FLOW PROCESSES IN LUNAR AND PLANETARY INTERIORS:

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Several flow processes may occur in the upper mantle rocks of terrestrial planets, and any evaluation of the flow properties requires a critical examination of these different processes over a range of possible conditions. This paper presents a brief summary of work in progress which is designed to examine the flow processes of olivine and to pictorially present the mechanisms in the form of deformation mechanism maps. The procedure adopted for this program involves two steps: first, a determination of the best available constitutive relationships for deformation at elevated temperatures; second, construction of the maps for depths of up to 350 km.

There are four major flow processes which are probably important in olivine at high temperatures.

First, the material may deform by dislocation creep, with a shear strain rate, $\dot{\gamma}_{dc}$, which is given by

$$\dot{\gamma}_{dc} = \frac{Gb}{kT} \{A_1 |\frac{\tau}{G}|^3 + A_2 |\frac{\tau}{G}|^5\} D_{o(\ell)} \exp |- \frac{Q_\ell + pV^*}{kT}| \qquad [1]$$

where G is the shear modulus (8.13×10^4 MPa at 300 K and 1 atmosphere), b is the Burgers vector (6.0×10^{-10} m), k is Boltzmann's constant, T is the absolute temperature, τ is the shear stress, $D_{o(\ell)}$ is the frequency factor for lattice self-diffusion ($0.1\ m^2\ s^{-1}$), Q_ℓ is the activation energy for lattice self-diffusion ($522\ kJ\ mol^{-1}$), p is the pressure, V* is the activation volume for the oxygen ion ($11\ cm^3\ mol^{-1}$) and A_1 and A_2 are constants. Equation [1] is based on an analysis of data by Kohlstedt and Goetze (1) and the values of A_1 and A_2 are, respectively, 0.45 and 5.4×10^4. As indicated, dislocation creep is given by a power-law relationship which combines stress exponents of 3 and 5.

Second, olivine may deform by diffusion creep, where the flow of vacancies takes place through the crystal lattice. This process is Nabarro-Herring creep, and the shear creep rate is given by

$$\dot{\gamma}_{NH} = A_{NH} \frac{Gb}{kT} |\frac{b}{d}|^2 |\frac{\tau}{G}| D_{o(\ell)} \exp |- \frac{Q_\ell + pV^*}{kT}| \qquad [2]$$

where d is the grain size and A_{NH} is a constant which, based on theory and experimental data for metals, is probably close to 84.

Third, if the vacancies flow along the grain boundaries as in Coble creep, the shear strain rate is equal to

$$\dot{\gamma}_{Co} = A_{Co} \frac{Gb}{kT} \left|\frac{b}{d}\right|^3 \left|\frac{\tau}{G}\right| \left|\frac{\delta D_{o(gb)}}{b}\right| \exp \left|\frac{-Q_{gb}}{kT}\right| \qquad [3]$$

where δ is the width of the grain boundary, $D_{o(gb)}$ is the frequency factor for boundary diffusion ($\delta D_{o(gb)} = 1 \times 10^{-10}$ m^3 s^{-1}), Q_{gb} is the activation energy for boundary diffusion (350 kJ mol^{-1}) and, from the theory of Coble creep, $A_{Co} = 100$.

Fourth, it has been established in metals that there is an additional process at low stress levels termed Harper-Dorn creep (2). This process occurs when the grain size is large, typically above about 0.5 mm, and it has been reported for several different metals (3). It seems likely that the same process would occur also in olivine, with a shear creep rate given by

$$\dot{\gamma}_{HD} = A_{HD} \frac{Gb}{kT} \left|\frac{\tau}{G}\right| D_{o(\ell)} \exp \left|- \frac{Q_\ell + pV^*}{kT}\right| \qquad [4]$$

where $A_{HD} = 5 \times 10^{-11}$ (3).

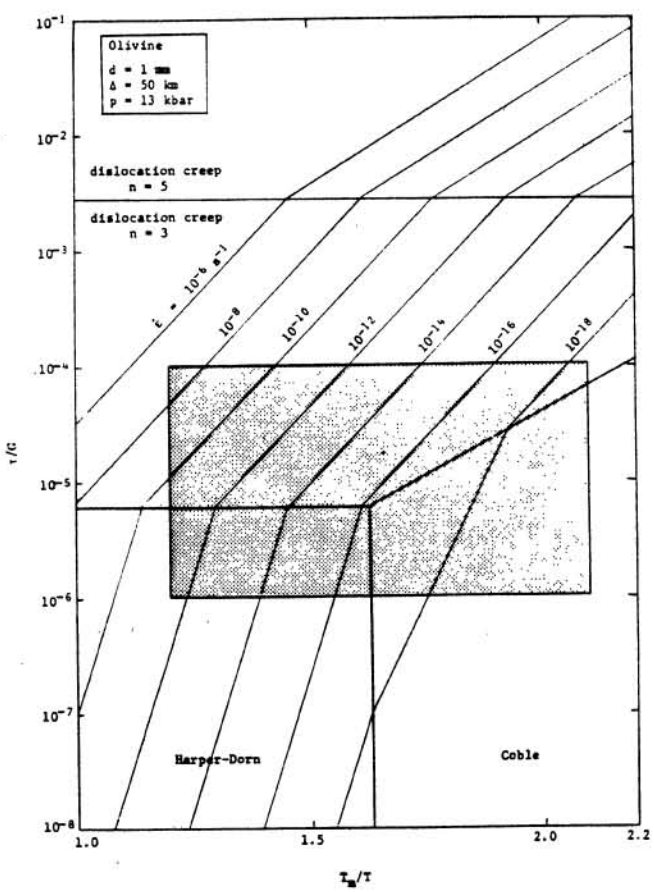

Fig. 1. Deformation mechanism map for olivine having a grain size of 1 mm at a depth of 50 km.

The four processes represented by equations [1] to [4] operate independently, so that the fastest mechanism is rate-controlling (4). Using this approach, deformation mechanism maps were constructed in the form of normalized shear stress, τ/G, versus the reciprocal of the homologous temperature, T_m/T, where T_m is the melting point in degrees Kelvin. An example is shown in Fig. 1 for a grain size of 1 mm and a pressure of 13 kbar, corresponding to a depth, Δ, of 50 km. It is important to note that, by plotting the map using the reciprocal of temperature, all of the lines appearing on the map are straight: this plotting procedure is described in detail elsewhere (5).

The thick lines in Fig. 1 separate regions in stress-temperature space where one of the flow processes is dominant. Nabarro-Herring creep does not appear on the map because the grain size is too large: at d = 1 mm, $\dot{\gamma}_{HD} > \dot{\gamma}_{NH}$ and Nabarro-Herring creep is therefore excluded by Harper-Dorn creep. The thin lines show strain rate contours for normal rates, $\dot{\varepsilon}$, from 10^{-6} to 10^{-18} s^{-1}. Finally, the shaded box indicates the approximate area of geological interest at a depth of 50 km. The map therefore suggests that three deformation processes play a role in the flow of upper mantle rocks at this depth: Coble diffusion creep, Harper-Dorn creep, and dislocation creep with a stress exponent, n, equal to 3.

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References

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