Observation of Crystal Plasticity under High Pressure with Applications to the Earth's Mantle

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Direct experimental measurement shows the activation volume for the motion of glide dislocations in crystals always to be less than the activation volume for thermally activated atom movements. The activation volumes for thermally activated atom movements remains, therefore, the rate limiting step in plastic flow at all depths in a mantle composed of solid close-packed oxides. The occurrence of partial melting and of pressure-induced phase transformations is expected to result in zones of low shear strength in the mantle. Plastic flow may largely be localized to these zones.

The motions thought to be occurring in the earth's mantle require rock to flow by plastic deformation. A test that can be applied to theories of these motions is that they be consistent with what can be inferred from solid-state physics about the plastic properties of rock under the temperature, pressure, and stress existing in the mantle. There is extensive experimental and theoretical knowledge of the plastic properties of crystalline materials at high temperature, but not of the response of solids to small deviator stresses in the presence of a large hydrostatic stress component, the stress state in the mantle. Many experiments on crystal plasticity have been made with samples placed under high pressure to suppress brittle fracture; the pressure dependence of the plastic flow properties has not been observed. In this paper the results of a series of experiments that establishes the pressure sensitivity of basic mechanisms of crystal slip are summarized and applied to the problem of the plastic properties of the earth's mantle.

Experiments in which plastic properties are observed under conditions duplicating the physical and chemical environment of the upper mantle are not yet possible. Instead, inferences about plastic properties must be drawn from knowledge of the basic deformation mechanisms active in all solids. Small-scale deformation at a slow rate can be achieved without dislocation motion by individual atom movements

alone (Nabarro-Herring creep). Large-scale deformation of a crystalline material is accomplished by the motion of glide dislocations. Barriers to the motions of dislocations can be removed or circumvented by thermally activated atom movements at high temperature. Steady-state creep results when the stress is low and the temperature high; then, at room pressure atomic mobility is rate limiting for this type of creep.

The variation of crystal plasticity with depth in a homogeneous mantle is dependent on how both atomic mobility and dislocation mobility change with pressure and temperature. The pressure and temperature dependence of the rate of atom movement is given by

$$\tau = \tau_0 e^{G^*/kT} \tag{1}$$

where τ is the mean residence time of an atom on a lattice site and the activation free energy $G^* = E^* + PV^* - TS^*$ depends on the activation energy E^*, volume V^*, and entropy S^*. In close-packed oxide structures V^* is about equal to the oxygen atomic volume V_a. Equation 1 can be used to estimate the dependence of atomic mobility in close-packed oxide crystals on depth in the earth [*Gordon*, 1965].

The motion of glide dislocations in a crystal can also be described in terms of rate theory since dislocation movements are thermally activated. The strain rate resulting from slip on a particular glide system is [*Gilman*, 1965]

$$\dot{\epsilon}' = \phi b N v = \phi b (N_0 + M\epsilon) v_0 e^{-(D+W\epsilon)/\sigma} \tag{2}$$