

On the viscosity and creep mechanism of Earth's inner core

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[1] The viscosity and creep mechanism of Earth's inner core are evaluated based on microphysical models of the flow properties of iron under high pressure and temperature, low stress and large grain size. Harper-Dorn creep, a Newtonian-viscous dislocation mechanism, is shown to be the likely deformation process, and the viscosity is predicted to be $\sim 10^{11}$ Pa s, at the low end of previous estimates. Such a low viscosity implies that the inner core can adjust its shape to maintain alignment with the gravitational field imposed by the mantle on a timescale of approximately one minute. It also implies that strain sufficient to produce significant lattice preferred orientation could develop in a few years to a few hundred years, which suggests that seismic anisotropy of the inner core is the product of active deformation and has no memory of primary crystallization. **INDEX TERMS:** 1213 Geodesy and Gravity: Earth's interior—dynamics (8115, 8120); 3902 Mineral Physics: Creep and deformation; 5120 Physical Properties of Rocks: Plasticity, diffusion, and creep; 7207 Seismology: Core and mantle. **Citation:** Van Orman, J. A. (2004), On the viscosity and creep mechanism of Earth's inner core, *Geophys. Res. Lett.*, *31*, L20606, doi:10.1029/2004GL021209.

1. Introduction

[2] The rotational dynamics of the inner core depend on the viscosity [Buffett, 1997; Greff-Lefftz *et al.*, 2000; Dumberry and Bloxham, 2002], as do the various mechanisms proposed for generating seismically anisotropic structures in the inner core [e.g., Jeanloz and Wenk, 1988; Yoshida *et al.*, 1996; Bergman, 1997; Karato, 1999]. Unfortunately, few observational constraints on inner core viscosity exist. Based on seismic inferences of ~ 1 degree per year super-rotation of the inner core with respect to the mantle, Buffett [1997] constrained the viscosity to be less than 3×10^{16} Pa s, or greater than 1.5×10^{20} Pa s in a less likely dynamic regime. These constraints must be relaxed if the rate of super-rotation is less than one degree per year, as recent body-wave and normal-mode studies indicate [Tromp, 2001, and references therein]. In principle, the viscosity of the inner core can be inferred from seismic attenuation data, since attenuation of seismic waves is due in part to non-elastic (anelastic and/or viscous) deformation. However, such estimates must be treated with caution since deformation mechanisms at seismic frequencies may differ from those at longer time-scales. Collier and Helffrich [2001] inferred a viscosity of $\sim 3.9 \times 10^{19}$ Pa s from the attenuation of a low-frequency (1.3/yr) oscillation in inner core rotation; however the oscillatory signal is not firmly established.

[3] Here I take a mineral physics approach to estimate the viscosity of the inner core. Previous materials-based estimates of inner core viscosity [Jeanloz and Wenk, 1988; Yoshida *et al.*, 1996] have not fully considered the creep mechanisms likely to operate under inner core conditions. These estimates have covered a wide range, from $\sim 10^{13}$ – 10^{21} Pa s. Experimental studies of creep in a broad range of crystalline materials have shown that at low and intermediate stress levels and absolute temperatures $T > 0.4 T_m$, (where T_m is the melting temperature) the creep rate can be represented generally by

$$\dot{\epsilon} = A \frac{D G b}{k T} \left(\frac{b}{d} \right)^p \left(\frac{\sigma}{G} \right)^n \quad (1)$$

where D is the diffusion coefficient, G is the shear modulus, b is the Burgers vector, k is Boltzmann's constant, d is the grain size, σ is shear stress, and p , n , and A are dimensionless constants. Because the inner core has a high homologous temperature (greater than $\sim 0.85 T_m$) and non-hydrostatic stresses must be small, the essential task in establishing a mineral physics constraint on inner core viscosity is to obtain reliable estimates of the parameters in equation (1).

