Proc. R. Soc. Lond. A **368**, 495–500 (1979)
Printed in Great Britain

The nickel silicide inner core of the Earth

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(*Communicated by H. C. Urey, For.Mem.R.S. – Received* 27 *November* 1978
– Revised 19 *April* 1979)

From observations of nature the suggestion is made that the inner core of the Earth consists not of nickel–iron metal but of nickel silicide.

Contemporary understanding of the physical state and chemical composition of the interior of the Earth is derived primarily from interpretations of seismological measurements and from inferences drawn from observations of meteorites. Seismological investigations by Oldham (1906), Gutenberg (1914) and others helped to establish the idea that a fluid core extends to approximately one half the radius of the Earth. The existence of a small, apparently solid inner core at the centre of the Earth was recognized by Lehmann (1936) from interpretations of earthquake records and has been confirmed by Gutenberg & Richter (1938), Jeffreys (1939), Bullen (1957) and others. Observations of meteorites consisting almost entirely of nickeliferous iron led, by inference, to the idea that the fluid core of the Earth consists of molten nickel–iron metal (see, for example, Buddington 1943; Daly 1943). Birch (1952) found from density distribution calculations, however, that pure iron (and, to a greater extent, nickel–iron alloy) would be more dense, by 5–15%, than the calculated core density, thus indicating that one or more light elements are alloyed with nickel–iron in the core. The variety of combinations of light elements proposed (table 1) can be taken as an indication of contemporary uncertainty in the understanding of the chemical composition of interior of the Earth.

Because elements heavier than iron and nickel are less than 1% as abundant in meteorites, it is widely believed that the inner core of the Earth, which has a mass of *ca.* 5% of that of the core, consists of partially crystallized, nickel–iron metal (Brett 1976). Such a metastable state would require the temperature at the inner core boundary to be equal to the melting point of nickel–iron at the relevant pressure and would require the heat content of the core to remain essentially unchanged with the passage of time. Otherwise, the inner core would either grow or diminish. The alternative suggestion that the inner core is the result of a pressure-induced electronic transition in iron (Elsasser & Isenberg 1949; McLachlan & Ehlers 1971) appears, from recent calculations (Bukowinski & Knopoff 1976) to be untenable.

The Earth and meteorites were derived from primordial matter of common origin. The individual elements that comprise the Earth and meteorites are ensembles of specific nuclear species which occur in remarkably unique relative proportions (figure 1).

TABLE 1. LIGHT ELEMENTS SUGGESTED BEING ALLOYED WITH NICKEL–IRON IN THE FLUID CORE OF THE EARTH

C, Si, H (Birch 1952)	Si (MacDonald & Knopoff 1958; Ringwood 1958)
C, S (Urey 1960)	C, S, Si (Clark 1963)
Si, O, S (Birch 1964)	S (Mason 1966; Murthy & Hall 1970; Lewis 1973)
Mg, O (Adler 1966)	O (Bullen 1973; Ringwood 1977)

The relative abundances of many elements in certain types of meteorites, called chondrites, are quite similar to corresponding abundances in the Sun, the latter being obtained from the spectral analysis of sunlight. Primordial elemental abundances appear to be related, although in a complex manner, to nuclear properties (Suess & Urey 1956; Suess & Zeh 1973; Urey 1972). Physical processes involved in the formation of chondrites did not appreciably separate the less volatile primordial elements from one another (figure 2).

