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Microstructural response of peridotite to experimental shear deformation

Question: *How does shear deformation due to the motion of tectonic plates affect the microstructure of mantle rocks?*

Introduction

The earth's crust is highly dynamic. Segmented portions of the crust and upper mantle (plates) move and rotate with respect to one another, and the effects of these motions, especially along the plate margins, have an enormous impact on humanity and nature. Cataclysmic earthquakes in Turkey, the rise of the Himalayas, the existence of the Caribbean islands and the eruption of Mt. St. Helens are all a direct result. The engine driving these plate motions is heat generated within the interior of the earth and the distribution, redistribution and release of that heat. The majority of heat is released along linear zones where the bottom of the plates approach the surface, at mantle "hot spots" and spreading centers; plates continuously move away from these zones, even when mountain-building collisions with other plates are occurring on the other side. Since the plates are relatively thin and do not extend deep into the earth's interior, there exists a zone of rock that must accommodate the plate motions over underlying portions of the mantle. This rock is largely made up of olivine, $(Mg,Fe)_2SiO_4$, and the deformation behaviour of that mineral and the rocks it comprises is of intense interest to geologists in fully understanding the dynamics of plate motion.

Since we cannot directly observe the processes taking place that far down, we rely on pieces of this rock that have been uplifted by tectonic processes and exposed on or near the earth's surface for observational evidence. Indirect evidence is gathered by observing the behaviour of seismic waves that have propagated through the crust and mantle. Other key areas of study in this effort include stress/temperature response modeling, and performing deformation experiments on synthetic high-olivine rocks under the expected conditions near the bottom of plates. Microstructural and textural characterization of the resulting specimens is fundamental in understanding the implications of these experiments, and EBSD is uniquely well suited for this task.

This application note examines some of the results of the first experimental work on olivine in simple shear, of interest because shear is one of the primary stresses acting on mantle rocks accommodating plate motion. Here, a synthetic rock of 100% olivine was squeezed under very high pressure and sheared by a piston in a hydraulic press. The specimen was then released, cross-sectioned, polished and analyzed by EBSD. Two mapping jobs at different spatial resolutions are presented. The lower resolution map is a 201 X 241 point orthogonal grid at 25 μm steps, while the higher resolution map is a 400 X 494 point orthogonal grid at 0.075 μm steps.

EBSD Conditions

Sample surface: Final polished with colloidal silica on vibratory polisher, with a thin C-coat
SEM: FEG-SEM operated at high vacuum
EBSD system: HKL CHANNEL5 with Nordlys I detector

Results

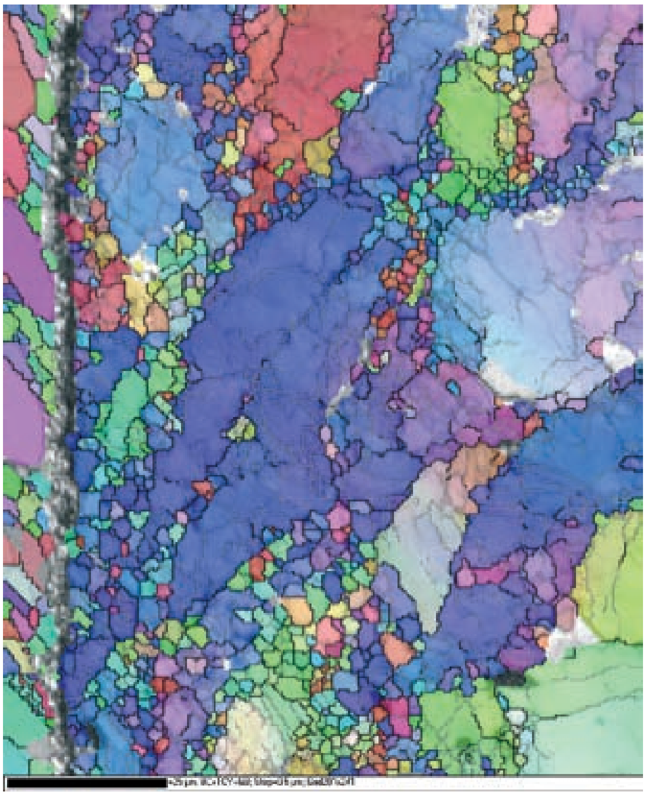

Figure 1:

Inverse pole figure-based orientation map with underlying pattern quality map from an EBSD job taken at 0.5 µm resolution, showing high angle grain boundaries (>10° disorientation between neighboring grains) in black and subgrain boundaries (≤10°) in silver. The larger primary grains are highly subdivided by subgrain boundaries, whereas most of the smaller grains are subgrain-free. The orientation colouring scheme describes which crystal axis is aligned with the shear direction (north-south), see legend. The preponderance of blue indicates a <100> || shear axis preferred orientation for many of the deformed and recrystallized grains, as corroborated by the clustering of <100> poles in the shear axis-projected inverse pole figure in the lower left. The grains at the left hand edge of the figure (to the left of the vertical crack) are part of the piston of the deformation apparatus.