2. Creep Mechanism

[4] Three distinct creep regimes are relevant to Earth's inner core. Power law creep ($p = 0$, $n = 3$ – 5) dominates at large grain sizes and intermediate stresses. At lower stresses there is a transition to Newtonian viscous flow ($n = 1$), which is insensitive to grain size ($p \approx 0$) when the grain size is large (Harper-Dorn creep) and varies inversely with grain size ($p \approx 2$ – 3) when the grain size is small. Grain-size sensitive Newtonian creep involves the stress-directed flow of vacancies to and from grain boundaries, in combination with some degree of grain boundary sliding, and is referred to here by the general term "diffusion creep". Harper-Dorn creep is the least familiar of the three creep regimes and has sometimes been neglected [e.g., Yoshida *et al.*, 1996]. This Newtonian, grain size insensitive flow mechanism was first observed in aluminum [Harper and Dorn, 1957] and has since been recognized in a broad range of metals, alloys and ceramics [Wang and Nieh, 1995, and references therein]. Harper-Dorn creep operates under conditions of high homologous temperature, large grain size, very low deviatoric stress and very low dislocation density (as low as $\sim 10^8$ m $^{-2}$). Experimental studies performed to large strains (~ 0.2) have demonstrated that Harper-Dorn creep is a genuine steady-state process [Mohamed and Ginter, 1982]. Although the microphysical mechanism has not been firmly established, a climb-controlled dislocation glide model with a constant dislocation density controlled by

the Peierls stress (τ_p) is in good agreement with experimental data for a wide range of materials [Wang, 1996].

[5] Both power law and Harper-Dorn creep are intra-granular dislocation processes. Power law creep operates at relatively high stresses, where the dislocation density increases with stress. The process that produces strain is dislocation glide, while the rate-limiting step is diffusion-controlled climb. Harper-Dorn creep may take place by a similar process, but with a dislocation density that does not vary with the applied stress. In a broad range of materials, the transition between power law creep and Harper-Dorn creep has been found to occur when the applied stress approaches the Peierls stress [Wang and Nieh, 1995]. The Peierls stress for an edge dislocation (at 0 K) is given by Wang [1996]:

$$\tau_p = \frac{G}{1-\nu} \cdot \exp\left[-\frac{2\pi}{1-\nu} \cdot \frac{d}{b}\right], \quad (2)$$

where G is the shear modulus, ν is Poisson's ratio, h is the spacing between slip planes and b is the distance between crystal planes normal to the line of the dislocation. The shear modulus and Poisson's ratio of hcp iron, the phase of iron thought to be stable at inner core conditions, have been calculated from first principles [Steinle-Neumann et al., 2001] and determined experimentally at high pressure [Mao et al., 2001]. At inner core pressures and low temperatures the shear modulus is ~ 500 GPa and Poisson's ratio is 0.32. Basal slip is likely to be the preferred mechanism for deformation of hcp iron at the conditions of the inner core, in which case $d/b = 0.5c/a = 0.80$ [Steinle-Neumann et al., 2001]. The Peierls stress at 0 K is thus calculated to be 450 MPa. At high temperature the Peierls stress can be approximated by multiplying τ_p/G at 0 K by a factor $0.077T_m/T$ [Wang, 1996], which gives $\tau_p \approx 12$ MPa for an inner core temperature of 5700 K [Steinle-Neumann et al., 2001], melting temperature of 6250 K [Alfè et al., 2002a] and shear modulus of 160 GPa [Dziewonski and Anderson, 1981]. Stresses associated with the magnetic field [Karato, 1999], gravitational coupling with the mantle [Buffett, 1997] and aspherical growth of the inner core [Yoshida et al., 1996] are orders of magnitude smaller, probably not exceeding 0.01 MPa. Power law creep is therefore unlikely in the inner core. Some metals with high initial dislocation densities do not undergo a transition to Harper-Dorn creep at low stresses, but instead follow (or even fall below) the stress/strain-rate curve for power law creep [Mohamed and Ginter, 1982]. However, this anomalous behavior is not likely to apply to the inner core, where low stresses and long annealing times should result in very low dislocation densities. The creep mechanism in the inner core is therefore expected to be either Harper-Dorn or diffusion creep.

