The Earth's Core

Indirect evidence indicates that it is an iron alloy, solid toward the center but otherwise liquid. It is the turbulent flow of the liquid that generates the earth's magnetic field

by Raymond Jeanloz

It is ironic that one of the great spectacles of terrestrial nature, the light of the aurora shimmering in the night sky, is a clue to the character of the earth's hidden and enigmatic core. The ultimate cause of the aurora is the interaction of the magnetic field generated in the core and the "wind" of electrically charged particles flowing outward from the sun. The core also has much to tell about the earth's formation and geologic history. Indeed, there are indications that it may still be influencing the distribution of temperature in the overlying mantle and thus may indirectly govern large-scale geologic processes at the surface. It is also clear that the composition of the core is a major factor in any model of the bulk chemistry of the earth.

The present nature of the core is best determined from seismological data, that is, the information gathered by studying the acoustic waves generated by earthquakes. Such data reveal that the core extends from a depth of about 2,900 kilometers (1,800 miles) to the center of the earth at 6,370 kilometers (3,960 miles). They also show that the inner core is solid, with a radius of about 1,200 kilometers, and that the outer core is liquid. What the composition of the solid and the liquid might be are matters to which I shall return.

Conditions are known to be extreme at these depths. The pressure ranges from 1.3 to 3.5 million atmospheres, which is to say from 1.3 to 3.5 million times the atmospheric pressure at the surface of the earth. Temperatures are estimated to be in the range from 4,000 to 5,000 degrees Celsius (7,200 to 9,000 degrees Fahrenheit).

The most direct information on the core in the past comes from studies of the ancient magnetic field of the earth. For example, the magnetization of some of the oldest rocks suggests that whatever process generates the magnetic field in the core was already operating 3.5 billion years ago. Students of such matters are still far from a thorough understanding of the geomagnetic field: how it is generated, when and how it started and how it has evolved. Nevertheless, it is now possible to begin to understand how the core might have formed and evolved and how these processes may have affected the geologic evolution of the earth.

The geomagnetic field is often described as being like that of a dipole. In other words, it looks like the field that would be generated by a bar magnet at the center of the earth, with the lines of force looping from the south magnetic pole to the north. This is actually a parochial description, because the magnetic field is like that of a dipole only near the surface of the earth, where it can be studied most readily.

Around the earth in the magnetosphere the lines of force in the magnetic field are strongly distorted by the solar wind; they are crushed toward the earth on the side facing the sun and swept far into space on the night side of the planet. Similarly, all models of the source of the magnetic field show distorted field lines in the core. Nevertheless, it is worth remembering that about 90 percent of the field now observed at the surface is dipolar. The rest consists of a more complex pattern of field lines that can be described in terms of several poles rather than just the two that describe most of the present field.

Since the pioneering work of Walter M. Elsasser of Johns Hopkins University, Edward C. Bullard of the University of Cambridge and others the geomagnetic field has been understood as originating with magnetohydrodynamic processes in the earth's liquid outer core. In general terms the processes entail convection in an electrically conducting fluid, with the result that the core acts as a dynamo maintaining and regenerating the magnetic field. Specifically, as the field lines directed toward the center of the earth (the poloidal lines) enter the outer core they are pulled in the direction of the earth's rotation. The rotation of the solid inner core probably tends to wrap the field lines around the earth's axis (producing a toroidal component).