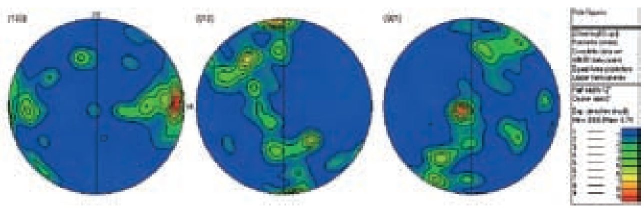

Figure 2:

{100}, {010} and {001} pole figures of the map area. Note the texture peak at {100} parallel to Y0 (shear direction).

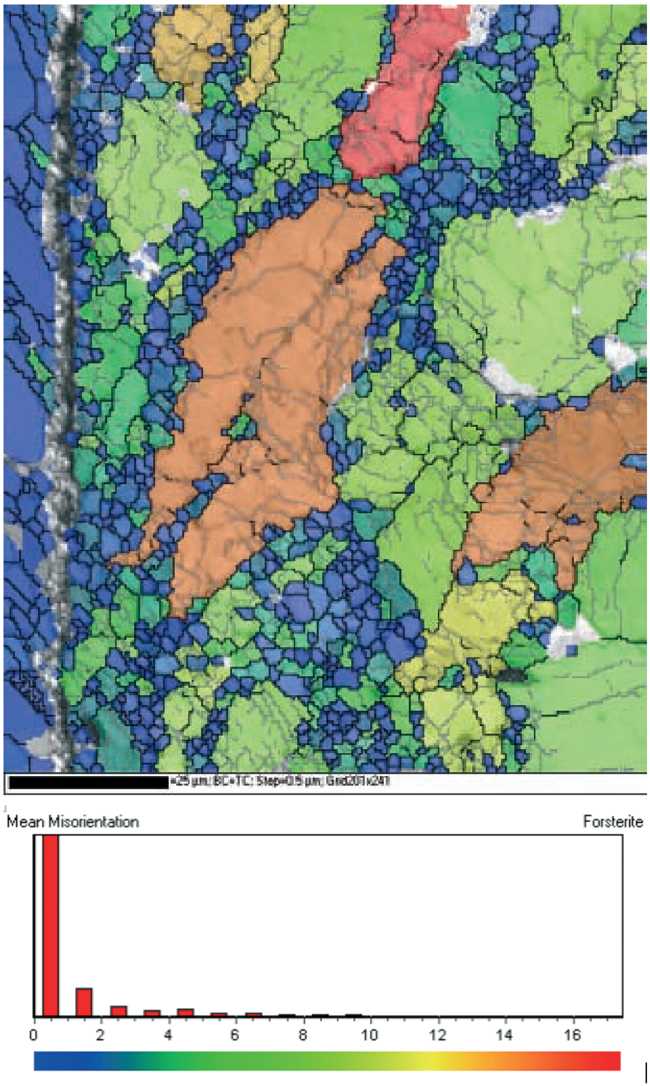

Figure 3:

Map with grains coloured by a rainbow-scale colouring scheme indicating average intragranular misorientation. Intragranular misorientation is the average difference in orientation between all pixels belonging to an individual grain, and is related to the state of deformation for that grain. The colour scale (in degrees) and corresponding histogram are also shown. All of the small grains are blue, possessing a small degree of average internal lattice rotation, whereas the larger grains display a higher degree of internal deformation. Thus, the small grains may be categorized as "recrystallized" and the larger as "deformed".

Figure 4:

For further comparative analysis, all grains were identified as belonging to the "recrystallized" or the "deformed" category, based on grain size using a user-set threshold of 6 µm diameter by equivalent circle area. This classification could also have been made by average intragranular misorientation, with a threshold of about 3 degrees from the map and histogram in Fig. 3. This orientation map shows the recrystallized subset in full colour, with the deformed category and the non-categorized piston grains toned up. Note also that most of the recrystallized grains have formed between, rather than within, the deformed grains.