[6] Harper-Dorn and diffusion creep are separate processes that act in kinetic parallel. The dominant process is the one that leads to the higher strain rate, and depends on the grain size. Harper-Dorn creep is independent of grain size, having $p = 0$, $n = 1$, and with D in equation (1) referring to the lattice diffusivity. For basal slip in hcp metals the distance b is equivalent to the crystallographic dimension a , and is equal to $\sim 2.15 \times 10^{-10}$ m for hcp iron at inner core conditions [Steinle-Neumann et al., 2001]. Constants A_{HD} have been determined for a large number of

materials from creep experiments and are in good agreement with the predictions of a physical model in which dislocations move by glide plus climb, with climb the rate-limiting step [Wang, 1996]. According to this model A_{HD} is given by $A_{HD} = 3.75(1-\nu)^2(\tau_p/G)^2$ (this expression differs from that given by Wang [1996] by a factor of 3/2 because the stress and strain considered here are shear rather than uniaxial). For nearly all materials in which Harper-Dorn creep has been documented, the value of A_{HD} calculated from this expression agrees with the value determined from creep data within less than an order of magnitude, and the agreement is even better for the hcp metals α -Ti and α -Zr [Wang, 1996]. The value of A_{HD} for hcp iron at the PT conditions of the inner core, where Poisson's ratio is 0.44 [Dziewonski and Anderson, 1981; Steinle-Neumann et al., 2001], is calculated to be 6.6×10^{-9} . Nickel and other substitutional impurities are unlikely to have a significant influence on A_{HD} , as experiments on Al alloys have demonstrated that the creep rate in the Harper-Dorn regime is independent of solute concentration for alloys containing up to 5 wt% Mg [Yavari et al., 1982]. In contrast to substitutional solutes, interstitial impurities create elastic distortions of the lattice that may have a strong strengthening effect. Some "light elements" might be incorporated onto interstitial sites in hcp-Fe, and may therefore have a strong influence on the rheology. *Ab initio* calculations [Alfè et al., 2002b] indicate that the most commonly cited "light elements", S, Si and O, are incorporated onto Fe sites in hcp-Fe, so should not have a significant effect on the mechanical strength. If carbon is present in the core it is likely to be incorporated onto interstitial sites in hcp-Fe; however a thermodynamic analysis indicates that even a small amount of carbon in the core is likely to stabilize Fe_3C rather than hcp-Fe as the liquidus phase [Wood, 1993]. It is possible that the inner core is composed of Fe_3C , or hcp-Fe strengthened by a significant concentration of interstitial carbon, but it is beyond the scope of this paper to evaluate A_{HD} for these hypothetical cases.

[7] Diffusion creep is sensitive to grain size, with $p = 2$, $n = 1$ and D referring to the bulk diffusion coefficient, which may include a grain boundary component. Grain boundary diffusion is expected to be negligible at the high homologous temperature ($>0.85T_m$) and relatively large grain size of the inner core, so the bulk diffusivity should be closely approximated by the lattice diffusivity. The constant A_D has a value of 14–160 depending on geometry and the relative contribution of grain boundary sliding [Frost and Ashby, 1982; Poirier, 1985; Wang, 2000]. The grain size at which Harper-Dorn and diffusion creep contribute equally to strain is calculated by comparing the rate equations for the two mechanisms. This gives a transition grain size $d = b\sqrt{A_D/A_{HD}}$, which is ~ 10 – 30 microns for hcp-Fe at inner core conditions. Bergman [1998] presented several lines of evidence suggesting that the grain size of the inner core is at least on the meter scale. Therefore Harper-Dorn creep is expected to be the dominant creep mechanism in the inner core.

