

The Object at the Centre of the Earth

J.M. Herndon

Herndon Science and Software, 11044 Red Rock Drive, San Diego, California 92131, USA

The foundation is described for understanding the chemical composition of the inner core, the core and the lower mantle of the Earth.

The Earth consists of concentric shells of matter surrounding a nearly spherical object at the centre. The dimensions of the Earth were first known by the geometry of the ancient Greeks, but knowledge of the matter within the Earth comes from more recent discoveries, primarily arising from investigations of meteorites and earthquake waves.

The mass of the Earth, 6.0×10^{27} g, was determined by Newtonian mechanics after the universal gravitation constant had been measured. The ratio of mass to volume of the Earth, 5.5 g/cm^3 , is larger than that of the rocks of its surface regions, 2.9 g/cm^3 , by an amount too great to be the result of gravitational compression alone. Having observed that some meteorites are composed almost entirely of a more dense, 7.8 g/cm^3 , iron-based alloy, Wiechert suggested in 1897 that the Earth has a core of similar matter [1]. Soon thereafter, in 1906, Oldham found, from studies of the nature and travel times of earthquake waves, evidence for the existence of a fluid core [2]. The Danish seismologist, Inge Lehmann discovered in 1936 that the fluid core was but another mass shell surrounding a solid object at the centre of the Earth, slightly larger than the moon, the so-called inner core [3].

Since the last century, ideas concerning the identification of the substances within the Earth have been evoked by observations of meteorites. Meteorites are rocks of extra-terrestrial origin that arrive from space and survive atmospheric entry [4]. The heat of friction developed during flight through the atmosphere causes some surface melting and evaporation. But

continuous removal of surface material by atmospheric drag confines thermal damage to the outer few millimeters. The identical nuclear compositions for many corresponding elements of the Earth and the more than two thousand known meteorites attests to their having been derived from primordial matter of common origin [5]. Meteorites formed about 4650 million years ago, only a few million years after the event(s) that created their elements and a few hundred million years before solidification of the oldest known Earth rocks [6]. Meteorites are mineralogically diverse. Some meteorites consist entirely of nickel-iron metal, whereas some are composed of stone and others of stone and metal together. Meteorites are diverse in elemental as well as mineral content [7]. The relative abundances of the elements in certain meteorites, called chondrites, are related to properties of the atomic nuclei [8] and are similar to corresponding abundances obtained from the spectral analysis of sunlight [9]. Some chondrites, called carbonaceous chondrites, contain organic compounds and several percent water by mass [10]. Other chondrites are anhydrous and have constituents that were at some time molten. The anhydrous chondrites consist of two principal components that are readily discerned by the criterion of whether or not light is transmitted through a thin piece of the meteorite. The translucent portion consists of oxygen-containing compounds, primarily silicate minerals. The silicate minerals generally have higher melting points and lower densities than the opaque substances that crystallized from the iron-based alloy.

The idea that the meteoritic silicate and iron-based alloy components are in some way similar to the mantle and core of the Earth has long been in the minds of scientists. But the situation is by no means straightforward. Meteorites display considerable diversity in the relative proportions of their opaque and translucent components, in the elements that comprise those components and in the compounds that crystallized