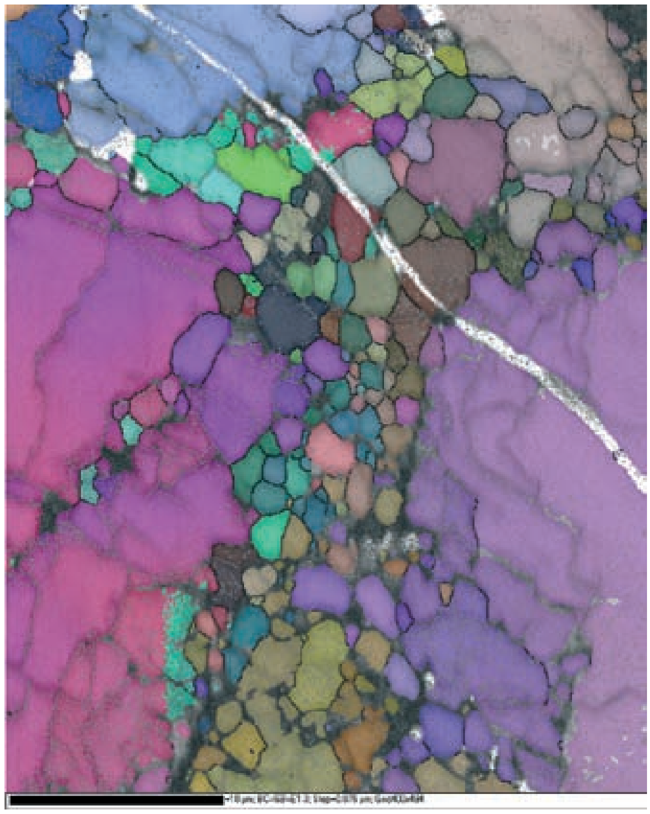

Figure 6:

Orientation map with grain boundaries, from a higher resolution (0.075 µm) job taken within the mapping area of the lower resolution job. Note the subgrains bounded by low angle grain boundaries (silver) in the large, deformed grains. The white line in the upper right is a crack.

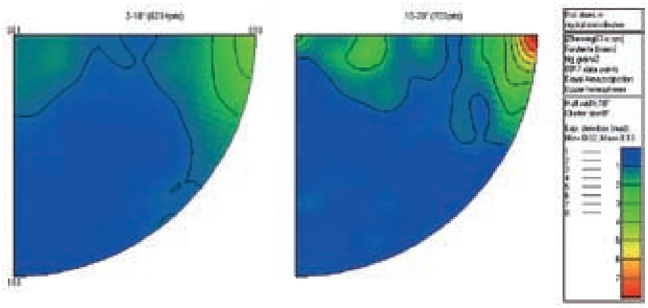

Figure 5a:

Distribution of grain boundary rotation axes in the deformed grains, purely in terms of the crystallographic axis of rotation and plotted on the non-projected inverse pole figure. Two ranges of boundary rotations are given: 2-10° (left) and 10-20° (right). Deformation, as determined by changes in crystallographic orientation within the deformed grains, is dominated by subgrain rotations about <010>.

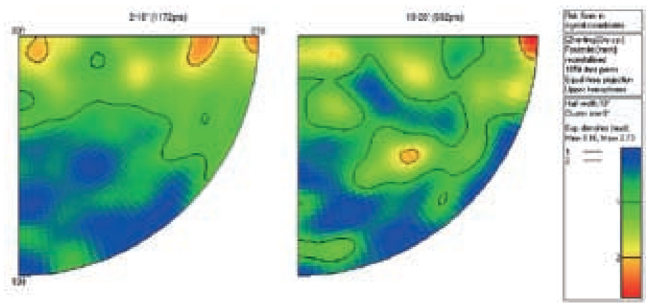

Figure 5b:

Grain boundary rotation axis distribution figures for the recrystallized grains. Note the slight concentration of rotations about <010> but overall much weaker clustering and peak strength than in the deformed grains.

