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The chemical composition of the interior shells of the Earth

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The suggestion is made that the core and lower mantle of the Earth are chemically analogous to the two principal components of highly reduced enstatite chondrite meteorites. This suggestion is supported by mass ratio comparisons.

The Earth consists of concentric shells of matter. Those beneath the surface are identified by the manner that their physical properties affect the passage of waves generated by earthquakes, nuclear explosions, etc. The physical states and densities of the concentric shells of the Earth are obtained from interpretations of seismological measurements (Oldham 1906; Gutenberg 1914; Lehmann 1936; Gutenberg & Richter 1938; Jeffreys 1939; Bullen 1957; Dziewonski & Gilbert 1971). Wave velocities and density as functions of radius, obtained from observations of the periods of the free oscillations of the Earth (Dziewonski & Gilbert 1972), are shown in figure 1 together with a schematic representation of the shells deduced therefrom. Their respective masses and volumes are shown in table 1.

The compositions of the outer shells are inferred primarily from chemical and isotopic analyses of near-surface matter, including rocks thought to have come from a depth of *ca.* 200 km (Jagoutz *et al.* 1979; Wasserburg & DePaolo 1979). The compositions of the interior shells are inferred primarily from observations of meteorites. The existence of meteorites consisting almost entirely of nickeliferous iron led, by inference, to the idea that the fluid shell of the Earth consists of molten nickel–iron metal (see, for example, Buddington 1943; Daly 1943). The variety of suggestions for combinations of light elements thought to be alloyed with molten nickel–iron metal (Birch 1952) is an indication of contemporary uncertainty in understanding the chemical composition of the interior of the Earth (table 2). Because meteoritic metal is typically an alloy of nickel and iron and because elements heavier than those are less than 1 % as abundant in meteorites, it has been widely believed that the solid sphere at the centre of the Earth (Lehmann 1936) consists of partially crystallized nickel–iron metal (Bukowinski & Knopoff 1976). From observations of nature I have suggested that the inner core of the Earth consists not of partially crystallized nickel–iron metal, but of fully crystallized nickel silicide (Herndon 1979).

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The Earth and meteorites were derived from primordial matter of common origin. The abundance ratios of the less volatile elements in chondritic meteorites are related to nuclear properties and are similar to corresponding ratios obtained from the spectral analysis of sunlight. Physical processes involved in the formation of chondrites did not appreciably separate the less volatile primordial elements from one another. Variation in oxygen content among different groups of chondrites is responsible for their major mineralogical differences (table 3). The most oxygen-rich chondrites contain little or no iron metal, the major portion of their

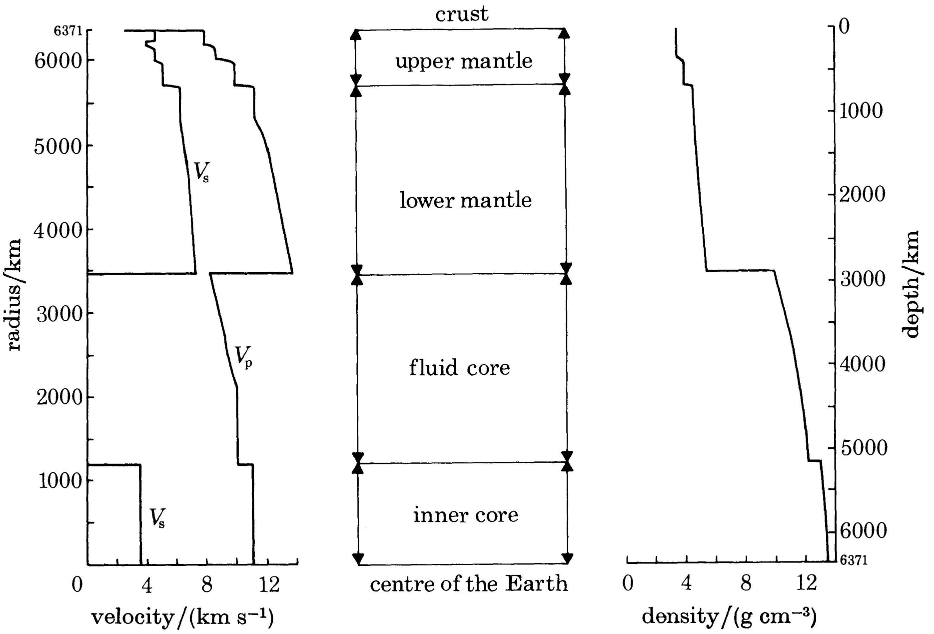

FIGURE 1. The principal divisions and physical state of the interior of the Earth are indicated by the compressional velocity V_p and the shear velocity V_s of earthquake waves, and the density as a function of depth (from Dziewonski & Gilbert 1972).

