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The role of dislocations in varied olivine deformation mechanisms investigated using high-angular resolution electron backscatter diffraction

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Experimentally-derived flow laws can be used to predict the rheology of rocks deformed under natural conditions only if the same microphysical processes can be demonstrated to control the rate-limiting deformation mechanism in both cases. Olivine rheology may exert a principle control on the strength of the lithosphere, and therefore considerable research effort has been applied to assessing its rheology through experimental, geological, and geophysical approaches. Nonetheless, considerable uncertainty remains regarding the dominant deformation mechanisms in the upper mantle. This uncertainty arises in large part due to our limited understanding of the fundamental deformation processes associated with each mechanism. Future improvements to microphysical models of distinct deformation mechanisms require new insight into the contributions those fundamental processes to the macroscopic behaviour.

The dynamics of dislocations is central to modelling viscous deformation of olivine, but characterisation techniques capable of constraining dislocation types, densities, and distributions over the critical grain to polycrystal length-scales have been lacking. High angular resolution electron backscatter diffraction (HR-EBSD), developed and increasingly applied in the material sciences, offers an approach capable of such analyses. HR-EBSD utilises diffraction pattern image cross-correlation to achieve dramatically improved angular resolution (∼0.01°) of lattice orientation gradients compared to conventional Hough-based EBSD (∼0.5°). This angular resolution allows very low densities (≥ 10̂11 m̂-2) of geometrically necessary dislocations (GND) to be resolved, facilitating analysis of a wide range of dislocation microstructures.

We have developed the application of HR-EBSD to olivine and applied it to samples deformed both experimentally and naturally in grain-size sensitive and grain-size insensitive regimes. The results quantitatively highlight variations in the types and distributions of dislocation substructures, such as slip bands and subgrain boundaries, formed by different deformation mechanisms under varied deformation conditions. Single crystals deformed by dislocation creep exhibit a transition in dominant GND structures from homogenously-distributed slip bands at low temperature to regular subgrain boundaries at high temperature. Polycrystals deformed by dislocation-accommodated grain-boundary sliding reveal more complex substructure, with high GND densities spatially associated with grain boundaries and triple junctions. Samples deformed by diffusion creep contain significant dislocation content distributed relatively homogenously within grains. Our results demonstrate the varied GND substructures formed by different deformation mechanisms at the grain- to aggregate-scales, and thereby provide valuable constraints for the microphysical models of olivine deformation that underpin rheological flow laws. Furthermore, these results provide a basis for quantitatively interpreting deformation mechanisms that operated in natural olivine-rich tectonites based on their dislocation substructure.