3. Viscosity

[8] Because conditions in the inner core appear to be well within the Harper-Dorn creep regime (Figure 1), the dynamic viscosity, $\eta = \sigma/2\dot{\epsilon}$, is independent of grain size and

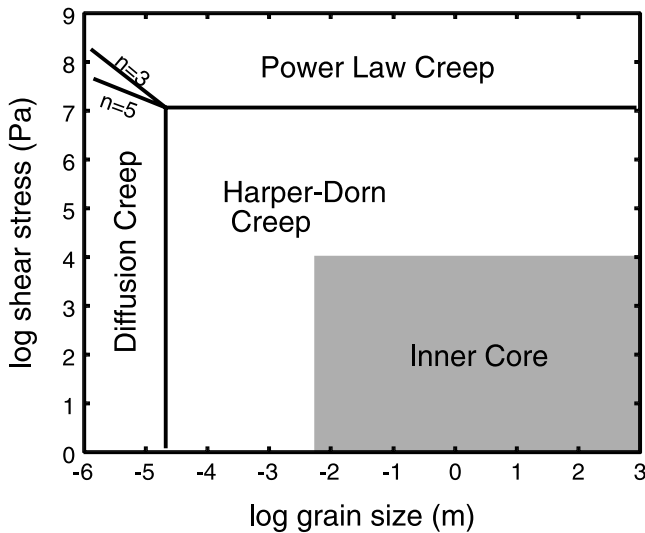


Figure 1. Predicted deformation mechanism map for hcp iron at the pressure-temperature conditions of Earth's inner core. Although creep experiments have so far been limited to stresses $>10^{-7}G$, there is no indication of a threshold stress for Harper-Dorn creep in metals at temperatures greater than $0.8T_m$. High temperature Harper-Dorn creep data for close-packed metals (including Al, Pb, α -Ti and α -Zr) extrapolate to zero strain rate at zero stress [Mohamed *et al.*, 1973; Malakondaiah and Rao, 1981; Novotny *et al.*, 1985].

shear stress. The principal unknown in calculating the viscosity is the lattice self-diffusion coefficient. Diffusion coefficients in hcp-Fe have not been measured experimentally but can be estimated based on an excellent correlation between D and melting temperature in hcp metals. Diffusion coefficients for the hcp metals Cd [Wajda *et al.*, 1955], Mg [Shewmon, 1956] and Zn [Peterson and Rothman, 1967] are described well by a homologous temperature relation (Figure 2),

$$D = \frac{D_{T_m}}{\exp(-g/R)} \exp\left(\frac{-gT_m}{RT}\right), \quad (3)$$

where g is an empirical constant and D_{T_m} is the diffusion coefficient in the solid at the melting point. A regression of the data for all three metals together gives $g = 133.1 \pm 2.8 (2\sigma)$ and $D_{T_m} = 1.4 \pm 0.8 \times 10^{-12} \text{ m}^2/\text{s}$. The homologous temperature relation has been found to hold at pressures up to $\sim 5 \text{ GPa}$ for a wide range of metals [Brown and Ashby, 1980], and recently has been confirmed by first-principles calculations for oxygen diffusion in MgO up to 140 GPa and 5000 K [Ita and Cohen, 1997], and by experimental measurements of Fe-Ni interdiffusion rates up to 23 GPa (M. L. Yunker and J. A. Van Orman, Interdiffusion of iron and nickel at high pressure, manuscript in preparation, 2004). The ratio T/T_m in the Earth's inner core is thought to be within the range $\sim 0.85-0.95$, corresponding to diffusion coefficients between 8.3×10^{-14} and $6.0 \times 10^{-13} \text{ m}^2/\text{s}$. The dynamic viscosity of the inner core is therefore predicted from equation (4) to be $\sim 10^{11\pm 1} \text{ Pa s}$, with error bounds estimated from the uncertainty in the diffusion coefficient and in the

semi-empirical estimate of A_{HD} . This estimate of inner core viscosity is much smaller than a previous estimate of $3 \times 10^{21} \text{ Pa s}$ by Yoshida *et al.* [1996], who used a similar approach but did not consider Harper-Dorn creep. It is within the range of estimates for fcc-Fe derived from low-pressure creep data ($10^{13\pm 3} \text{ Pa s}$ [Jeanloz and Wenk, 1988]), and from seismic frequency forced oscillation and microcreep tests at similar homologous temperatures ($\sim 2 \times 10^{12} \text{ Pa s}$ [Jackson *et al.*, 2000]).