TABLE 1. MASSES AND VOLUMES OF THE PRINCIPAL SHELLS OF THE EARTH

division	mass/g	volume/cm³
crust	1.23×10^{25}	5.093×10^{24}
upper mantle	1.086×10^{27}	3.071×10^{26}
lower mantle	2.922×10^{27}	5.993×10^{26}
total core (including inner core)	1.957×10^{27}	1.768×10^{26}
inner core	1.014×10^{26}	7.625×10^{24}

TABLE 2. LIGHT ELEMENTS SUGGESTED BEING ALLOYED WITH NICKEL–IRON IN THE FLUID CORE OF THE EARTH

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

iron occurring as the oxide in silicate minerals. The most oxygen-poor chondrites, on the other hand, are so highly reduced that elemental silicon is present in the metal phase and the silicates are virtually devoid of oxidized iron. It is in these oxygen-poor enstatite chondrites that nickel silicide occurs (Herndon, 1979).

Ultramafic nodules from alkali basalts, thought by some to be representative of upper mantle material, contain oxidized iron and have ratios of siderophile elements, such as Ni, Co, Cu and W, that are the same as corresponding ratios in chondritic meteorites (Jagoutz *et al.* 1979).

TABLE 3. MINERAL ASSEMBLAGES CHARACTERISTIC OF THE CHONDRITIC METEORITES

hydrous chondrites
epsomite, $MgSO_4 . 7H_2O$
complex hydrous layer lattice silicates e.g. $(Mg, Fe)_6 Si_4O_{10}(O, OH)_8$
magnetite, Fe_3O_4

anhydrous chondrites

oxygen-rich carbonaceous chondrites	ordinary chondrites	oxygen-poor enstatite chondrites
olivine, $(Fe, Mg)_2 SiO_4$	olivine, $(Fe, Mg)_2 SiO_4$	pyroxene, $Mg SiO_3$
pyroxene, $(Fe, Mg) SiO_3$	pyroxene, $(Fe, Mg) SiO_3$	complex mixed sulphides e.g. (Ca, Mg, Mn, Fe) S
pentlandite, $(Fe, Ni)_9 S_8$	troilite, FeS	metal, (Fe–Ni–Si alloy)
troilite, FeS	metal, (Fe–Ni alloy)	nickel silicide, Ni_2Si

This oxygen-rich undifferentiated chondritic component appears as a veneer atop the differentiated interior of the Earth, which, because of its high metallic iron content, must be significantly more reduced. In fact, an inner core of nickel silicide would indicate a state of reduction comparable to that observed in the oxygen-poor enstatite chondrites.

Anhydrous chondritic meteorites consist primarily of two components: (i) silicate minerals, transparent in thin section and (ii) opaque minerals that crystallize from sulphur–iron based alloys. The silicate minerals have higher melting points and lower densities than either the sulphur–iron based alloys or the opaque minerals that crystallize from them, with only minor exceptions (e.g. CaS).

I suggest that the lower mantle and the core of the Earth, respectively, are chemically analogous to the two primary components of the highly reduced, volatile-rich enstatite chondrites: the silicates and the sulphur-based iron alloy. In support of this suggestion I present in table 4 the silicate to alloy mass ratio of the Abee enstatite chondrite for comparison with the lower mantle to core mass ratio of the Earth. For reference, similar ratios are shown for more oxidized meteorites as well as the upper-plus-lower mantle to core mass ratio. In further support of this suggestion I present in table 5 the inner core to lower mantle-plus-core mass ratio of the Earth for comparison with the theoretical mass ratios that would result were all nickel in the Abee enstatite chondrite to exist as one of the indicated compositions of nickel silicide. A necessary condition for the existence of nickel silicide is presence of elemental silicon. The oxidized iron content of the silicates precludes the existence of elemental silicon and thus precludes the existence of nickel silicide in the alloy of the more highly oxidized ordinary chondrites.