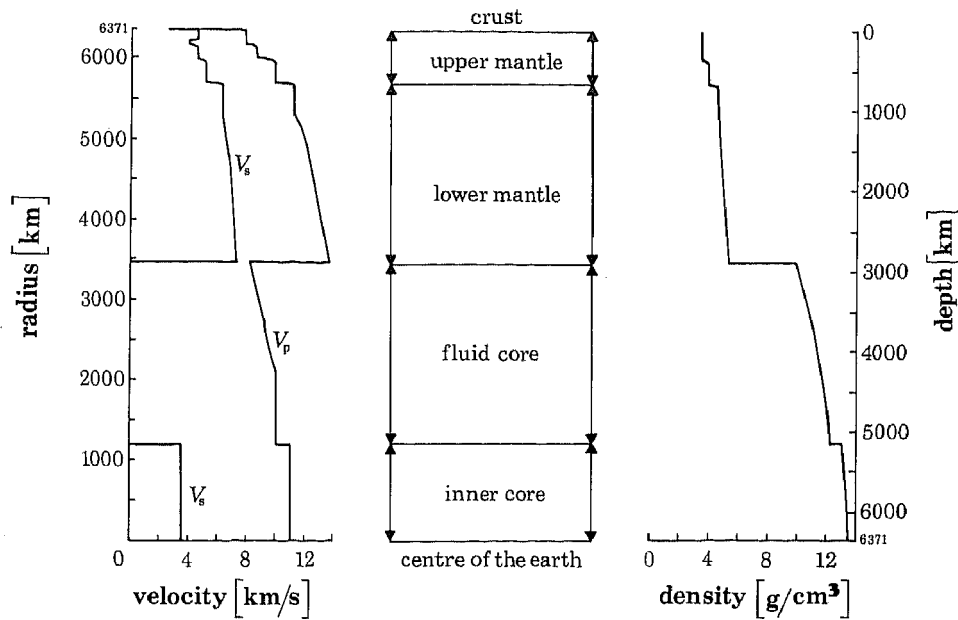


Fig. 1. The principal divisions and physical states of the interior parts of the Earth are indicated by the compressional velocity V_p and the shear velocity V_s of earthquake waves, and the density as a function of depth (from [16], based on the data of [18])

from them. The two principal components of the Earth are also complex. The mantle of the Earth is subdivided into two major parts, the upper and lower mantles, on the basis of the seismic discontinuity that occurs at a depth of about 700 km. The fluid mass shell of the core is bounded by the lower mantle and the solid object at the centre (Fig. 1). The identification of the composition of the solid object at the centre of the Earth is inextricably related to the abundances of the elements in meteoritic matter. Because iron and nickel are alloyed in most meteorites and because heavier elements are less than one

percent as abundant, it had been thought that the inner core, which has a mass of about five percent that of the total core, consists of partially crystallized, nickel-iron metal [11]. One suggestion not related to abundances, that the inner core is the result of a pressure-induced electronic transition in iron [12, 13], was disqualified by calculations showing the Earth to be insufficiently massive for the required compression [14].

I was first to conceive of the idea that the inner core consists, not of nickel-iron metal, but of nickel silicide [15], a mineral discovered in the 1960's in members of a rare group of enstatite meteorites. Subsequently, I discovered [16], using published data [17–19], a fundamental relationship between the components of a particular type of meteoritic matter and the interior parts of the Earth, expressed as ratios of mass:

$$1.49 = \frac{\text{lower mantle mass}}{\text{total core mass}}$$

$$1.43 = \frac{\text{Abee enstatite chondrite silicate mass}}{\text{Abee enstatite chondrite alloy mass}}$$

$$0.0208 = \frac{\text{inner core mass}}{\text{lower mantle-plus-core mass}}$$

$$0.0206 = \frac{\text{Abee nickel silicide mass (theoretical Ni}_2\text{Si)}}{\text{Abee meteorite mass}}$$

The relative abundances of the major elements of the Abee meteorite are compared in Table 1 to those of the more oxygen-rich H and L group chondrites. The similarity in their elemental abundances stems from their having formed from primordial matter of

Table 1. Atomic abundances of the sixteen most abundant elements relative to iron in the Abee enstatite chondrite and in the H and L group chondrites [20]

	Abee	H group	L group
O	3.18×10^6	4.14×10^6	6.59×10^6
Na	6.05×10^4	5.17×10^4	7.45×10^6
Mg	7.46×10^5	1.19×10^6	1.63×10^6
Al	4.93×10^4	7.52×10^4	1.07×10^5
Si	1.03×10^6	1.23×10^6	1.73×10^6
P	1.20×10^4	7.15×10^3	8.32×10^3
S	3.08×10^5	1.36×10^5	1.73×10^5
Ca	3.66×10^4	6.14×10^4	8.39×10^4
Ti	2.05×10^3	2.59×10^3	3.64×10^3
Cr	1.04×10^4	1.31×10^4	1.89×10^4
Mn	1.03×10^4	8.38×10^3	1.13×10^4
Fe	$\equiv 10^6$	$\equiv 10^6$	$\equiv 10^6$
Co	2.26×10^3	2.96×10^3	2.25×10^3
Ni	5.23×10^4	5.67×10^4	4.85×10^4
Cu	5.13×10^2	2.96×10^2	3.29×10^2
Zn	1.03×10^3	1.60×10^3	2.25×10^3

