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Geophysics

Substructure of the inner core of the Earth

(nuclear fission/chondrite/oxidation state/seismology/composition)

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ABSTRACT **The rationale is disclosed for a substructure within the Earth's inner core, consisting of an actinide subcore at the center of the Earth, surrounded by a subshell composed of the products of nuclear fission and radioactive decay. Estimates are made as to possible densities, physical dimensions, and chemical compositions. The feasibility for self-sustaining nuclear fission within the subcore is demonstrated, and implications bearing on the structure and geodynamic activity of the inner core are discussed.**

Two conflicting ideas exist for the composition of the Earth's inner core, ideas that have fundamentally different implications for its substructure and for geodynamic processes in general.

Soon after the discovery of the inner core in 1936 (1), its composition was thought, by inferences from meteorites, to be nickel–iron metal that had crystallized from the fluid nickel–iron alloy core and that had settled to the center of the Earth (2, 3). The nickel–iron inner-core idea persists to the present and is an underlying assumption for much experimental and computational activity. The reason that the inner core was considered to be composed of nickel–iron metal is that nickel and iron were thought to be essentially inseparable from one another by natural processes in the alloy of meteorites, and heavier elements are not sufficiently abundant, relative to iron, to constitute a mass as large as the inner core. An inner core composed of nickel–iron metal, similar to the metal of ordinary chondrites, would be expected on the basis of ordinary chondrite chemistry neither to contain radioactive nuclides nor to possess a significant physical or chemical substructure.

In the 1970s, I realized (4) that a mineral discovered (5, 6) in the 1960s in rare enstatite meteorites proved that nickel could in fact be separated from iron by natural processes. The entirety of the abstract of that paper (4) is as follows: "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." Meteoritic nickel silicide (mainly Ni_2Si), also called perryite, was unknown at the time of the discovery of the inner core in 1936. Initially, I derived the nickel silicide inner-core suggestion logically from observations (4). Subsequently, I supported that suggestion, using published data to demonstrate that seismologically determined mass ratios of major interior portions of the Earth are virtually identical to mass ratios for corresponding components of enstatite chondrites, particularly the Abee meteorite (7–9). Geophysical implications of the interior portion of the Earth being of enstatite-chondrite composition are related to the highly reduced state of oxidation. One notable consequence of such a highly reduced state of oxidation, as discussed below, is the anticipated presence of radioactive and fissionable elements within the inner core which, because of density and decay products, would result in an inner-core substructure.

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Chemical Considerations

For more than a century, ideas about the internal compositions of planets, especially the Earth, have been inspired by observations of meteorites, particularly chondrites, and technological knowledge of steel-making. Only five elements (Fe, Mg, Si, O, and S) constitute approximately 95% of the mass of each of the hundreds of anhydrous chondrites and, by inference, each of the terrestrial planets. Fig. 1 shows that the mass ratio of opaque to translucent minerals of chondrites is related to the relative abundance of oxygen, even though chondrites differ somewhat from one another in major-element compositions. The mass ratio of opaque to translucent minerals of individual chondrites, shown in Fig. 1 and calculated from mineral and chemical data incorporating both major and minor elements, is essentially the chondrite's alloy-to-slag ratio, which is essentially the chondrite's (metal + sulfides)-to-silicates ratio. Comparable core-to-mantle ratios for the Earth, calculated from seismic-based data and indicated in Fig. 1, show that the Earth as a whole has a state of oxidation similar to certain highly reduced enstatite chondrites and unlike other types of chondrites.

The fundamental differences between the Earth's being of enstatite-chondrite composition and its being like other, more oxidized, types of chondrites, as previously thought, arise from the limited relative abundance of oxygen. Enstatite chondrites formed under such oxygen-deficient conditions that certain lithophile (oxiphile) elements, such as silicon, magnesium, calcium, and uranium, occur in part as nonoxides and, together with sulfur, iron, and nickel, constitute the alloy portion corresponding to the Earth's core. Lithophile elements, such as calcium, are incompatible in an iron-based alloy and tend to form metallurgical precipitates (15). In the core of the Earth, one may anticipate the collection–location of high-temperature precipitates to be related to their respective densities relative to the densities of the fluid core and the inner core. At the core–mantle boundary, one may expect low-density, high-temperature precipitates, such as CaS and MgS, and, at the center of the Earth, one or more high-density, high-temperature precipitates. The highest density and most important high-density, high-temperature precipitate would be uranium or a compound thereof (9, 16).

