Viscosity of the Outer Core

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Estimates of outer core viscosity span 14 orders of magnitude. This wide range of values may be partially explained by the difference in type of viscosity, molecular viscosity (a rheological property of the material) vis-à-vis a modified or eddy viscosity (a property of the motion), inferred from the various observational and theoretical methods [24]. The motion associated with eddy viscosity implies the possibility of non-viscous dissipative mechanisms such as ohmic dissipation. Molecular viscosity is separated into nearly equal components of shear viscosity, η_s, and bulk or volume viscosity, η_v, depending on the type of strain involved [14,15]. η_s is a measure of resistance to isochoric flow in a shear field whereas η_v is a measure of resistance to volumetric flow in a 3-dimensional compressional field. In cases where outer core viscosity estimates are based on observations of the attenuation of longitudinal waves, both η_s and η_v play significant roles but only η_s is important for damping whole Earth torsional mode oscillation and η_v for damping radial mode oscillation [4].

The majority of estimates of outer core viscosity is based on whole Earth geodetic and seismological observations. In terms of the observation times required by a particular method, studies of p-wave attenuation benefit from their short periods (seconds) and all 7 studies cited in Table 2 give upper bound viscosity values within a very confined range of 10^8-10^9 poises. While long period (minutes to years) geodetic phenomena, such as the radial and torsional modes of free oscillation, length of day variations, and polar motion can all be accurately measured, the outer core viscosity estimates inferred from these measurements, ranging from 10^{-1} to 10^{10} poises, suffer from long observation times which can introduce large uncertainties from additional energy sources and/or sinks affecting the observed phenomenon. It must be noted, however, that time independent factors that affect seismic wave amplitudes such as scattering, geometrical spreading, radial and lateral inhomogeneities will be embodied in derived attenuation values. Confirmation of any observation of inner core oscillation has not yet been made and therefore any so-derived viscosity estimate from geodetic observation or theory must be admitted with caution. Other methods of outer core viscosity estimation are from extrapolations launched from experimental data at low (relative to core) pressures and temperatures using various theories of liquid metals and from geomagnetic field observations at Earth's surface. Both of these suffer from large extrapolations and from the lack of any experimental viscosity data on liquid Fe at pressures of even a few kilobars. Most of the experimental data on liquid Fe and liquid Fe-Ni, Fe-S, Fe-O and Fe-Si alloys is found in the metallurgical literature and they are all restricted to measurements at a pressure of 1 atm.

The data and references are presented in 9 tables. Tables 1 and 2 are viscosity estimates based on geodetic and seismological studies, respectively. Tables 3 and 4 are viscosity estimates from geomagnetic and liquid metal theory studies, respectively. A brief description of the method used for each estimate or measurement is also given. Values of kinematic viscosity, ν, reported in some references have been converted to dynamic viscosity, η, by $\nu = \eta/\rho$, using a value of 10 g/cm^3 for ρ, the density. The data in Tables 1-4 are graphically presented in Figure 1. Table 5 contains experimental shear viscosity data for

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TABLE 1. Dynamic Viscosity Estimates of Outer Core from Geodetic Studies

Reference	Dynamic Viscosity (Poises)	Method[t(o)]
Sato and Espinosa (1967)	$0.35 - 4.7 \times 10^{11}$	[o]Torsional free oscillations of whole Earth
Verhoogen (1974)	2.6×10^{-1}	[o]Chandler wobble
Yatskiv and Sasao (1975)	5×10^{9}	[o]Chandler wobble
Anderson (1980)	5×10^{2}	[o]Damping of free oscillation radial modes
Molodenskiy (1981)	$\leq 10^{7}$	[o]Forced nutation of the Earth (value for MCB)
Molodenskiy (1981)	$\leq 10^{8}$	[o]Tidal variations in the length of day
Molodenskiy (1981)	2×10^{10}	[o]Chandler wobble
Gwinn et al (1986)	$<5.4 \times 10^{4}$	[o]Retrograde annual Earth nutation - VLBI measurements (value for MCB)
Neuberg et al (1990)	$<3.3 \times 10^{5}$	[o]Viscous damping only for nearly diurnal free wobble (tidal measurements)
Smylie (1992)	7.7×10^{8}	[o]Damping of inner core translational modes (superconducting gravimeter data)
Bondi and Lyttleton (1948)	$<10^{12}$	[t]Theoretically required for secular deceleration of core by viscous coupling
Stewartson and Roberts (1963)	$<10^{9}$	[t]Theory of rotating fluids
Toomre (1966)	$>6 \times 10^{5}$	[t]Theoretically required for steady precession by core/mantle viscous coupling
Won and Kuo (1973)	$> 10^{-1}$	[t]Theoretical evaluation of decay time of inner core oscillation (value for ICB)
Toomre (1974)	$<10^{6}$	[t]18.6 year principal core nutation (value for MCB)
Aldridge and Lumb (1987)	2.9×10^{7}	[t]Decay of inertial waves in outer core

