A Glassy Lowermost Outer Core
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ABSTRACT

New theories for the viscosity of metallic melts at core pressures and temperatures, together with observations of translational modes of oscillation of Earth’s solid inner core, suggest a rapid increase in the dynamic viscosity near the bottom of the liquid outer core. If the viscosity of the lowermost outer core (F region) is sufficiently high, it may be in a glassy state, characterized by a frequency dependent shear modulus and increased viscoelastic attenuation. In testing this hypothesis, the amplitudes of high frequency PKIKP waves are found to be consistent with an upper bound to shear velocity in the lowermost outer core of 0.5 km/sec at 1 Hz. The fit of a Maxwell rheology to the frequency dependent shear modulus constrained by seismic observations at both low and high frequencies favors a model of the F region as a 400 km thick chemical boundary layer. This layer has both a higher density and higher viscosity than the bulk of the outer core, with a peak viscosity on the order of 107 Pa-sec or higher near the inner core boundary. If lateral variations in the F region are confirmed to correlate with lateral variations observed in the structure of the uppermost inner core, they may be used to map differences in the solidification process of the inner core and flow in the lowermost outer core.

CONSTRANTS ON THE VISCOSITY OF EARTH’S LIQUID OUTER CORE

1) Damping/non-observation of translational modes of inner core -> high viscosity in lowermost outer core
2) Qg > 10,000 from PKKP -> low viscosity in middle of outer core
3) Dynamo -> low upper bound to viscosity in a large volumetric fraction of outer core
4) PKKP amplitudes at narrow and wide angles of incidence -> complex high frequency shear modulus in lowermost outer core
5) PKP-C diffracted decay with distance -> complex high frequency shear modulus in lowermost outer core

A GLASSY VISCOELASTIC RHEOLOGY

Assume a frequency dependent shear modulus of a simple Maxwell fluid:

\[ G(\omega) = G_\infty + \eta \omega \tau \]

where \( G_\infty \) is the shear modulus at infinite frequency and \( \tau \) is a relaxation time give by the ratio of dynamic viscosity \( \eta \) to \( G_\infty \), i.e.,

\[ \tau = \frac{\eta}{G_\infty} \]

The real frequency dependent shear velocity is defined from

\[ V_s(\omega) = \sqrt{\frac{2G(\omega)}{\rho}} \]

and a frequency dependent shear wave attenuation from

\[ Q_s^\prime = \frac{2\text{Im}(G(0))}{\text{Re}(G(0))} \]

Figure 2. (a) and (b) above: frequency dependent shear velocity Vs and compressional wave attenuation above the inner core boundary constrained to fit Vs = 0.5 km/sec (soft outer core) at 1 Hz from: observations shown in (c) and (d) of PKKP amplitudes [1, 2] and the amplitude of PKKP-Cdiffactefed shown in (e) and (f) [3]. Observations of 1 Hz body waves and Smylie et al. [4] estimate of damping of translational modes of the inner core are consistent with \( V_s = 10^9 \) Pa-s in the lowermost outer core.

Alternatively, \( \eta = 10^9 \) Pa-s is consistent with \( V_s = 0.5 \) km/sec at 1 Hz and Touboul and Saito’s [5] estimate of Vs = 0.001 Hz from their observation of splitting of the s52 spheroidal mode.

LATERAL VARIATION IN INNER CORE COUPLED TO STRUCTURE AND FLOW IN LOWERMOST OUTER CORE

(a) Contours thickness of anomalous lower velocity layer in the uppermost inner core determined in the study by Stroujkova and Cormier [6].
(b) excitation of backscattered PKIKP coda from heterogeneity in the uppermost inner core determined in the study by Leyton and Koper [7].
(c) summary of lateral variations in attenuation and P velocity in the equatorial region of the inner core determined in the study by Yu and Wen [8].
(d) uppermost inner core P velocity perturbations (solid contours) and predicted inner core growth rate variations (colors) from a numerical dynamo simulation with lateral variations in heat extraction at the core-mantle boundary inferred from seismic tomographic imaging (Aubert et al. [9]).

CONCLUSIONS

(1) Seismic data from 5 x 10^-5 Hz to 1 Hz suggest that the lowermost 40 to 400 km of Earth’s outer core is characterized by a strong increase in viscosity up to \( 10^9 \) to \( 10^{11} \) Pa-s, which may be high enough to exhibit a frequency dependent shear modulus.

(2) The high P velocity gradient of the lowermost outer core is difficult to explain without appealing to the existence of a chemical boundary layer. The global nature of this layer is consistent with it having both higher density and higher viscosity.

(3) Large-scale lateral heterogeneity in this layer may record lateral variation in the solidification process of the inner core.

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References