Certain chondrites, such as the Orgueil meteorite, consist almost exclusively of

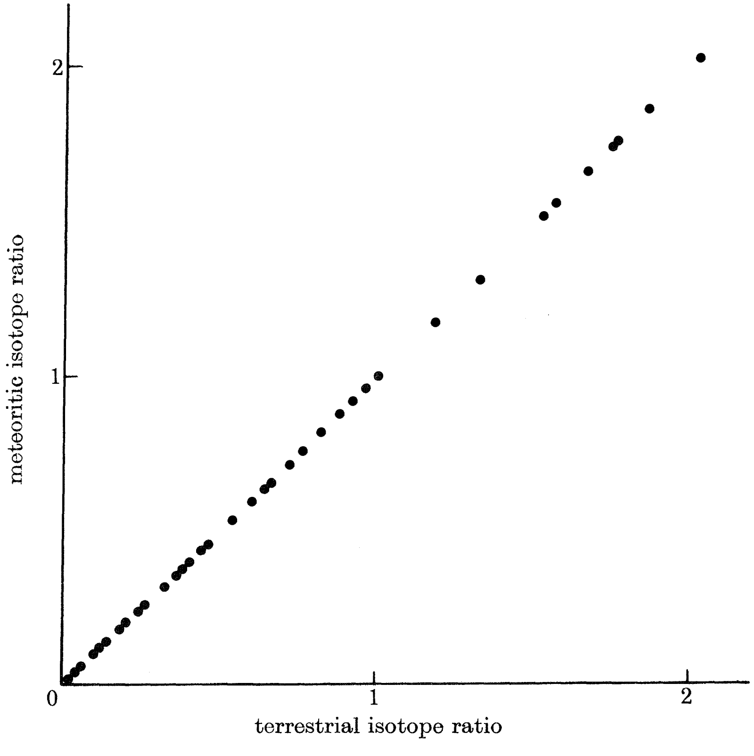

FIGURE 1. Comparison of meteoritic and terrestrial isotope ratios of 15 elements. Some of the 52 isotope ratios plotted from literature values are coincident on this scale (see, for example, Kielbasinski & Wanat 1968).