Unfortunately, experimental investigations of the consequences of Ca and Mg on phase relations for the system Fe–Ni–S–Si have not been conducted at core pressures, $\approx$3.6 Mbar (1 bar = 100 kPa) although metallurgical behavior at near ambient pressure in a portion of the Ca–Fe–S system is known (15). Mineralogical investigations of enstatite meteorites presently provide the best reference as to the natural behavior of this highly reduced assemblage.

In enstatite chondrites the trace element uranium occurs concentrated in sulfide minerals (17); leaching experiments suggest its chemical behavior to be chalcophile (18). As other normally lithophile, incompatible elements, such as calcium and magnesium, precipitate as monosulfides in enstatite-chondrite matter, the tentative assignment of uranium as a monosulfide is not unreasonable.

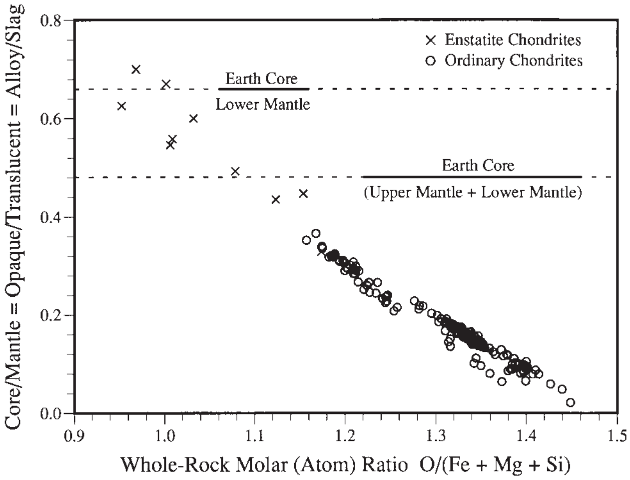

FIG. 1. Mass ratio of (metal + sulfides) to silicates as a function of whole-rock molar ratio of oxygen to the three major elements with which oxygen forms compounds in anhydrous chondrites. Data on 167 chondrites are shown. The core-to-lower-mantle ratio and the core-to-(upper + lower)-mantle ratio are indicated by broken lines. This representation shows that, if the Earth has a chondritic composition as widely believed, then the Earth as a whole (especially the inner 82%) must have a state of oxidation like certain highly reduced enstatite chondrites. Meteorite data are from refs. 10–13. Earth data are from ref. 14.

Physical Considerations

For most of the twentieth century, ideas as to the composition of the interior regions of the Earth developed through inferences derived from the more abundant, more oxidized chondrites and from iron meteorites with comparable states of oxidation. The inner regions of the Earth, however, have a highly reduced state of oxidation like certain enstatite chondrites (as shown in Fig. 1), and the consequence of this state is fundamentally different interpretations of seismic data. Contrary to earlier ideas based upon more oxidized meteorites: (*i*) The presence of silicon in the core may be expected to lead to the precipitation of a nickel silicide inner core (4). (*ii*) The presence of alkaline-earth elements in the core may be expected (9) to lead to low-density, high-temperature Earth-core precipitates—e.g., CaS and MgS—collecting at the core–mantle boundary, thus accounting for the observed lack of uniformity of the transition zone, D″ (19). (*iii*) The presence of uranium (and thorium) in the core may be expected to lead to the precipitation of a high-density, high-temperature subcore within the inner core (9, 16).

Fig. 2*A* shows the anticipated substructure of the inner core beside a schematic representation (Fig. 2*B*) of the shell structure of the interior of the Earth, revealed from seismic data (14). The inner-core substructure was calculated with uranium assumed to be the monosulfide, present in the same relative proportion as in the alloy portion of the Abee enstatite chondrite (17); for lack of substantive data, no other high-density, high-temperature precipitates, such as a compound of thorium, were included. The subshell surrounding the subcore, shown in Fig. 2*A*, arises from lower-density products of the natural decay and of the fission of uranium. Consequently, one may anticipate the subshell to have a poorly defined crystal structure, possibly even to be a slurry or a fluid. The densities of the subcore (26 g/cm^3) and subshell (23 g/cm^3) were calculated from a published Thomas–Fermi–Dirac equation of state (20). The substructure dimensions, shown in Fig. 2*A*, may be underestimated as a consequence of ignoring other possible high-density, high-temperature precipitates.

