small-angle tilt boundaries are among the topics that can be studied in a practical way only by the decoration technique.

3) Since the depth of decoration in a decorated thin section is at least one order of magnitude greater than the thickness of a TEM specimen, at least ten times as many dislocations are visible in the former than in the latter for a particular dislocation density and viewing area. This effect, coupled with the fact that optical magnifications are considerably lower than conventional TEM magnifications, can lead to spectacular results. Where a TEM view at a magnification of 10,000 might show a few dislocations in a frame, a decorated section from the sample viewed at a magnification of 200 would show several hundred dislocations, revealing the extended structures that result from long-range dislocation interactions. Such structures in most mantle-derived olivine-bearing xenoliths, whose dislocation densities are less than 10^8 cm^{-2}, would likely be overlooked in a TEM examination.

Three additional points deserve comment. (i) As the decoration reaction involves the oxidation of the iron-rich component of the olivine, the technique will not work in pure forsterite, quartz, or calcite. (ii) In decorated samples the Burgers vector of a dislocation can be determined with certainty only if it can be traced into a small-angle tilt boundary, where the Burgers vector is normal to the plane of the boundary, or into a twist boundary, where Burgers vectors are parallel to dislocation line directions. (iii) Lastly, economic factors favor optical microscopy. Preparing decorated thin sections involves little more effort than preparing a standard petrographic thin section, or about one-tenth the effort of preparing a good TEM specimen. There is a similar saving in both cost and time in viewing the specimen.

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Bioluminescent Countershading in Midwater Animals: Evidence from Living Squid

Abstract. *Midwater squid respond to overhead illumination by turning on numerous downward-directed photophores; they turn off the photophores when overhead illumination is eliminated. The squid are invisible when the intensity of the photophores matches the intensity of the overhead illumination. These results strongly support the theory of ventral bioluminescent countershading.*

Bioluminescence is undoubtedly the most characteristic feature of the midwater fauna of the open ocean. Numerous functions have been suggested to explain luminescent structures (*1*). One function, camouflage, would seem especially important in the open ocean, where an animal has no holes in which to hide. An opaque animal in the dimly lit midwaters, silhouetted against the highly directional downwelling light, will be visible to predators below. Animals under these conditions might conceal themselves by eliminating their silhouettes with ventrally directed bioluminescent light (*2*). This theory of ventral bioluminescent countershading is supported for various squid, fish, and shrimp by vertical distributional patterns, photophore patterns, photophore structure, the radiance pattern of emitted light, and luminescent feedback mechanisms (*3*–*5*). However, the most critical evidence, direct observations of living animals, is almost totally lacking (*6*). Hastings (*7*) found that a flashlight stimulated a luminous response in the shallow-water pony-