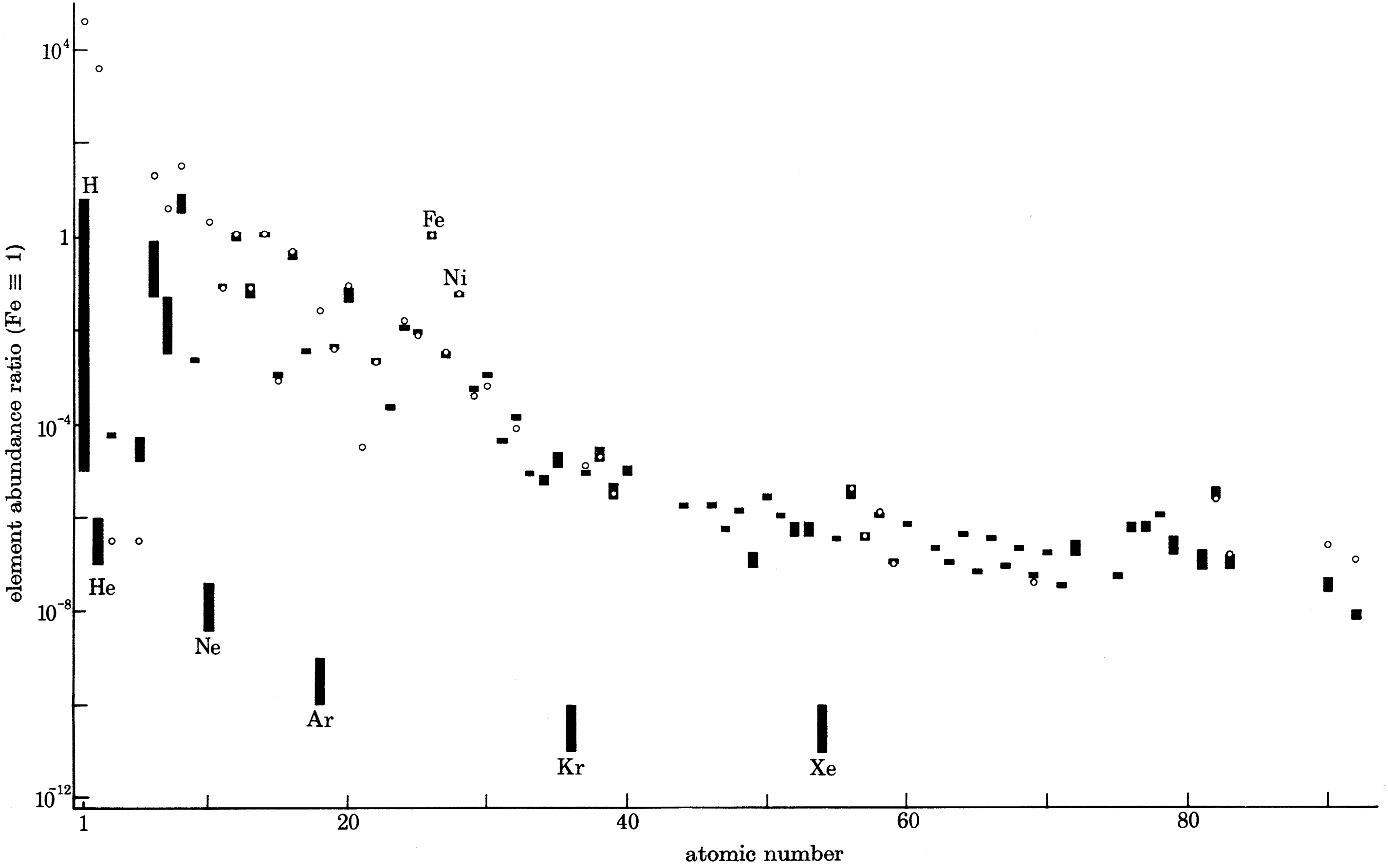

FIGURE 2. Comparison of elemental abundance ratios obtained from spectral analysis of sunlight (○) with corresponding ratios, normalized to iron, obtained from chemical analysis of chondritic meteorites (■): the tops of the bars represent literature values for the hydrated oxygen-rich Orgueil meteorite, the bottoms, those for the anhydrous oxygen-poor Abee enstatite chondrite (see, for example, Holweger 1977).

low temperature hydrated minerals (Boström & Fredriksson 1966). Most chondrites, however, contain minerals which formed under anhydrous conditions at temperatures sufficiently high as to have resulted in melting (Rose 1825; Ramdohr 1973). Igneous chondrites differ in their respective oxygen content and, consequently, in the relative proportions of their principal components: silicate/oxide minerals, sulphides and metal (table 2).

TABLE 2. MINERAL ASSEMBLAGES CHARACTERISTIC OF THE CHONDRITIC METEORITES

hydrated chondrites

epsomite, $MgSO_4.7H_2O$
complex hydrated layer lattice silicates, e.g. $(Mg, Fe)_6Si_4O_{10}(O, OH)_8$
magnetite, Fe_3O_4

anhydrous chondrites

oxygen-rich carbonaceous chondrites	*ordinary chondrites*	*oxygen-poor enstatite chondrites*
pentlandite, $(Fe, Ni)_9S_8$	troilite, FeS	complex mixed sulphides e.g. (Ca, Mg, Mn, Fe)S
troilite, FeS	olivine $(Fe, Mg)_2SiO_4$	pyroxene, $MgSiO_3$
olivine $(Fe, Mg)_2SiO_4$	pyroxene $(Fe, Mg)_2SiO_3$	metal (Fe–Ni–Si alloy)
pyroxene $(Fe, Mg)SiO_3$	metal (Fe–Ni alloy)	nickel silicide, Ni_2Si

Many of the oxygen-rich carbonaceous chondrites contain almost no metal (Herndon *et al.* 1976). Most chondrites, however, contain less oxygen. Certain of these, called ordinary chondrites, consist principally of iron oxide-bearing silicate minerals, iron sulphide and nickeliferous iron metal (Keil 1962). The metal of ordinary chondrites is similar in composition to the metal meteorites that evoked early ideas about the core of the Earth. The oxygen-poor enstatite chondrites, on the other hand, consist of silicates almost totally devoid of iron oxide. Iron sulphide occurs, as do sulphides of some elements, such as magnesium, that occur as silicate/oxide minerals in ordinary chondrites. Elemental silicon is present in the metal, and nickel silicide occurs. Meteoritic nickel silicide occurs both as lamellar exsolutions from silicon-bearing iron metal (Ramdohr & Kullerud 1962; Ramdohr 1964; Fredriksson & Henderson 1965; Wasson & Wai 1970; Wai 1970) and as more massive forms intimately associated with metal and iron sulphide in certain enstatite chondrites (Reed 1968; Ramdohr 1973). Among different meteorites, little variation in elemental composition has been reported: 75–81 % Ni, 3–7 % Fe, 12–15 % Si and 2–5 % P.

