

Fig. 1. Dependence of temperature on depth assumed for the calculation of effective viscosity shown in Figure 2.

ponential term. To evaluate the effective viscosity of periclase at temperatures and pressures comparable to those in the mantle, allowance should be made for the possibility that either O-ion or Mg-ion diffusion may be rate-limiting. If $1 \leq D_0 \leq 10$, $3 \text{ ev} \leq E^* \leq 6 \text{ ev}$, and $0.5V_a \leq V^* \leq 2V_a$ are considered, both possible mechanisms are encompassed. In periclase the atomic volume per O atom is 18 \AA^3 . The increase of pressure with depth is known accurately but the temperature gradient is uncertain. A smoothed temperature-depth curve which lies about midway of the extremes of the curves that have been proposed by various investigators is shown in Figure 1. The dependence of η on depth for this temperature distribution and for $R = 0.05 \text{ cm}$ and $D_0 = 5 \text{ cm}^2/\text{sec}$ is shown in Figure 2 for several values of E^* and V^* . These curves are easily adjusted up or down for a different choice of R and D_0 . V_a in (1) should be taken equal to V^* but, as η is not strongly sensitive to the exact choice, it suffices to take $V_a = 10 \text{ \AA}^3$.

The initial steep drop in η is due to the rapid

rise in T at shallow depths where the pressure is relatively low. Beyond the depth corresponding to the minimum η , the direct effect of P on atomic mobility becomes large and pressure has an important influence not only on diffusion creep but on other processes dependent on atomic mobility, e.g., steady-state creep and recrystallization. The sensitivity of η to the choice of E^* and V^* is shown in the figure; the experimental evidence now available indicates that the best choice for these quantities is $E^* = 5.5 \text{ ev}$ and $V^* = 10 \text{ \AA}^3$. The effective viscosity is also sensitive to temperature, as shown in Figure 3. Here $E^* = 6 \text{ ev}$ and $V^* = 10 \text{ \AA}^3$, and the temperature distributions proposed by Gutenberg [1951] and Lubimova [1958] have been used.

The results in Figures 2 and 3 show that at the temperatures and pressures corresponding to depths of about 1000 to 1500 km, periclase

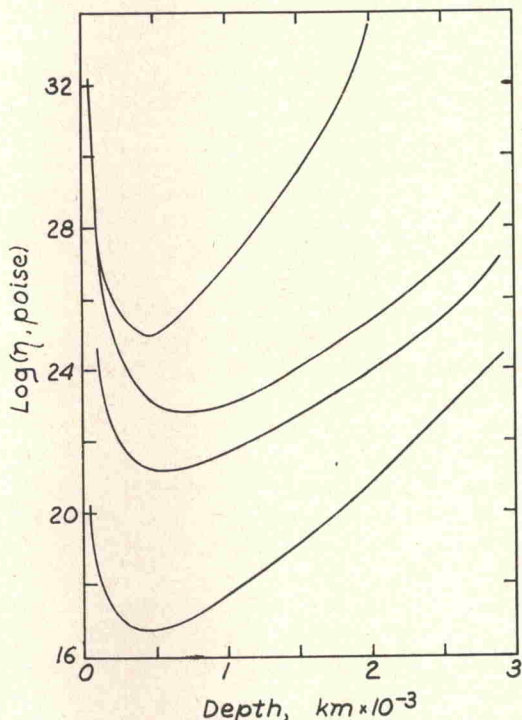


Fig. 2. The effective viscosity due to diffusion creep in a polycrystalline material with $D_0 = 5 \text{ cm}^2/\text{sec}$ and $R = 0.05 \text{ cm}$. Temperature as a function of depth is taken from Figure 1. From top to bottom the curves correspond to $E^* = 6 \text{ ev}$, $V^* = 20 \text{ \AA}^3$; $E^* = 6$, $V^* = 10$; $E^* = 5$, $V^* = 10$; $E^* = 3$, $V^* = 10$, respectively.