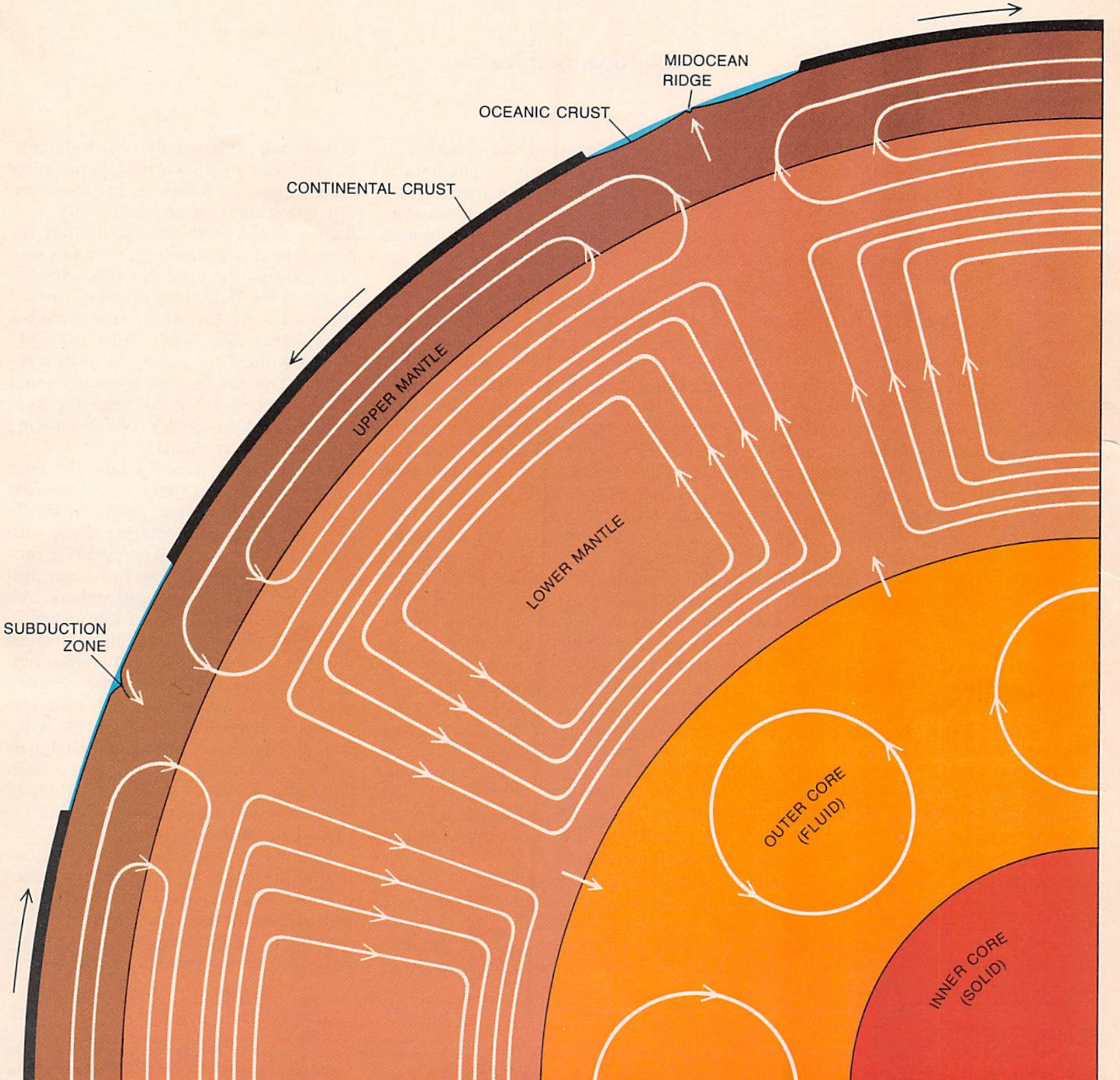
Furthermore, it is thought the field lines become contorted by smaller-scale cyclonic motions that result from the fact that the core is rotating along with the rest of the earth. The cyclonic motions are analogous to the hurricane patterns that arise in the atmosphere. Although the contortions of the magnetic field lines play a central role in current theories of the magnetic dynamo, neither the exact origin nor the detailed pattern of the contortions is known. It is worth emphasizing, however, that without the dynamo process the magnetic field would certainly die out within 10,000 years or so. Therefore the field must be continuously maintained or regenerated by the fluid motions.

In order to better understand the nature of the magnetic field within the core it is necessary to know the convective-flow pattern of the liquid. The trouble is that the magnetic field can significantly modify the flow generating the field in

MAGNETISM OF THE EARTH is visible in these images of the aurora made from data transmitted by the spacecraft *Dynamics Explorer 1*. The aurora is the circle at the lower right in each image. It is created when electrically charged particles in the "wind" of the sun's expanding atmosphere are trapped in the earth's magnetic field. Plunging into the earth's atmosphere along the magnetic lines of force descending toward the magnetic poles, the solar-wind particles interact with molecules in the earth's atmosphere to generate the light of the aurora (here actually detected at ultraviolet wavelengths). The bright area at the upper left in each image is the side of the earth lighted by the sun. Each image represents data received for a 12-minute period. The images show a hitherto unknown configuration of the aurora, in which the circular area of emission is crossed by a linear one; the configuration is called the theta aurora because of its resemblance to the Greek letter. The images were obtained with the University of Iowa's auroral-imaging instrumentation. They are provided through the courtesy of Louis A. Frank.

mains but as interacting parts of a larger system whose properties and dynamics are modeled by geophysicists, geochemists and petrologists.

Earth scientists have long been familiar with the ways in which the actions of the interior affect the exterior through volcanism, mountain building, the flow of heat and the geomagnetic field. Now they are seeing how chemical weathering and the differentiation of the materials of the interior as they are brought to the surface react on the interior as the altered material is plowed back into the mantle by subduction. In this way the surface machine is further coupled to the interior machine. As the subsystems are linked the earth may come to be thought of more in the ways one thinks of a highly differentiated organism: as a system so complex that the ultimate reduction to simple forces and bulk compositions does not lead to a satisfactory understanding of the wonderful diversity and detail that can be observed directly at the surface and sensed remotely in the interior.



LARGE-SCALE MOTIONS of the major parts of the earth are indicated by arrows in this highly schematic diagram. Heat-driven convection in the fluid outer core has a dynamo effect that is responsible for the geomagnetic field. Convection in the upper mantle drives plate tectonics. Volcanism transports molten material to the surface at midocean ridges and other places. Solid material is returned to the interior at subduction zones. The degree of mixing between the upper mantle and the lower mantle is a subject of debate; in this case a model calling for separate convection cells has been adopted. Mixing of material between the lower mantle and the outer core is still speculative.

the first place. Hence no one has yet fully solved the problem of determining the fluid motions in the outer core.