[t] theory
[o] observation

TABLE 2. Dynamic Viscosity Estimates of Outer Core From Seismological Studies

Reference	Dynamic Viscosity (Poises)	Method
Jeffreys (1959)	5×10^8	Attenuation of p-waves
Sato and Espinosa (1965, 1967)	8.6×10^{12}	Multiply reflected s-waves at mantle/core boundary.
Sacks (1970)	10^8	Attenuation of p-waves
Suzuki and Sato (1970)	$3\text{-}7 \times 10^{11}$	Attenuation of s-waves
Buchbinder (1971)	2×10^8	Attenuation of p-waves
Adams (1972)	4×10^8	Attenuation of p-waves
Qamar and Eisenberg (1974)	$1\text{-}2 \times 10^8$	Attenuation of p-waves
Zharkhov and Trubitsyn (1978)	$<<10^9$	Attenuation of p-waves
Anderson and Hart (1978)	1.4×10^9	Attenuation of body waves and checked against radial mode Q data

TABLE 3. Dynamic Viscosity Estimates of Outer Core from Geomagnetism Studies

Reference	Dynamic Viscosity (Poises)	Method
Bullard (1949)	10^{-2}	Magnetic damping of core fluid motions
Hide (1971)	10^7	Magnetohydrodynamic interactions between fluid motions and bumps on MCB
Schloessin and Jacobs (1980)	2×10^5	Decay of free dynamo action during polarity transitions
Officer (1986)	2×10^8	Value predicts correct order of magnitude of external field and westward drift

TABLE 4. Dynamic Viscosity Estimates of Outer Core from Theories of Liquid Metals

Reference	Dynamic Viscosity (Poises)	Method
Bullard (1949)	10^{-2}	From experimental values for liquid metals at STP
Miki (1952)	10^{-2} - 10^{-1}	Quantum statistical thermodynamics of liquid metals
Backus (1968)	5×10^{2}	From experimental values of liquid Hg at 10 kb and 400K
Gans (1972)	$3.7\text{-}18.5 \times 10^{-2}$	Andrade formula for melting point viscosity (value for ICB)
Leppaluoto (1972)	$1\text{-}5 \times 10^{-1}$	For a pure Fe outer core, from significant structure theory of liquids (value for MCB)
Bukowinski and Knopoff (1976)	$>10^{1}$	For a pure Fe outer core, from band structure calculations
Schloessin and Jacobs (1980)	3.4×10^{2}	From experimental values for liquid Fe and Andrade's pressure effect on viscosity
Anderson (1980)	10^{1} - 10^{4}	Two structure state theory extrapolated to core pressures
Poirier (1988)	3×10^{-2}	Thermodynamic scaling relation between melting temperature and viscosity and diffusivity of metals
Svendsen et al (1989)	2.5×10^{-2}	Liquid state model fitted to high pressure melting data on Fe

pure liquid Fe and Tables 6-9 contain experimental shear viscosity data for liquid Fe alloys, all measured by the oscillating crucible method. The viscosities in Tables 6-9 are presented as either dynamic or kinematic viscosities, as in the reference, because of insufficient density data for many of the alloy compositions.

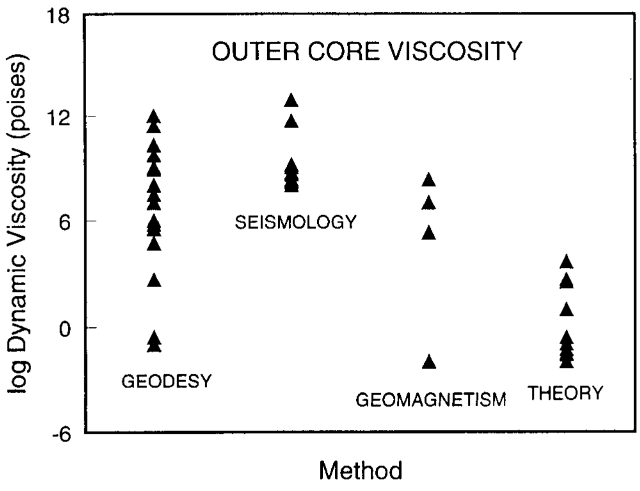

Fig.1. The common logarithm of dynamic viscosity (poises) of the outer core plotted as a function of method used for its determination.