[9] The above analysis assumes that the inner core is composed purely of hcp iron. Other possibilities are that a bcc phase [Vocadlo *et al.*, 2003] or mixture of bcc and hcp phases [Lin *et al.*, 2002] is stable. In either case the viscosity would likely be even lower than for pure hcp-Fe. Bcc metals are significantly weaker than close-packed metals at high temperature [Frost and Ashby, 1982], mainly because the self-diffusion coefficient for bcc metals is two orders of magnitude larger than for hcp metals at the same homologous temperature [Brown and Ashby, 1980].

4. Implications

[10] Harper-Dorn creep is a dislocation process that may lead to strong lattice preferred orientation (LPO), in contrast to diffusion creep which tends not to produce strong LPO even after large shear strains. In combination with the expected low viscosity, this suggests that the observed inner core anisotropy is a product of active deformation rather than a feature developed during primary crystallization from the liquid outer core. Assuming that a shear strain of ~ 4 is sufficient to develop a steady-state LPO in hcp iron [Yamazaki and Karato, 2002], the timescale required for production of anisotropy is $\sim 3-300$ years for shear stresses between 10^2 and 10^4 Pa . Ishii and Dziewonski [2002] presented intriguing evidence that the innermost inner core has anisotropic structure distinct from the rest of the inner core. Considering the rheological constraints, this observation appears difficult to explain without postulating the existence of another solid phase in this region.

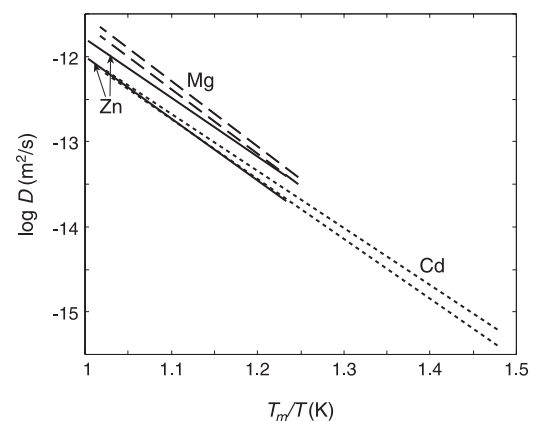


Figure 2. Homologous temperature scaling for self-diffusion in the hcp metals Cd, Zn and Mg. Two lines are shown for each element, one for diffusion parallel to the hexagonal axis and the other for diffusion perpendicular to the hexagonal axis. For Cd and Zn, diffusion along the c axis is faster, while the opposite is true for Mg.

[11] The predicted viscosity is such that the inner core can quickly adjust its shape to maintain alignment with the gravitational field imposed by the mantle. The timescale for viscous relaxation is given by $\tau = (C\eta)/(\Delta\rho gR)$ [Buffett, 1997] where C is a constant equal to 1.9, $\Delta\rho$ and g are the density jump and gravitational acceleration at the inner core boundary and R is the radius of the inner core. For a viscosity of 10^{11} Pa s, the relaxation time is calculated to be only 60 seconds. Such a short relaxation time implies that the rotation axis of the inner core cannot maintain a significant tilt with respect to that of the mantle, and is therefore unlikely to influence the direction of Earth's axis of rotation [Dumberry and Bloxham, 2002]. It also means that the inner core is free to spin at a different rate than the mantle [Buffett, 1997]. The absence of significant differential rotation may indicate not that the inner core is gravitationally locked to the mantle, but that eastward motion of the fluid above the inner core may be somewhat less than suggested by early calculations [e.g., Glatzmaier and Roberts, 1996].

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