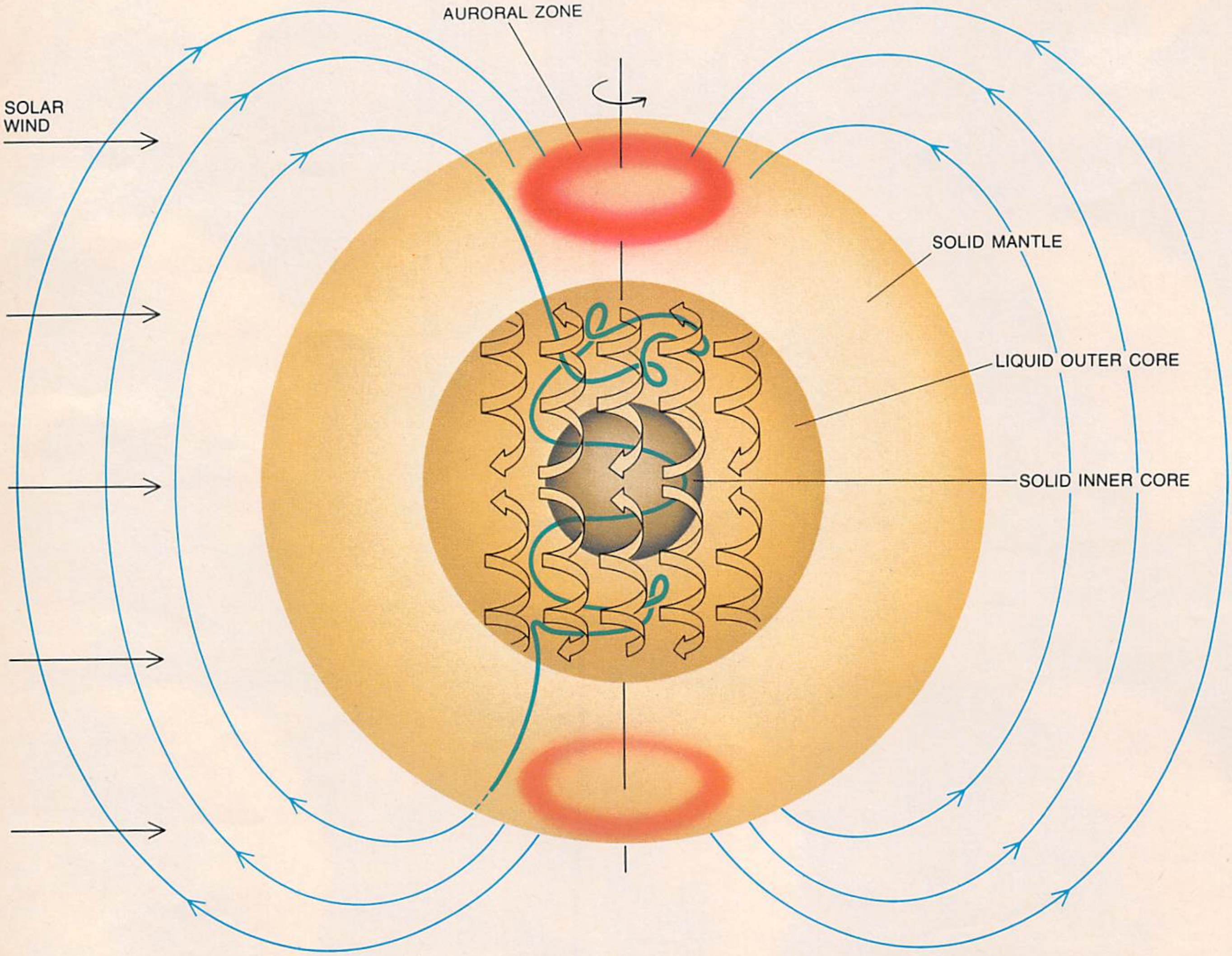
A logical starting point, however, is to first ask what the flow would look like if there were no magnetic field. Possible answers to this purely hydrodynamic question are emerging from the theoretical and experimental work of Friedrich H. Busse and his colleagues at the University of California at Los Angeles. They find that both the presence of the solid inner core and the rotation of the earth are major influences on the flow pattern in the liquid outer core. In conditions thought to be appropriate to the earth's core the pattern takes the form of screwlike rollers. One can speculate that if this pattern of flow is not too strongly modified by the presence of the magnetic field, the rollers are intimately associated with the contortion of the field lines that is required for the dynamo.

The magnetization that is retained in rocks of different ages has been studied by, among others, M. W. McElhinny and his colleagues at the Australian National University. They find that a geomagnetic field of about the same intensity as the present one existed at least 2.5 billion years ago and probably existed 3.5 billion years ago. (The latter determination was made on the basis of only a few samples.) Although data are absent for a substantial fraction of the earth's history, inasmuch as the planet is 4.6 billion years old, it seems that the geodynamo started operating fairly early in geologic time.

The fact that the presence of an inner core appears to be important in the process generating the magnetic field leads to the further inference that this solid region at the center of the earth has existed for at least 3.5 billion years. Even though the inner core may have grown or shrunk since then, there is no reason to infer that the general nature of the flow in the outer core has changed substantially throughout recorded geologic time. In other words, the magnetic evidence suggests that the basic structure of the liquid outer core surrounding the solid inner core has existed for at least three-fourths of the earth's history.