Table 2. Distribution of the elements among the lower mantle and total core (fluid mass shell plus inner core), calculated from the data of [17, 18, 23] (in g)

Lower mantle			
O	1.53×10^{27}	Al	3.96×10^{25}
Si	7.85×10^{26}	Na	3.36×10^{25}
Mg	5.05×10^{26}	Ca	2.38×10^{25}
Total core			
Fe	1.45×10^{27}	Ca	1.84×10^{25}
S	2.84×10^{26}	Cr	1.58×10^{25}
Ni	8.31×10^{25}	P	9.32×10^{24}
Mg	4.75×10^{25}	Mn	5.34×10^{24}
Si	3.26×10^{25}	Co	4.15×10^{24}
		Mn	5.77×10^{24}
		Fe	5.02×10^{24}
		Ti	2.23×10^{24}
		Zn	2.09×10^{24}
		Cu	8.61×10^{23}

Table 3. Combinations of light elements previously suggested as being alloyed with nickel and iron in the core of the Earth

C, Si, H [24]	Si [28, 29]
C, S [25]	C, S, Si [30]
Si, O, S [26]	S [31-33]
Mg, O [27]	O [34, 35]

well defined chemical composition. The compounds formed of the elements in Abee and in the rare enstatite meteorites are unlike those found in other types of meteorites or in the surface regions of the Earth. In the more oxygen-rich meteorites all silicon, all magnesium, and some iron, are combined with oxygen as silicate minerals. That results in their having significantly greater silicate to alloy mass ratios than the 1.43 of the Abee meteorite [21], for example:

$$3.58 = \frac{\text{H group chondrite silicate mass}}{\text{H group chondrite alloy mass}}$$

$$7.28 = \frac{\text{L group chondrite silicate mass}}{\text{L group chondrite alloy mass}}$$

The Abee meteorite and the interior of the Earth formed under conditions of limited available oxygen. The silicate phase, corresponding to the lower mantle of the Earth, consists primarily of enstatite (MgSiO_3) that is practically devoid of oxidized iron. During formation, available oxygen was so limited that even some magnesium and some silicon remained uncombined as components of the iron-based alloy [22]. The presence of elemental silicon is a necessary condition for the initial precipitation of nickel silicide.

The distribution of the elements among the lower mantle and total core shown in Table 2 is predicted by analogy with the components of the Abee meteorite. Only those elements are shown whose distribution is known among the silicates and the minerals that crystallized from the iron-based alloy of the Abee meteorite [17].