For the reasons set forth above it appears that the Earth consists of two components: the *endo-Earth*, defined here as being comprised of the matter that lies beneath the seismic discontinuity that describes the boundary between the upper and lower mantles and the *exo-Earth*, or upper mantle plus crust. Distribution of the elements among the two major shells of the endo-Earth, shown in table 6, is predicted by analogy with components of the Abee enstatite chondrite.

TABLE 4. COMPARISON OF MASS RATIOS OF THE INTERIOR SHELLS OF THE EARTH WITH METEORITIC SILICATE TO ALLOY MASS RATIOS

Abee enstatite chondrite	$\frac{\text{silicate}}{\text{alloy}}$	= 1.43	(Keil 1968)
	$\frac{\text{lower mantle}}{\text{total core}}$	= 1.49	(Dziewonski & Gilbert 1972)
H-group chondrite	$\frac{\text{silicate}}{\text{alloy}}$	= 3.58	(Keil 1962)
L-group chondrite	$\frac{\text{silicate}}{\text{alloy}}$	= 7.28	(Keil 1962)
	$\frac{\text{upper and lower mantle}}{\text{total core}}$	= 2.05	(Dziewonski & Gilbert 1972)

TABLE 5. COMPARISON OF INNER CORE TO LOWER MANTLE-PLUS-CORE MASS RATIO WITH THEORETICAL NICKEL SILICIDE MASS RATIOS FOR THE ABEE ENSTATITE CHONDRITE

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

$$\frac{\text{mass Ni}_2\text{Si}}{\text{meteorite mass}} = 0.0206\text{–}0.0237\dagger$$

$$\frac{\text{mass Ni}_3\text{Si}}{\text{meteorite mass}} = 0.0192\text{–}0.0221$$

$$\frac{\text{mass perryite}\ddagger}{\text{meteorite mass}} = 0.0204\text{–}0.0235$$

† The range of values results from using two different nickel analyses: 1.66% (Dawson *et al.* 1960); 1.91% (Baedecker & Wasson 1975).

‡ Meteoritic nickel silicide (75–81% Ni; 3–7% Fe; 12–15% Si; 2–5% P).

It has long been recognized that the terrestrial planets differ from one another in zero pressure-density (Urey 1952). Lewis (1974) attempted to explain this as being the result of the cessation of condensation at different temperatures from a homogeneous nebula. On the basis of what has been presented in this paper it seems worthwhile to speculate that the density differences among the terrestrial planets may arise from their having different relative proportions of highly reduced and highly oxidized matter. Mercury would thus contain a greater proportion of

TABLE 6. ESTIMATED ELEMENTAL COMPOSITION OF THE ENDO-EARTH IN GRAMS†

lower mantle	
O	1.52×10^{27}
Si	0.79×10^{27}
Mg	5.05×10^{26}
Al	3.96×10^{25}
Na	3.36×10^{25}
Ca	2.38×10^{25}
Mn	5.77×10^{24}
Fe	5.02×10^{24}
total core	
Fe	1.45×10^{27}
S	2.84×10^{26}
Ni	8.31×10^{25}
Mg	4.75×10^{25}
Si	3.26×10^{25}
Ca	1.84×10^{25}
Cr	1.58×10^{25}
P	9.32×10^{24}
Mn	5.34×10^{24}
Co	4.15×10^{24}
Ti	2.23×10^{24}
Zn	2.09×10^{24}
Cu	8.61×10^{23}

† Calculated from the data of Keil (1968), Baedecker & Wasson (1975) and Dziewonski & Gilbert (1972).

reduced matter whereas Mars would contain a greater proportion of oxidized matter.

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ERRATA

Table 1. Lower mantle mass is 2.922×10^{27}

Table 6. the upper mantle values are in error. Should be

O	1.53×10^{27}
Si	0.79×10^{27}
Mg	5.05×10^{26}
Al	3.96×10^{25}
Na	3.36×10^{25}
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