The understanding of the geomagnetic dynamo and of the convective-flow pattern in the core has advanced considerably in the past several years. It is reasonable to predict that the theoretical and experimental work now being done will lead to major new insights. Nevertheless, certain aspects of the problem are still baffling.

A good example is the reversal of the magnetic field that has occurred hundreds if not thousands of times in geologic history. In a reversal the north magnetic pole switches from pointing toward geographic north to pointing south (or vice versa). Reversals appear not only in the earth but also in the sun and even in laboratory dynamos, presumably in response to the chaotic nature of magnetohydrodynamic processes. On a practical level the frequent and apparently random geomagnetic reversals have provided an exceedingly useful clock for timing geologic events and correlating geologic deposits. In-



MAGNETIC FIELD IS GENERATED by a dynamo in the core. The details of how the dynamo works are not known, but in the model depicted here it is assumed that the electrically conducting metallic liquid of the core flows in screwlike rollers. The lines of force in the magnetic field would be threaded through the rollers; here a single such line is depicted. It is the thick line from north to south.

deed, it is the magnetic reversals recorded in the rocks of the ocean floor that have yielded one of the main lines of evidence for the theory of plate tectonics.

It is only fairly recently that high-quality data have become available to trace in detail what happens when the magnetic field reverses. Apparently the magnetic pole follows a convoluted path at the earth's surface. It is clear, however, that the field can reverse completely within just a few thousand years.

Several models have been proposed for what the field should look like during a reversal. According to one of them, as an example, either the north or the south magnetic pole should appear to follow a line of constant longitude, with the pole crossing through any given sampling location on the surface of the earth in the course of a reversal. One can visualize the magnetic pole as splitting into a hoop that sweeps the surface in a north-south direction. The data now available, however, do not support this hypothesis.

A major difficulty in modeling the field as it reverses is that during the process the absolute intensity of the field is reduced to about 10 percent of its normal value [*see illustration on next page*]. At present the geomagnetic field is about 90 percent dipolar, the rest being multipolar. No one is certain what fraction of the reduced field is dipolar while a reversal is under way. To derive the poles shown in the illustration it is necessary to assume that the field was dipolar during the depicted reversal. Perhaps, however, there are effectively several magnetic poles existing simultaneously during a reversal. If they fluctuate in strength, they can give rise to the erratic path seen in the illustration. This possibility can be investigated only by studying the same reversal at several different places.

Reversals seem to be more than just a passive dying out and rebirth of the field because they appear to happen on a time scale that is much shorter than the time it would take for the field to be regenerated. Hence one may ask: Are reversals caused by turbulence or shifts in the detailed flow patterns in the outer core? No one has been able to answer the question. It is quite possible the dynamo is self-reversing, that is, a reversal can be initiated internally, without any external trigger.

Regardless of the mechanism, one consequence of reversals is only now beginning to be recognized. What is being found in the growing new discipline of biomagnetism is that complex organisms synthesize magnetic components whereby their behavior can be significantly affected by changes in the geomagnetic field. Therefore one may speculate that reversals play a role in biological evolution.

The geologic record of the earth's magnetic field yields information on the nature of the core in the past. In order to proceed further in understanding the core it is necessary to consider the available data bearing on its present nature as well. The only detailed and direct information comes from seismological studies, which provide values of the density of the material and the velocity and attenuation of sound as a function of depth in the earth. "Sound" is employed here in a loose sense to refer to the mechanical waves produced by earthquakes (or large manmade explosions) and propagated through and around the globe. Such waves are of low frequency compared with audible sound: from about 10^{-4} to 10 hertz, or cycles per second, which is some 100 to a million times lower in "pitch" than the concert A. From these data the pressure can be calculated at each depth. Moreover, liquid and solid regions can be distinguished because a liquid transmits only compressional waves (waves moving back and forth in the direction of their travel), whereas a solid transmits both compressional waves and shear waves (waves moving at right angles to their direction of travel).

The basic structure of the earth implies a crude but strong constraint on the deep temperature. Evidently the geotherm (the average temperature as a function of depth) is below the melting point of the inner core and the mantle, since they are both solid. By the same token the geotherm is above the melting point of the outer core.

Usually this argument is taken one step further on the assumption that the inner core is solidified outer-core material. The assumption is plausible and is not contradicted by any data now available. No one has yet demonstrated, however, that the inner and outer core are in chemical equilibrium, as the assumption would imply. In fact, the inner core may be in chemical disequilibrium with the outer core, which in turn may be (and is often taken to be) in disequilibrium with the mantle. In other words, the composition of the inner core may not be related in any direct way to the composition of the outer core.

If the inner core has formed (or is still forming) by crystallization from the liquid outer core, the boundary between them is fixed within the temperature interval of melting and solidification of core material at a pressure of 3.25 million atmospheres for the present size of the inner core. For example, the inner core could be pure iron that has crystallized out of the alloy liquid of the outer core. The temperature at the boundary between the inner and the outer core is similarly constrained even if the outer core is heating up and hence is growing by the melting of the solid inner core. In either case one would in general expect a region of partial melting between the inner and the outer core, because only the simplest chemical systems melt at a sharply defined temperature, that is, begin melting or begin solidifying at the same temperature.