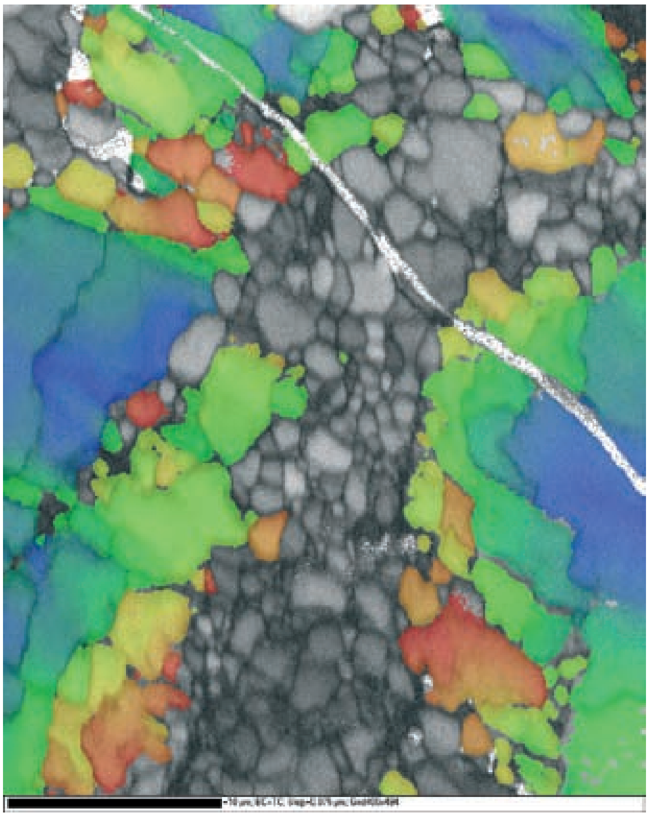

Figure 7:

Misorientation map for the deformed grains; recrystallized grains in pattern quality grayscale. For each deformed grain, the pixels are coloured by degrees of crystallographic misorientation relative to a selected reference point within the grain, where blue = closest to the reference orientation, red = farthest. Note the subgrains with semi-uniform colouring, bounded by low angle grain boundaries. This is distinctive from other intragranular deformation microstructures, such as continuous lattice rotation where the colour scale changes continuously across the grain.

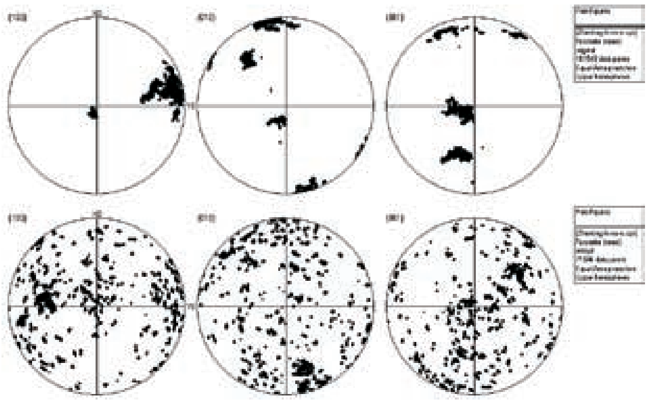

Figure 8:

Pole figures ({100}, {010} and {001}) for the deformed grains (top) and the recrystallized grains (bottom). Note that the recrystallized grains have a significantly different crystallographic preferred orientation to the deformed grains. If the smaller grains were formed from extended subgrain rotation and dissociation within the deformed grains, one would expect a textural similarity or relationship to the parent deformed grains. The dissimilar textures imply that subgrain rotation may not be the formation mechanism for the "recrystallized" grains, and another method of formation, such as nucleation & growth at grain boundaries ("diffusion creep"), may be more consistent with the analysis seen here. The clustering of the recrystallized grains at grain boundaries rather than within the deformed grains is also more consistent with the nucleation & growth theory.

Conclusion

EBSD analysis of grain structure, crystallographic preferred orientation, grain boundary character, and especially the comparative evaluation of different grain populations within this experimental sample has revealed some interesting and important information. Deformation of the original grains yielded a strongly subgranular microstructure, with well developed subgrain boundaries exhibiting a preferred <010> rotation axis. A separate population of smaller, much less deformed "recrystallized" grains exists primarily between the deformed grains, and possess a much weaker and apparently different crystallographic texture than the deformed grains. Results such as these help geologists better understand how mantle rocks flow as a response to tectonic plate motion, and how the resulting crystallographic textures affect seismic wave propagation through the earth.

Answer: *Olivine-rich rocks (peridotites) respond to shear stresses in the upper mantle by subgrain formation and rotation, primarily about <010>, and the formation of smaller deformation-free grains with a different crystallographically preferred orientation than the deformed parent grains.*

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