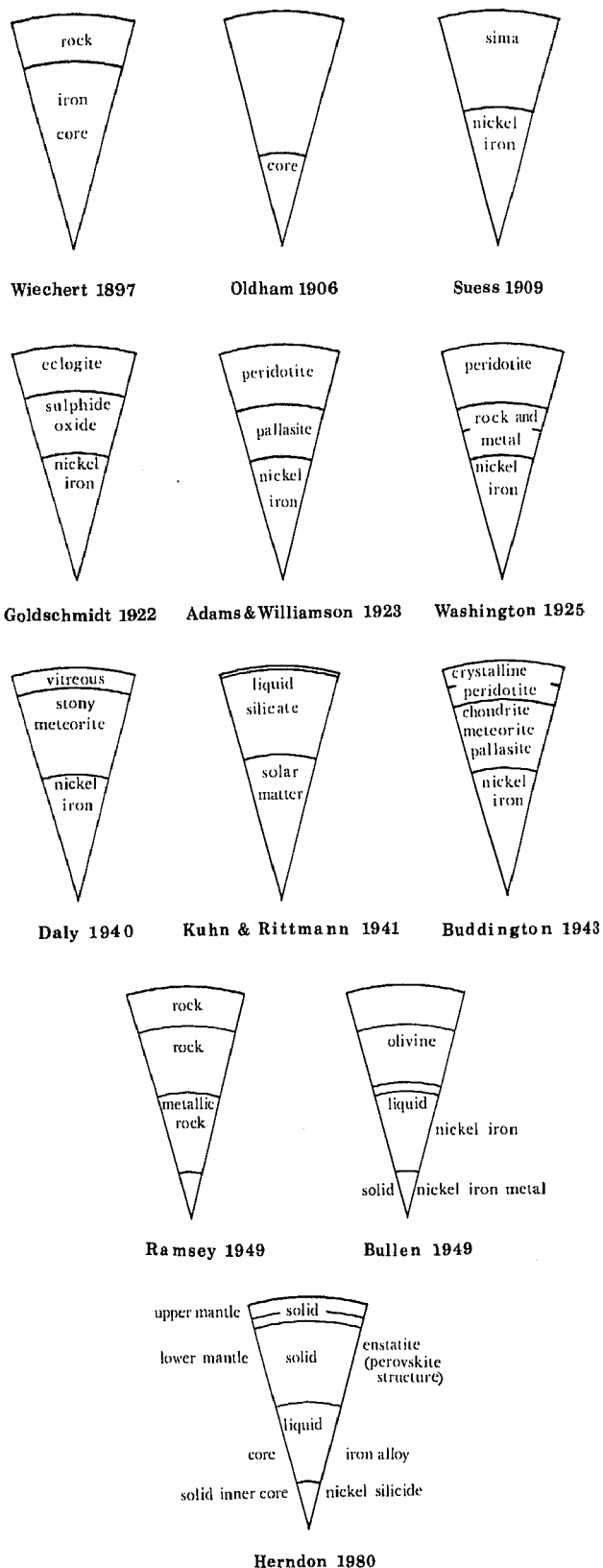


Fig. 2. Schematic representation of the evolution of ideas bearing on the composition of the interior of the Earth [1, 2, 16, 37-45]

Birch [21] found from density distribution calculations that the mean uncompressed density of the total core of the Earth is 5–15% less dense than iron or, alternatively, that the mean atomic mass of the total core is 5–15% lighter than the atomic mass of iron. The mean atomic mass of the iron-based alloy of the Abee meteorite and, hence, of the total core of the Earth, calculated from the abundance distribution shown in Table 2, is 13.9% lighter than the atomic mass of iron. Various combinations of light elements have been suggested as being alloyed with nickel and iron in the core of the Earth (Table 3), but none are like the combination of elements shown in Table 2.

The values for mean atomic number and mean atomic mass of the total core of the Earth found by Knopoff and MacDonald [36] to be consistent with shock wave velocity data and density measurements and with seismic observations are identical to those of the iron-based alloy of the Abee meteorite calculated from the mineralogical data of Keil [17].

	Z	\bar{M}
Abee meteorite iron-based alloy	22.8	48.08
Seismologically deduced values	23	48

The evolution of ideas bearing on the composition of the interior of the Earth is schematically represented in Fig. 2.

Whereas determination of the mass distribution or pressure within the Earth is straightforward, estimation of the temperature is not. The idea is invalidated that the temperature at the boundary of the inner core can be obtained by extrapolation of the melting point curve of iron to the respective pressure [46]. Until such a time that melting point measurements as functions of pressure have been made for nickel silicide and until phase relations in the medium of the composition shown in Table 2 have been elucidated, the temperature near the centre of the Earth will remain unknown.

1. Wiechert, E.: *Nachr. Ges. Wiss. Göttingen, Math. Phys. Kl.* 3, 1 (1897)
2. Oldham, R.D.: *Quart. J. Geol. Soc. Lond.* 62, 456 (1906)
3. Lehmann, I.: *Publs. Bur. Cent. Seism. Int. A* 14, 3 (1936)
4. Chladni, E.F.F.: *Über den Ursprung der von Pallas gefundenen und anderer ihr ähnlicher Eisenmassen und über einige damit in Verbindung stehende Naturerscheinungen.* Riga: J.F. Hartknoch 1794