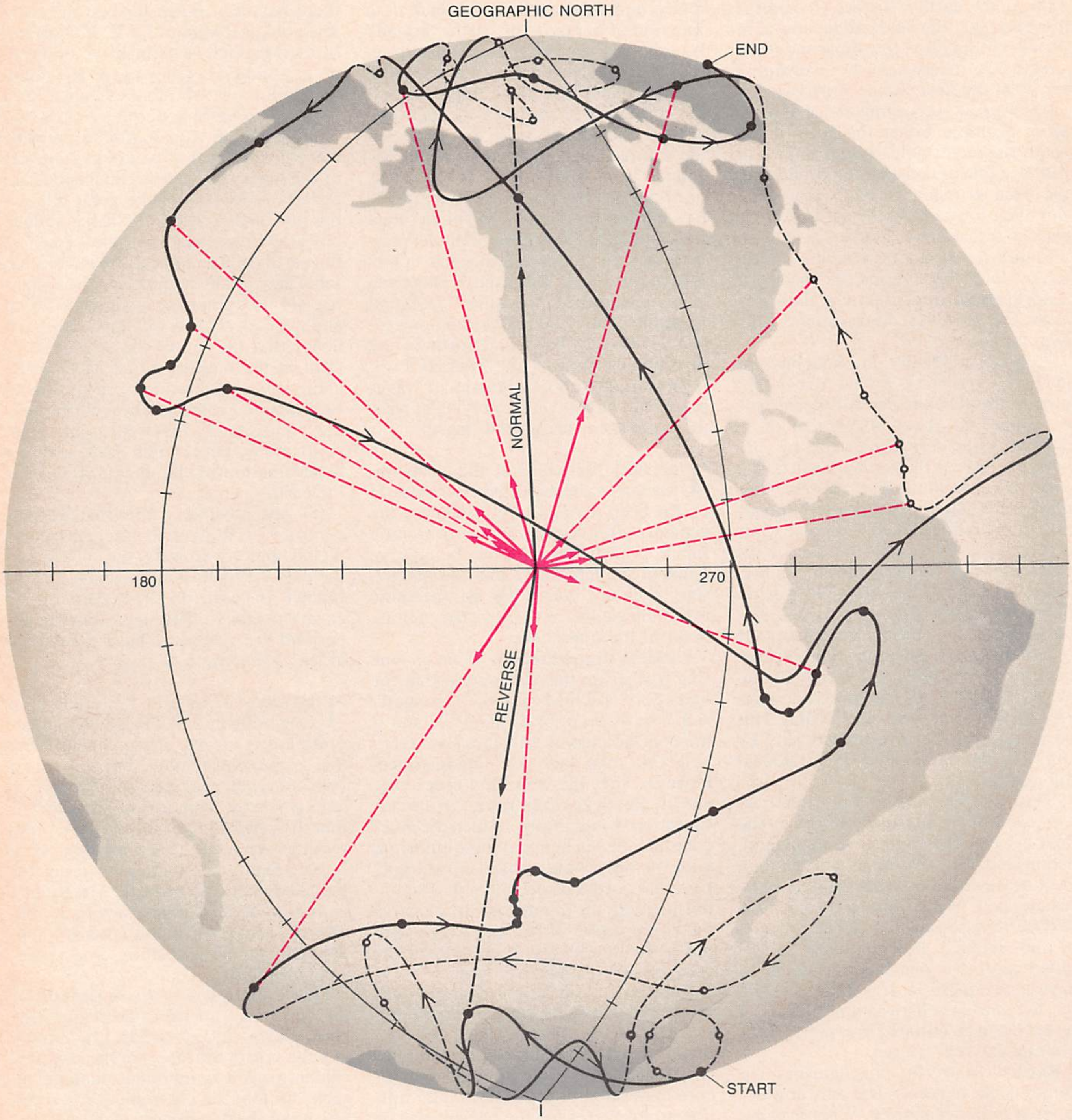
The core is thought to be a complex alloy, which would therefore melt over a range of temperatures. As a result there has been much interest in recent seismological studies by V. F. Cormier of the Massachusetts Institute of Technology and G. L. Choy of the U.S. Geological Survey, who find evidence for a "mushy" zone of reduced velocity and relatively high attenuation of seismic waves in the top few hundred kilometers of the inner core. Their conclusions are uncertain because of the great difficulties involved in resolving such details of physical properties near the center of the earth. It does appear, however, that there may be an anomalous zone such as one would expect for a slurry of liquid and crystals. This is circumstantial evidence that the top of the inner core is right at the melting point. Thus if the composition of the core were known, an experimental determination of the melting point of this material at the pressures of the core would yield a direct determination of the temperature near the earth's center.

It is also possible to infer that the temperature has not varied enough to completely melt (or solidify) the core within the past 2.5 to 3.5 billion years. The inference is based on the record of the earth's magnetic field suggesting the inner and the outer core have existed for at least that length of time.