At ambient pressure nickel silicide of composition Ni_2Si has a melting point (1309 °C) nearly as high as that of pure iron (1533 °C) and even higher than the melting points of some iron-based alloys (Hansen 1958). At ambient temperature and pressure, Ni_2Si has a density of 7.2 g/cm^3; Ni_3Si, 7.9 g/cm^3. The density of nickel silicide is almost identical to that of pure iron (7.86 g/cm^3) and is thus more than the uncompressed density of the core of the Earth (Birch 1952). The occurrence of nickel silicide in enstatite chondrites is proof of its insolubility in oxygen-poor primordial matter.

I suggest that the inner core of the Earth consists of nickel silicide that crystallized from the liquid and settled by the action of gravity to the centre of the Earth. Because nickel is *ca.* 5% as abundant as iron in primordial matter, a fully crystallized inner core of the composition of meteoritic nickel silicide would comprise a mass remarkably similar to that inferred from seismological data. The existence of a nickel silicide inner core would indicate that the interior of the Earth was formed from primordial matter that was sufficiently oxygen-poor as to have caused elemental silicon to be present in the iron liquid. The physical state and chemical composition of the Earth, as derived from earthquake waves times of travel and from the above considerations, is illustrated in figure 3.

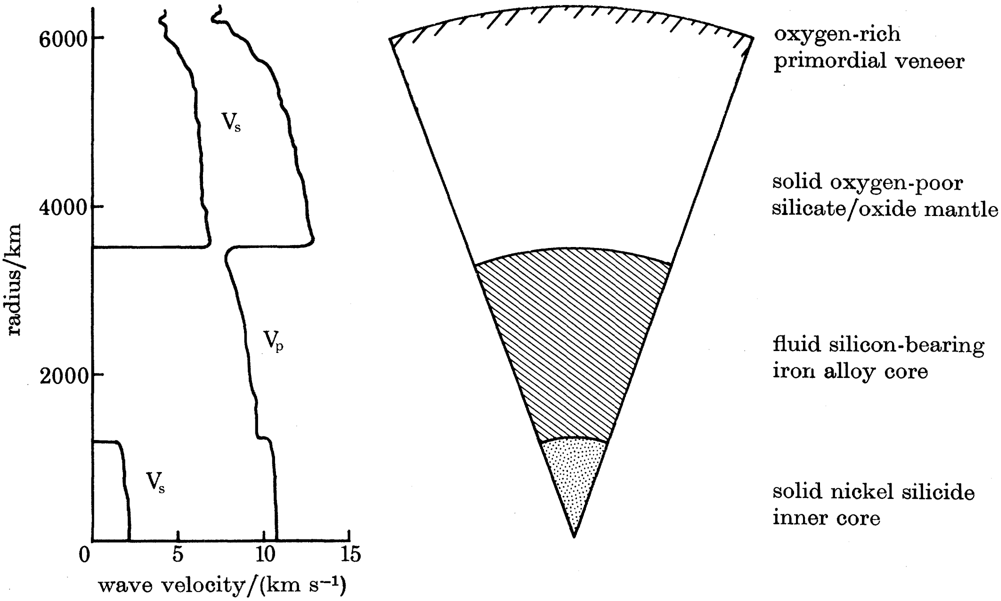

FIGURE 3. The principal divisions and physical state of the interior of the Earth is indicated by the compressional velocity, V_p, and the shear velocity, V_s, of earthquake waves (after Anderson *et al.* 1971). The fluid core cannot support shear waves. The identification of these features with the principal components of oxygen-poor primordial matter is indicated. The oxidized iron and siderophile element content of rocks from the surface regions suggests a veneer of more oxygen-rich primordial matter. The depth and extent of mixing with the reduced silicate/oxide minerals is unknown.

This work was supported by N.A.S.A. grant NSG 7474.

REFERENCES

Alder, B. J. 1966 *J. geophys. Res.* **71**, 4973–4979.

Anderson, D. L., Sammis, C. & Jordan, T. 1971 *Science, N.Y.* **171**, 1103–1112.

Birch, F. 1952 *J. geophys. Res.* **57**, 227–286.

Birch, F. 1964 *J. geophys. Res.* **69**, 4377–4388.