I have demonstrated the feasibility of a concentration of uranium metal at the center of the Earth undergoing self-sustaining nuclear fission reactions and have made estimates of resultant energy production. Unlike previously envisioned planetary-scale energy sources that change gradually and generally change in only one direction through time, variable and intermittent output is possible from nuclear fission reactors, for example, as a result of changes in composition or position of fuel or reactor poisons. I have further suggested that reversals of the geomagnetic field have their origins in intermittent or interrupted nuclear reactor operation (9, 16). Concomitant to the above calculated substructure, the nuclear fission feasibility of a concentration of uranium monosulfide is demonstrated in Fig. 3.

From nuclear reactor theory, the condition for sustained nuclear reactor operation is that the infinite multiplication factor k_∞ is ≥ 1 (22). Fig. 3 shows the infinite multiplication factor as a function of time before present for a theoretically infinite accumulation of US and, for reference, U metal. Approximately 3000 million years ago and earlier, the terrestrial $^{235}U/^{238}U$ ratio was sufficiently great for a "theoretically infinite" critical mass of uranium monosulfide ($\approx 10^2$ kg) to undergo self-sustaining nuclear fission chain reactions; the continuity of nuclear fission to the present would depend upon the nature of fuel breeding reactions.

Geophysical Implications

Energy production, as envisioned within the framework of the concept of the Earth's inner core being composed of nickel–

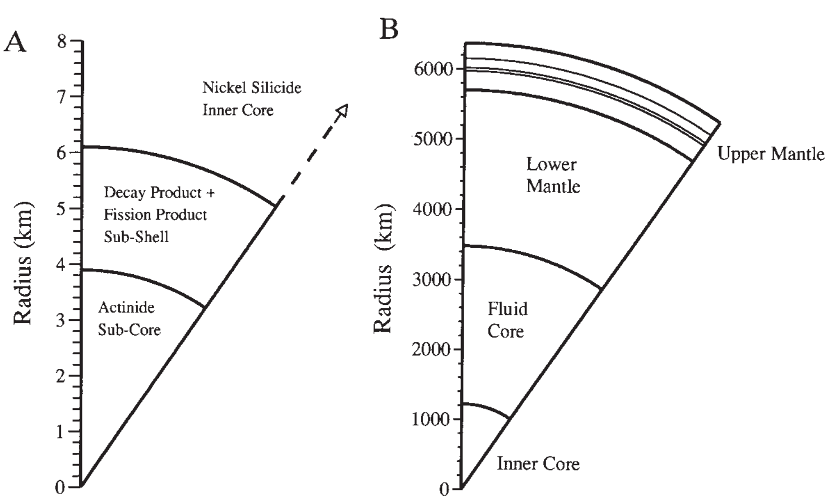

FIG. 2. (*A*) Schematic representation of inner-core substructure, calculated with uranium assumed to be the monosulfide, present in the same relative proportion as in the alloy portion of the Abee enstatite chondrite (17). For lack of data, other possible subcore trace elements, particularly thorium, were not considered. (*B*) Shell structure of the interior of the Earth, indicated by changes ≥5% in seismic P wave velocity (14), shown for reference.