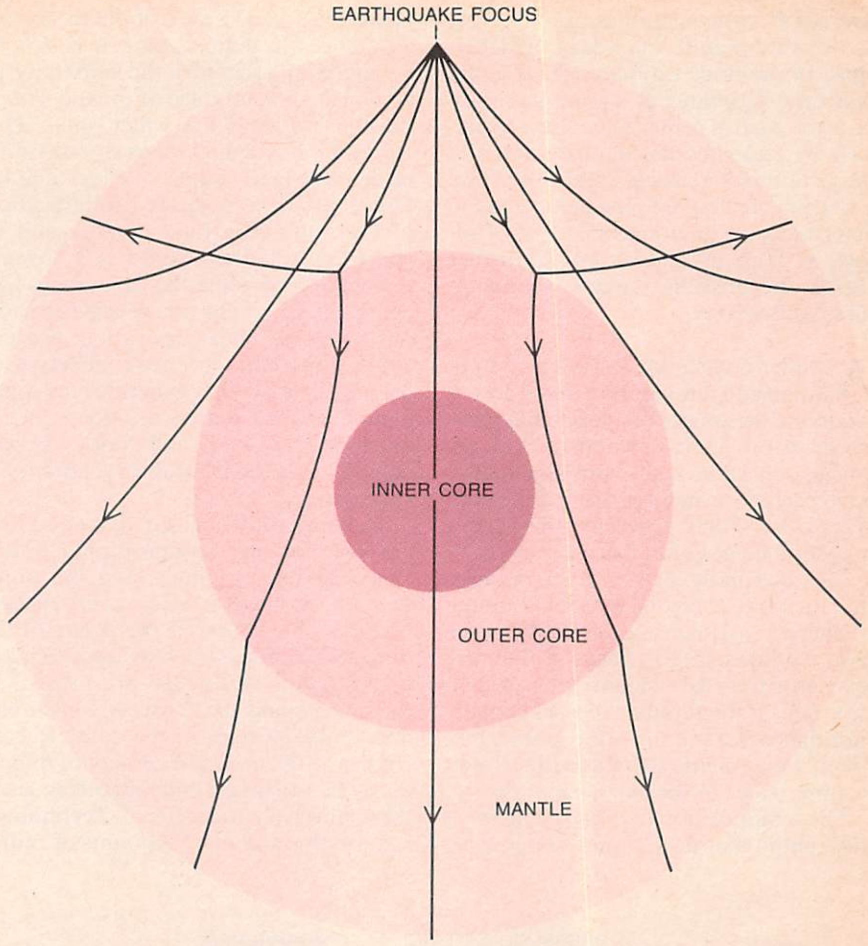
The core is usually represented as consisting mainly of iron. This interpretation is clearly in agreement with the seismological data, but two other lines of evidence can be invoked to strengthen the conclusion. The first is that the generation of the magnetic field requires the core to be metallic (that is, electrically conducting) in order for the geodynamo to operate. The second is that no other element having the observed properties of the core is abundant enough in the cosmos to be a plausible candidate.

Hence there is a gross separation of the earth into an iron-rich region (the core) and a silicate region (the mantle and the crust). Silicates are the complex silicon-oxygen compounds making up rocks, so that the two regions are reminiscent of the two general classes of meteorites: iron and stony. Beyond this, however, there is no evidence for a more detailed analogy between the earth's core and the nature of meteorites. In fact, it is not possible that the core is made up only of iron or the nickel-iron alloy commonly observed in iron meteorites. This is evident from a comparison of the density of iron alloys at high pressures with the density of the core: a small amount of a component less dense than iron, such as sulfur, oxygen or silicon, must also be present.

There is no consensus on the composition of the core other than that it is predominantly iron. In part the reason is that gross physical properties, such as the measured densities and seismic velocities within the core, cannot be exploited to uniquely determine the core's chemical composition. Moreover, only a small amount of any of the alloying elements that have been proposed is required in order to match the observed properties of the core. (Typical values are about 8 to 10 percent by weight.) Finally, it is quite possible—probable according to many investigators—that the core alloy has many components in addition to iron.



REVERSAL OF THE GEOMAGNETIC FIELD gives clues to the action of the dynamo in the core. A reversal that took place 15 million years ago is traced here on the basis of the magnetism recorded in a sequence of lava flows at Steens Mountain in Oregon. The switch was from reverse to normal, with normal meaning that magnetic and geographic north are in the same direction. The north magnetic pole followed a convoluted path, recorded here for a period of 15,000 years; each filled circle represents a separate measurement of the pole position. The field's strength and direction are indicated at approximately 500-year intervals by the colored arrows. During the reversal the geomagnetic field did not necessarily have two poles, as it does today, so that the poles depicted here represent only a schematic view. The erratic path of the pole could result from variations in the dipole and nondipole components of the field or from shifts in field's main direction. The data on which the drawing of a magnetic reversal is based are from Robert S. Coe of the University of California at Santa Cruz, M. Prévot of the University of Paris and E. A. Mankinen and Charles S. Grommé of the U.S. Geological Survey.



