Unexpected extreme softening of Mg2GeO4 with minor MgGeO3 between 1000 and 1200°C: a transient metastable phase at the lithosphere-asthenosphere boundary?

Ultrafine-grained aggregates of Mg2GeO4 and minor MgGeO3 (≈7%) were synthetized using spark plasma sintering and deformed using an 1-atm deformation rig between 950°C and 1250°C. Observations with SEM, EBSD, XRD and Raman together confirm that the samples consist of the germanate equivalents of α-olivine and minor orthoenstatite, with a grain size of 1-10 microns. The mechanical data demonstrate that, for 1000 < T < 1150°C, the shear strength of the material drops down to zero once a critical stress as low as 30-100 MPa is reached. This results in an extreme softening, which is followed by a sharp hardening, suggesting that the fast deformation process ended.

The olivine-spinel transition in Mg2GeO4 occurs at T = 810°C, and all experiments were done at T > 950°C, i.e. in the stability field of α-olivine. The deformation curves are consistent with a transformation similar to what is commonly observed in steels during the shear-induced transformation from austenite to martensite, the final material being significantly harder. This is referred to as Transformation-Induced Plasticity (TRIP), widely observed in metal alloys (TRIP alloys) but evidenced here for the first time in this mantle analogue. The CPO is consistent with high-T solid-state olivine deformation and develop in the absence of dislocation activity, as confirmed by TEM imaging. I suspect transformation-assisted grain-boundary sliding, due to a stress-induced metastable phase that would transiently form within the samples between 1000 and 1150°C. This phase could be the ω-olivine, expected by Poirier in 1981, and observed in Mg2GeO4 within a meteorite in 2017. Its stability field in a P-T-σ diagram is unknown. Another possibility could be the transition from orthoenstatite to protoenstatite, whose stability limits are debated, but the amount of MgGeO3 is limited and only orthoenstatite is observed. Microstructural observations confirm coeval grain rotation and grain boundary sliding of olivine, and the EBSD mapping is consistent with the activation of the [010][100] easy slip system. The absence of amorphization at grain boundaries is also documented. It seems that the transition occurs as a result of a competition between diffusional and displacive processes, i.e. temperature vs strain rate, making the material harder at 1200°C than at 1100°C thanks to diffusion that would stabilize α-olivine. The extreme softening evidenced by the experiments brings into light another scenario to explain the lithosphere-asthenosphere boundary, which does not require water.

In addition, the existence of transient ω-olivine in stressed mantle regardless of stability fields could also have major consequences on how we understand the solid-state olivine-spinel transitions and related earthquakes triggering. For instance, if a volume of olivine within a subducting slab remains relatively cold (T < 1200°C) and unstressed, the ω-olivine would not form and the α-olivine would remain metastable in the mantle transition zone.