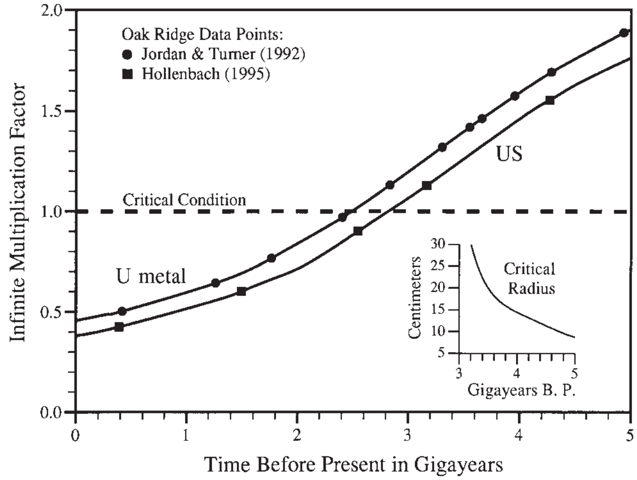

FIG. 3. The infinite multiplication factor k as a function of time before present for uranium monosulfide (■) and, for reference, uranium metal (●). Self-sustaining nuclear fission chain reactions can be initiated for a theoretically infinite mass of natural uranium sulfide—i.e. $\geq \approx 10^2$ kg—when $k_\infty \geq 1$. Fuel breeding reactions may result in $k_\infty \geq 1$ to the present (9). (*Inset*) Critical radius of a reflected sphere of natural uranium monosulfide, 26 g/cm^3, as a function of time before the present. Oak Ridge data points, based upon 27-group calculations, are from ref. 21 and D. F. Hollenbach (personal communication).

iron metal, is often thought to occur within the fluid core and/or at the boundary between the inner core and the fluid core. By contrast, energy production from a uranium (and thorium) subcore would be expected to occur at the center of the Earth, deep within the inner core. Implications, necessarily sketchy considering the unknowns and uncertainties involved, are briefly mentioned, mainly as guideposts for interested specialists. For brevity, I reiterate neither estimates of nuclear energy production nor implications of variable or intermittent nuclear fission energy output on global geophysical parameters, such as magnetic field reversals (9, 16).

Geophysical activity within the deep interior of the Earth is manifest at the surface as the geomagnetic field, the existence, direction, and, to a more limited extent, intensity of which are documented through geological time by paleomagnetic techniques. Since early investigations (23, 24), the idea that the geomagnetic field arises through the mechanism of a self-excited dynamo has received much greater support than other ideas, such as a mechanism involving the thermoelectric effect. In addition to the energy produced, natural decay of radioactive actinides and, especially, nuclear fission of actinides produce large quantities of charged particles, directly, through the decay of radioactive daughter and fission products, and through the interaction of γ radiation with matter. The effect of nuclear activity on geomagnetic field production should not be discounted. For example, a magnetic field arising from electric currents induced by nuclear activity might be shown as a mechanism for seeding dynamo action that is particularly important during reversals when the magnetic induction diminishes or passes through zero during polarity change.

The idea of an energy source residing at the center of the Earth, deep within the inner core, may have fundamentally different implications than energy production in the fluid core and/or at the boundary between the inner core and the fluid core. Recent seismic data seem to indicate that earthquake waves travel more quickly through the inner core in a north–south direction than in an east–west direction (25–27); the possibility of either an apparent or real ellipticity of the inner core, as a consequence of an inner-core magnetic field, should be considered. With respect to apparent ellipticity, Knopoff and MacDonald (28) recognized that the existence of a toroidal magnetic field within the inner core might lead to observable differences between axial and equatorial P-wave transit times as a consequence of the presence of a magnetic field perturbing the P-wave velocity in the inner core. With respect to real ellipticity, I point out that an inner-core solenoid, if responsible for the main, dipole component of the geomagnetic field, would be subject to (real) axial compression and (real) circumferential tension (also called hoop stress) that would tend to result in a real ellipticity of the inner core, precisely in the directions indicated by seismic data (29). Requisite inner-core current densities might be possible, however, only if much ohmic heating occurs in the fluid core.

Whereas ideas bearing on generation of the geomagnetic field are steeped in extreme uncertainty, the data presented in this paper demonstrate quite substantially that, if the Earth has a chondritic composition, as widely believed for good reasons, then the Earth as a whole (especially the inner 82%) must have a state of oxidation like certain highly reduced enstatite chondrites. I have provided a basis for anticipating actinide concentration at the center of the Earth and have demonstrated the feasibility for self-sustained nuclear fission (9, 16). In this paper I have described the inner-core substructure expected to result therefrom and have briefly indicated certain important implications. The above-described substructure should be discernible with sufficiently precise seismic data, if not now, then when precision is improved, through technology and/or as the result of additional data from future, powerful, deep-seated earthquakes.

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