SEISMIC WAVES provide data on the physical properties of the core. Two types of waves move through the earth from the focus of an earthquake: *P*, or compressional, waves (waves that move back and forth in their direction of travel) and *S*, or shear, waves (waves that move at right angles to their direction of travel). *S* waves, which cannot travel through the body of a liquid, do not pass directly through the core, demonstrating that at least the outer core is liquid. *P* waves go through both solids and liquids. Besides information on the state of the core, seismology yields data on density, which make it possible to calculate the pressure at each depth.

In view of these uncertainties it is best just to summarize contemporary thinking by saying the present favorites for the main light components in the core are sulfur and oxygen. Sulfur was proposed by V. R. Murthy and H. T. Hall of the University of Minnesota primarily because it is depleted in the rest of the earth in relation to cosmic abundances. If enough sulfur could be assigned to the core, the planet as a whole might turn out to be undepleted in sulfur. It is relevant that iron sulfides are found in meteorites.

The trouble with this argument is that sulfur is relatively volatile, and it has long been recognized that the bulk earth is depleted in volatiles in relation to cosmic abundances (most notably in hydrogen and helium but also, for example, in potassium). In addition the high-pressure data indicate that only about 8 percent by weight is required for sulfur to lower the density of iron to the density of the core. That amount of sulfur is not nearly enough to make up the deficiency of the bulk earth.

This relation weakens the original justification for invoking sulfur as the lighter component, but it does not rule sulfur out. Indeed, an iron sulfide combination is regarded by many workers as being the most plausible one for the core. It is worth noting that iron sulfide is a good electrical conductor and that it melts at temperatures several hundred degrees below the melting point of mantle minerals. Its properties are therefore consistent with those of the core, and one can see how the bottom of the mantle could be solid (a silicate with a high melting point) and the outer core liquid (a sulfide with a lower melting point).

The main proponent of oxygen as the light component in the core is A. E. Ringwood of the Australian National University. He suggests that at high pressures iron oxide becomes metallic. The point is crucial because at low pressures iron oxide is not metallic. The required metallization would necessitate a drastic change of properties.

There is as yet no clear evidence by which to judge Ringwood's hypothesis, although shock-wave experiments in the laboratory have demonstrated that at something less than a million atmospheres of pressure iron oxide does undergo a transformation. Unfortunately in the experiments the nature of the transition could not be determined. In the transition does the bonding become metallic, or is there just a change in crystal structure? Answers to this question and others about the properties of iron oxide at high pressures await the conclusion of additional experiments now in progress. In any case the proposed metallization of iron oxide should not be regarded as improbable. After all, the evidence is that even oxygen can become metallic at high pressure, and molten iron oxide appears to be a semimetal at high temperatures.

One of the main differences between the oxide and the sulfide hypotheses is that under the oxide hypothesis the core must have acquired its present composition at high pressures. Ringwood concludes that below the metallization pressure oxygen does not combine with iron in any significant amount (in relation to the silicates of the mantle). This is why the core would have to form at high pressures to incorporate oxygen. In contrast, sulfur can readily be alloyed with iron at low pressures.

The effect of combining either sulfur or oxygen with iron is that the melting point of the compound is lowered. At low pressures sulfur has a much larger effect than oxygen on the melting point of iron, and it is thought this difference may persist at high pressures. Therefore a notable difference between the sulfide and oxide models for the core is that melting would begin at significantly lower temperatures in a sulfide composition than it would in an oxide one. As a result it may be easier for a core to start forming if it is sulfur-rich than if it is oxygen-rich.

In order to apply this information it is necessary to know the melting temperatures of iron alloys at the pressures of the core. The melting point of iron itself has recently been determined in the shock-wave experiments of J. M. Brown and R. G. McQueen at the Los Alamos National Laboratory. For the first time they were able to discern the onset of melting in pure iron at 2.5 million atmospheres.

Applying these data, Brown and McQueen have modeled the melting in iron alloys at pressures corresponding to those at the boundary of the inner and the outer core. On the assumption that this boundary corresponds to the melting-freezing transition and that the core is iron sulfide, they are able to estimate temperatures throughout the core. For example, they arrive at a value of 3,700 degrees C. (plus or minus 500 degrees) at the core-mantle boundary, which is close to previous estimates. This is the first time estimates of the temperature near the earth's center have been bracketed by experimental data obtained at the conditions existing within the core. Experiments that are now being done to determine the melting behavior of alloys at high pressures should further clarify the possible range of temperatures in the core.

A subtler connection between composition and temperature at the core is related to the source of energy that powers the geodynamo. Two distinct mechanisms—thermal and compositional—have been proposed for driving the convective flow that generates the earth's magnetic field within the outer core.

The thermally driven flow requires that the fluid be heated by a local source of energy. Warmer regions of the outer core would then rise because they are less dense than the colder regions, which sink. This is the familiar type of convection that occurs in the atmosphere, in a pot of water on the stove and (on a longer time scale) in the earth's mantle.