5. Kielbasinski, J., Warnat, L.: *Nuclear Energy Information Center Review Report No. 32, Warsaw, Poland* (1968)
6. Gray, C.M., Compston, W.: *Nature* 251, 495 (1974)
7. Mason, B.: *Meteorites.* New York: Wiley 1962
8. Suess, H.E., Urey, H.C.: *Rev. Mod. Phys.* 28, 53 (1956)
9. Holweger, H.: *Earth Planet. Sci. Lett.* 34, 152 (1977)
10. Hodgson, G.W., Baker, B.L.: *Nature* 202, 125 (1964)
11. Birch, F.: *Am. J. Sci.* 238, 192 (1940)
12. Elsasser, W.M., Isenberg, I.: *Phys. Rev.* 76, 469 (1949)
13. McLachlan, D.W., Ehlers, E.: *J. Geophys. Res.* 76, 2780 (1971)
14. Bukowski, M.S.T., Knopoff, L.: *Geophys. Res. Lett.* 3, 45 (1976)
15. Herndon, J.M.: *Proc. Roy. Soc. Lond. A* 368, 495 (1979)
16. Herndon, J.M.: *ibid.* 372, 149 (1980)
17. Keil, K.: *J. Geophys. Res.* 73, 6945 (1968)
18. Dziewonski, A.M., Gilbert, F.: *Geophys. J. Roy. Astr. Soc.* 72, 393 (1972)
19. Dawson, K.R., Maxwell, J.A., Parsons, D.E.: *Geochim. Cosmochim. Acta* 21, 127 (1960)
20. Mason, B.: *Handbook of Elemental Abundances in Meteorites.* New York: Gordon & Breach 1971
21. Keil, K.: *J. Geophys. Res.* 67, 4055 (1962)
22. Herndon, J.M., Suess, H.E.: *Geochim. Cosmochim. Acta* 40, 395 (1976)
23. Baedeker, P.A., Wasson, J.T.: *ibid.* 39, 735 (1975)
24. Birch, F.: *J. Geophys. Res.* 57, 227 (1952)
25. Urey, H.C.: *Geochim. Cosmochim. Acta* 18, 151 (1960)
26. Birch, F.: *J. Geophys. Res.* 69, 4377 (1964)
27. Alder, B.J.: *ibid.* 71, 4973 (1966)
28. MacDonald, G.J.F., Knopoff, L.: *Geophys. J. J.* 284 (1958)
29. Ringwood, A.E.: *Geochim. Cosmochim. Acta.* 15, 195 (1958)
30. Clark, S.P., Jr., in: *The Earth Sciences* (ed. T.W. Donnelly). Chicago: Univ. of Chicago Press 1963
31. Mason, B.: *Nature* 211, 616 (1966)
32. Murthy, V.R., Hall, H.T.: *Phys. Earth Planet. Interiors* 6, 123 (1970)
33. Lewis, J.S.: *Ann. Rev. Phys. Chem.* 24, 339 (1973)
34. Bullen, K.E.: *Nature* 243, 68 (1973)
35. Ringwood, A.E.: *Publ. No. 1299, Res. School of Earth Sciences, Australian Nat. Univ. Canberra* (1977)
36. Knopoff, L., MacDonald, G.J.F.: *Geophys. J. Roy. Astr. Soc.* 3, 68 (1960)
37. Suess, E.: *Das Antlitz der Erde.* Wien 1909
38. Goldschmidt, V.M.: *Naturwissenschaften* 10, 918 (1922)
39. Adams, L.J., Williamson, E.D.: *J. Wash. Acad. Sci.* 13, 413 (1923)
40. Washington, H.S.: *Am. J. Sci.* 9, 351 (1925)
41. Daly, R.A.: *Strength and Structure of the Earth.* New York: McGraw-Hill 1940
42. Buddington, A.F.: *Am. Miner.* 28, 119 (1943)
43. Kuhn, W., Rittmann, A.: *Geol. Rdsch.* 32, 215 (1941)
44. Ramsey, W.H.: *M.N. Roy. Astr. Soc., Geophys. Suppl.* 5, 409 (1949)
45. Bullen, K.E.: *ibid.* 5, 355 (1949)
46. Strong, H.M.: *Nature* 183, 1381 (1959)

Received February 9, 1981