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When minerals fight back: The relationship between back stress and geometrically necessary dislocation density

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The dynamics of several geophysical phenomena, such as post-seismic deformation and post-glacial isostatic readjustment, are inferred to be controlled by the transient rheology of olivine in Earth's mantle. However, the physical mechanism(s) that underlie(s) this behavior remain(s) relatively unknown, and most experimental studies focus on quantifying steady-state rheology. Recent studies have suggested that back stresses caused by long-range elastic interactions among dislocations could play a role in transient deformation of olivine. Wallis et al. (2017) identified an internal back stress in olivine single crystals deforming at 1573 K, which gave rise to anelastic transient deformation in stress dip experiments. Hansen et al. (2019) quantified the room-temperature strain hardening of olivine deforming by low-temperature plasticity and measured a back stress that gave rise to a Bauschinger effect, a well-known phenomenon in materials science wherein the yield stress is reduced upon reversing the sense of direction of the deformation.

To explore deformation at very high dislocation density, we have developed a novel nanoindentation load drop method to measure the back stress in a material at sub-micron length scales. Using a self-similar Berkovich tip, we measure back stresses in single crystals of olivine, quartz, and plagioclase feldspar at a range of indentation depths from 100–1700 nm, corresponding to geometrically necessary dislocation (GND) densities of order 10^{14}–10^{15} m^{-2}. Our results reveal a power-law relationship between back stress and GND density with an exponent ranging from 0.44-0.55 for each material, with an average across all materials of 0.48. Normalizing back stress by the shear modulus measured during the indentation test results in a master curve with a power-law exponent of 0.44, in close agreement with the theoretical prediction (0.5) derived from the classical Taylor hardening equation (Taylor, 1934). For olivine, the extrapolation of our fit quantitatively agrees with other published data spanning over 5 orders of magnitude in GND density and temperatures ranging from 298-1573 K. This work provides the first experimental evidence in support of Taylor hardening in a geologic material, supports the assertion that strain hardening is an athermal process that can occur during high-temperature creep, and suggests that back stresses from long-range interactions among dislocations must be considered in rheological models of transient creep.