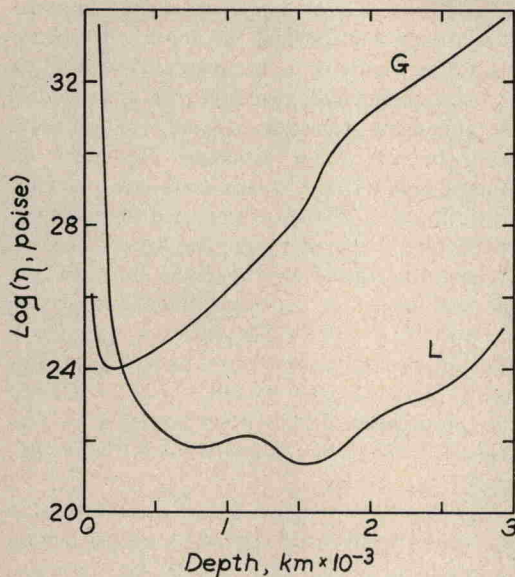


Fig. 3. The effective viscosity as a function of depth for $D_0 = 5 \text{ cm}^2/\text{sec}$, $R = 0.05 \text{ cm}$, $E^* = 6 \text{ ev}$, and $V^* = 10 \text{ \AA}^3$. Curve *G* is for the Gutenberg [1951] temperature distribution and curve *L* is for the Lubimova [1958] distribution.

(or any other polycrystalline material of comparable atomic mobility) is expected to display diffusion creep leading to an effective viscosity of the same order of magnitude as that indicated for the upper mantle by geological evidence. Before it is decided that this viscous behavior is or is not representative of diffusion creep in the earth's mantle, these factors must be considered:

1. *Activation energies.* The activation energies $3 \text{ ev} \leq E^* \leq 6 \text{ ev}$ bracket the observed values for periclase, a supposedly important constituent of the mantle. It is expected that E^* nearer to 6 ev than to 3 ev will be appropriate for the mantle. The low E^* is expected only if there is enhanced anion diffusion in the grain boundaries. Because of the relatively open structure of a grain boundary, even low pressure should rapidly suppress such enhanced diffusion. The observed E^* for O-ion diffusion in corundum is 6.6 ev [Oishi and Kingery, 1960]. Since stishovite has a close-packed oxygen structure, it is expected to have $E^* \approx 6 \text{ ev}$. To make a major change in the η versus depth curves, E would have to be different from the value used above by an unreasonably large amount.

2. *Activation volumes.* Experiments on metals with close-packed structures are consistent in showing $V_v + V_m \approx 0.8V_a$. However, these results are based on experiments over a limited range of pressure ($< 10 \text{ kb}$). They are consistent with the model used in the absolute reaction rate theory of diffusion but as yet there have been no predictions of activation volumes on the basis of this theory. According to the semiempirical theory of Keyes [1963], the activation volume is related to the activation free energy by

$$V^* = 2G^*(\gamma - 1/2)\beta$$

where γ is Grüneisen's constant and β is the isothermal compressibility. V^* is expected, then, to decrease only slowly with increasing P . Variation of V^* with depth by an amount large enough to make a major alteration of the curves of Figures 2 and 3 is not expected.

3. *Grain size.* By equation 1, $\eta \propto R^2$. At room pressure and at high temperature where atomic mobility is large, large grains grow in high-purity materials; the grain growth is arrested when the boundaries form a geometrically stable network (like a stable soap bubble foam). Unusual conditions are required to generate grain sizes larger than about 1 mm diameter. When two or more phases are present in the microstructure (almost certainly the case throughout the mantle), grain growth is inhibited by the tendency of grain boundaries to be held up by second-phase particles. If there are internal steady-state sources or sinks for vacancies, R is reduced [Freidel, 1964]. Thus, it is not expected that variation in grain size could alter η from the values shown in Figures 2 and 3 by more than about a factor of 100 at most.

4. *Grain boundary properties.* Internal friction experiments show that grains slide past each other with a liquid-like viscosity [Ké, 1947]. It is expected, therefore, that tangential stresses at the grain boundaries will always be relaxed at any temperature where diffusion creep may occur. If applied pressure were to strongly decrease the atomic mobility in the boundaries relative to that in the grains, the numerical coefficient in (1) would have to be changed but the curves in Figures 2 and 3 would hardly be altered.