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THE HOMOLOGOUS TEMPERATURE DEPENDENCE OF CREEP

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We have developed an apparatus that permits high precision axial compression constant-strain-rate experiments to be conducted at temperatures up to 1700K and pressure up to 3.2 GPa. Platinum-encapsulated specimen (9mm X 3mm diam) are surrounded by molten alkali halide with a temperature difference from one end to the other of usually less than 10K. This apparatus has allowed us to test experimentally the prevailing philosophy that the pressure dependence of power law creep can be expressed by an activation volume, ΔV^* , that approximates the atomic volume of the slowest-diffusing atomic species. We have conducted a series of experiments ($T = 1100-1700K$; $P = 1.2 - 3.2$ GPa; $\dot{\epsilon} = 10^{-4} - 10^{-5} \text{ sec}^{-1}$) on a polycrystalline ceramic composed of olivine, $(Mg,Fe)_2SiO_4$, the dominant phase in the earth's upper mantle. Our results [1,2] show that:

- (i) The pressure dependence of creep is far too great to be consistent with the atomic volume of any single atomic species.
- (ii) The apparent activation enthalpy and the apparent activation volume are strongly pressure and temperature dependent.
- (iii) Despite the systematics of (ii), at constant homologous temperature (T/T_m), where T_m represents the solidus of the material, the steady-state creep strength is independent of pressure (Fig.1).

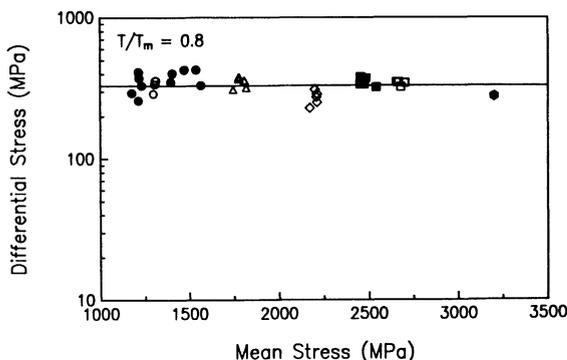


Fig.1. Data normalized to constant T/T_m using the curve of Fig. 2. At constant T/T_m , the flow stress is independent of pressure.

In Fig. 2, we present all of our data normalized to the solidus and corrected through the power-law creep equation to a common strain rate of $2 \times 10^{-4} \text{ sec}^{-1}$ using our experimentally-

determined value of $n = 3.5$. The curvature in Fig. 2 implies that, despite the independence of strength on pressure at constant T/T_m (Fig.1) the activation parameters vary with both T and P in such a way that the two effects exactly counterbalance each other. That is, temperature and pressure are not independent parameters; they combine to constitute a single parameter, the homologous temperature. We have developed a generalization of previous attempts to normalize creep data to the melting curve that satisfies earlier work as well as our own [1]:

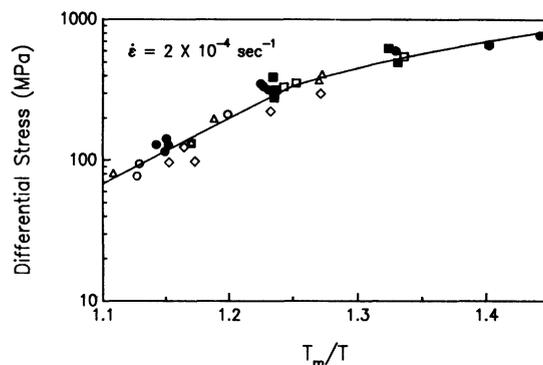


Fig.2. Plot of experiments conducted between confining pressures of 1.1-3.2 GPa, temperatures of 1100-1700K, and strain rates of $2 \times 10^{-4} \text{ sec}^{-1} - 3 \times 10^{-5} \text{ sec}^{-1}$, reduced to a common strain rate of $2 \times 10^{-4} \text{ sec}^{-1}$ using the power-law creep equation. The slope of the solidus is 0.1K/MPa and T_m is estimated. Experiments conducted at different pressures are symbolized by circles (1.1-1.3 GPa), diamonds (1.6-1.8 GPa), triangles (2.1-2.3 GPa), squares (2.5-2.7 GPa) and hexagons (3.2 GPa).

$$\left(\frac{\partial \ln \sigma}{\partial P}\right)_{T, \dot{\epsilon}} = \left(\frac{\partial \ln \sigma}{\partial T_m/T}\right)_{\dot{\epsilon}} \left(\frac{\partial T_m/T}{\partial P}\right)_T = \frac{1}{T_m} \left(\frac{\partial \ln \sigma}{\partial T/T}\right)_{P, \dot{\epsilon}} \frac{dT_m}{dP} \quad (1)$$

This development allows extrapolation of creep data to other conditions if the solidus is known.

Using the counterbalancing effect of T and P and the Clapeyron equation, we derived the relationship $\Delta V^*/\Delta H^* = \Delta V_m/\Delta H_m$, where ΔV_m and ΔH_m are, respectively, the change of molar volume and enthalpy on melting [1]. Inverting this relation, one can eliminate P arriving at:

$$\frac{\Delta E^*}{\Delta V^*} = \frac{\Delta E_m}{\Delta V_m} \approx 17 \text{ GPa for our data.} \quad (2)$$

For portions of Fig. 2 that approximate a straight line, one can obtain ΔE^* from:

$$\Delta E^* = \left(\frac{\partial \ln \sigma}{\partial T_m/T} \right)_\xi nR {}^\circ T_m, \quad (3)$$

where ${}^\circ T_m$ is the zero pressure melting point and R is the gas constant. Approximating the curve of Fig. 2 with two straight lines and using (3) and (2) yields $\Delta E^* = 530 \text{ kJ/mole}$; $\Delta V^* = 31 \text{ cm}^3/\text{mole}$ for $T/T_m > 0.8$, and $\Delta E^* = 230 \text{ kJ/mole}$; $\Delta V^* = 15 \text{ cm}^3/\text{mole}$ for $T/T_m < 0.8$.

These results demonstrate that, at least for the high homologous temperatures, ΔV^* is too large to be associated with any single atom in the olivine structure (oxygen, the largest ion has a partial molar volume of $\sim 12 \text{ cm}^3/\text{mole}$). The

pronounced variation of both ΔE^* and ΔV^* with T/T_m suggests a change of rate-controlling mechanism, yet the homologous temperature dependence of the flow stress persists through the change of mechanism.

We currently are pursuing the underlying reasons for the homologous temperature dependence of creep in olivine by using single crystals to determine the pressure dependence of different slip systems. We also are initiating similar studies on a variety of metallic, ionic and covalent materials.

[1] Green, H. W. and R. S. Borch, *Acta Metall.* (in press).

[2] Borch, R. S. and H. W. Green, (submitted to *Nature*).