Boström, K. & Fredriksson, K. 1966 *Smithson. misc. Collns* **151**, no. 3, p. 39.

Brett, R. 1976 *Rev. Geophys. Space Phys.* **14**, 375–383.

Buddington, A. F. 1943 *Am. Miner.* **28**, 119–140.

Bukowinski, M. S. T. & Knopoff, L. 1976 *Geophys. Res. Lett.* **3**, 45–48.

Bullen, K. E. 1957 *Nature, Lond.* **180**, 49–50.

Bullen, K. E. 1973 *Nature, Lond.* **243**, 68–70.

Clark, S. P., Jr 1963 in *The earth sciences* (ed. T. W. Donnelly). Chicago: University of Chicago Press.

Daly, R. A. 1943 *Bull. geol. Soc. Am.* **54**, 401–456.

Elsasser, W. M. & Isenberg, I. 1949 *Phys. Rev.* **76**, 469.

Fredriksson, K. & Henderson, E. P. 1965 *Trans. Am. geophys. Un.* **46**, 121.

Gutenberg, B. 1914 *Göttinger Nachr.* **166**, 218.

Gutenberg, B. & Richter, C. F. 1938 *Mon. Not. R. astr. Soc. geophys. Suppl.* **4**, 363–372.

Hansen, M. 1958 *Constitution of binary alloys.* New York: McGraw-Hill.

Herndon, J. M., Rowe, M. W., Larson, E. E. & Watson, D. E. 1976 *Earth Planet. Sci. Lett.* **29**, 283–290.

Holweger, H. 1977 *Earth Planet. Sci. Lett.* **34**, 152–154.

Jeffreys, H. 1939 *Mon. Not. R. astr. Soc. geophys. Suppl.* **4**, 548–561.

Keil, K. 1962 *J. geophys. Res.* **67**, 4055–4061.

Kielbasinski, J. & Wanat, L. 1968 *Nuclear Energy Information Centre Review Report* no. 32. Warsaw, Poland.

Lehmann, I. 1936 *Publs Bur. cent. sism. int.* **A14**, 3–31.

Lewis, J. S. 1973 *A. Rev. phys. chem.* **24**, 339–351.

MacDonald, G. J. F. & Knopoff, L. 1958 *Geophys. J.* **1**, 284–297.

Mason, B. 1966 *Nature, Lond.* **211**, 616–618.

McLachlan, D. W. & Ehlers, E. 1971 *J. geophys. Res.* **76**, 2780–2789.

Murthy, V. R. & Hall, H. T. 1970 *Phys. Earth planet. Interiors* **6**, 123–130.

Oldham, R. D. 1906 *Q. J. geol. Soc. Lond.* **62**, 456–475.

Ramdohr, P. 1964 *Sber. dt. Akad. Wiss.*, Kl. Chem., Geol., Biol., no. 5, 1–40.

Ramdohr, P. 1973 *The opaque minerals in stony meteorites.* New York: Elsevier.

Ramdohr, P. & Kullerud, G. 1962 *Carnegie Inst. Wash. Yb.* **61**, 163.

Reed, S. J. B. 1968 *Mineralog. Mag.* **36**, 850–854.

Ringwood, A. E. 1958 *Geochim. cosmochim. Acta* **15**, 195–212.

Ringwood, A. E. 1977 *Publ.* no. 1299, Research School of Earth Sciences, Australian National University, Canberra.

Rose, G. 1825 *Annln Phys.* **4**, 173–204; (abstract) *Edinb. phil. J.* **13**, 368.

Suess, H. E. & Urey, H. C. 1956 *Rev. mod. Phys.* **28**, 53–74.

Suess, H. E. & Zeh, H. D. 1973 *Astrophys. & Space Sci.* **23**, 173–187.

Urey, H. E. 1960 *Geochim. cosmochim. Acta* **18**, 151–153.

Urey, H. C. 1972 *Ann. N.Y. Acad. Sci.* **194**, 35–44.

Wai, C. M. 1970 *Mineral. Mag.* **37**, 905–908.

Wasson, J. T. & Wai, C. M. 1970 *Geochim. cosmochim. Acta* **34**, 169–184.