TABLE 5. Experimental Data of Shear Dynamic Viscosity (centipoises) of Liquid Fe at 1 atm

Reference T(°C)	1536	1550	1600	1650	1700	1750	1800	1850
Barfield and Kitchener (1955)	7.60[e]	6.79[i]	6.41	5.89[i]	5.70	5.48[i]	5.31	5.22
Thiele (1958)	4.7	4.6	4.2	3.9	3.7	3.4		
Hoffman (1962)	5.42	5.30	4.90	4.55	3.98			
Cavalier (1963)	4.95	4.87	4.54	4.30	4.10	3.92		
Lucas (1964)	5.03	4.93	4.58	4.28	4.00	3.76		
Vostryakov et al (1964)		5.91						
Nakanishi et al (1967)	5.54[e]	5.44[i]	5.01[i]	4.69[i]	4.44[e]			
Kaplun et al (1974)		5.60	5.01					
Arkharov et al (1978)				5.96				
Steinberg et al (1981)			5.03					

[i] interpolated

[e] extrapolated

TABLE 6. Experimental Data of Shear Viscosity of Liquid Fe-Ni Alloys at 1 atm

Reference	Composition wt% Ni	Temperature (°C)	Viscosity	
			Dynamic (centipoises)	Kinematic (millistokes)
Adachi et al (1973)	4.9	1516	6.11	
		1550	5.91	
		1604	5.69	
		1633	5.54	
		1665	5.36	
	9.7	1502	6.02	
		1513	5.95	
		1550	5.72	
		1596	5.43	
		1652	5.04	
		1693	4.81	

TABLE 6 (continued)

Reference	Composition wt% Ni	Temperature (°C)	Viscosity Dynamic (centipoises)	Kinematic (millistokes)
	28.6	1471	6.15	
		1519	5.62	
		1545	5.37	
		1581	5.11	
		1615	4.91	
Arkharov et al (1978)	0.52	1600		8.48
	1.04			8.28
	1.49			8.15
	1.99			8.13
	2.46			7.98

TABLE 7. Experimental Data of Shear Viscosity of Liquid Fe-S Alloys at 1 atm

Reference	Composition wt% S	Temperature (°C)	Viscosity Dynamic (centipoises)	Kinematic (millistokes)
Barfield and Kitchener (1955)	1.16 (+0.02 wt%C)	1529	7.00	
		1600	6.45	
		1700	5.84	
		1800	5.41	
Vostryakov et al (1964)	0.39	1600	6.00	
	4.70			6.61
	8.51			6.41
	18.56			3.43

TABLE 8. Experimental Data of Shear Dynamic Viscosity of Liquid Fe-O Alloys at 1 atm

Reference	Composition wt% O	Temperature (°C)	Dynamic Viscosity (centipoises)
Nakanishi et al (1967)	0.012	1600	5.02
	0.046		5.43
	0.071		5.40
	0.072		5.39

TABLE 9. Experimental Data of Shear Viscosity of Liquid Fe-Si Alloys at 1 atm

Reference	Composition wt% Si	Temperature (°C)	Viscosity	
			Dynamic (centipoises)	Kinematic (millistokes)
Romanov and Kochegarov (1964)	0.1	1540		9.62
		1580		8.72
		1621		7.78
		1668		7.55
		1743		7.04
		1782		6.66
		1806		6.61
	0.6	1549		7.70
		1605		6.92
		1642		6.83
		1707		6.36
		1756		6.15
	2.0	1508		7.39
		1553		6.90
		1592		6.46
		1654		5.85
		1712		5.69
		1758		5.49
	5.0	1454		8.14
		1508		6.78
		1575		6.02
		1627		5.61
		1677		5.40
		1716		5.37

TABLE 9 (continued)

Reference	Composition wt% Si	Temperature (°C)	Viscosity Dynamic (centipoises)	Viscosity Kinematic (millistokes)
Nakanishi et al (1967)	0.9	1615	4.13	
	2.9		3.54	
Kaplun et al (1979)	1.0	1550	5.41	
	2.0	1550	5.29	
		1600	4.89	
	3.0	1500	5.74	
		1550	5.18	
		1600	4.84	
	4.5	1500	5.51	
		1550	5.05	
		1600	4.72	
	6.0	1500	5.04	
		1550	4.65	
		1600	4.35	

Acknowledgements. I gratefully acknowledge helpful discussions with H.H. Schloessin and L. Mansinha, comments in reviews by D.L. Anderson and an anonymous reviewer, as well as financial support by the Natural Sciences and Engineering Research Council of Canada.

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