The compositionally driven flow is different in that dense and less dense regions are formed even if there are no differences in temperature. It is simply an unmixing process of the kind that can take place in a mixture of oil and water; the oil rises and the water sinks. David Gubbins of the University of Cambridge and D. E. Loper of Florida State University have suggested solidification of the outer-core fluid could result in dense crystals that would sink toward the inner core while the remaining, less dense liquid would rise toward the top of the core. This separation process could apparently be quite effective in driving the flow that generates the magnetic field. The details are not well understood, however, and most workers consider this model of the dynamo to be speculative.

The thermally driven dynamo does not call for any compositional difference between the inner and the outer core. All it needs is a source of energy. One possible source is the decay of radioactive isotopes such as uranium 238 or potassium 40, which are present in the mantle and the crust. Are such elements also present in the core? Recent studies of the uranium content of minerals by D. S. Burnett and his colleagues at the California Institute of Technology suggest that sufficient amounts of radioactive uranium are capable of partitioning into core-forming metal to be an important source of heat. Furthermore, both theoretical results and new experimental data support the idea that the chemical bonds of potassium change at high pressures in such a way that radioactive potassium could also combine with the metallic iron of the core.

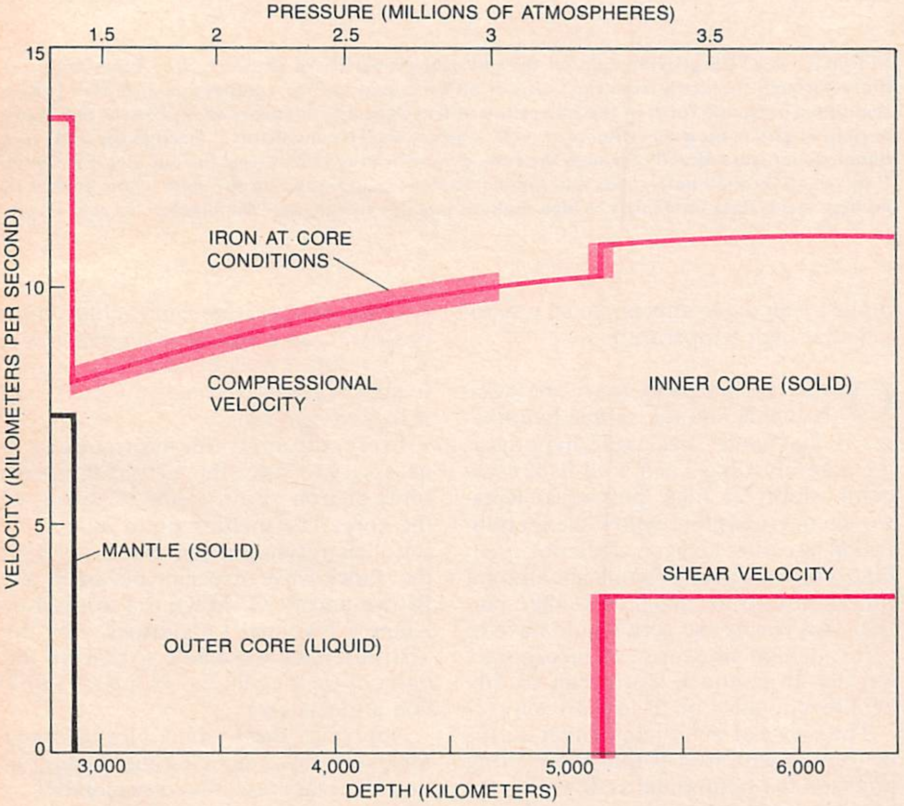
In each case the data are too scanty to allow anything more than speculation about heat sources in the core. The point is that according to present knowledge radioactive decay could be the dominant source of energy driving the flow in the core. Incidentally, one reason some geophysicists argue for significant amounts of potassium in the core is that it could partly explain why the mantle and crust are depleted in potassium in relation to cosmic abundances.

There may be other sources of energy to drive convection in the outer core. For example, considerable heat could have been released when the earth originally assembled or when the core formed. This "primordial heat" hypothesis, to which I shall return, is intimately associated with whatever view one might hold on how the earth was formed.

Another possibility is that if the inner core is freezing out of the surrounding liquid, there could be enough heat from the latent heat of crystallization to power the geodynamo. This hypothesis has been discussed extensively by John Verhoogen of the University of California at Berkeley, who emphasizes the uncertainties in such a model arising from the lack of data on melting in complex alloy systems at high pressures.

Whatever the precise source of energy may be, the fundamental instability driving thermal convection is that less dense fluid lies under denser fluid. This situation arises because there is a sufficient increase, on the average, of temperature with depth and because thermal expansion causes the density of materials to decrease as the temperature is increased by the heat sources.

If the geodynamo is thermally driven, the temperature of the vigorously flowing region in the outer core increases adiabatically with depth (that is, with pressure). In an adiabatic process the energy content of a given parcel of fluid remains the same, which is to say there is not enough time for heat to flow out of the parcel as it moves over long distances, and energy is not lost to the surroundings. Thus if the parcel is compressed, its energy density increases: the fluid gets hotter. This increase in temperature with depth in the core is estimated to be rather small, about .8 degree C. per kilometer. Nevertheless, the adiabatic gradient that would exist in the thermally convecting core would have a profound influence on the evolution of the mantle and crust above.



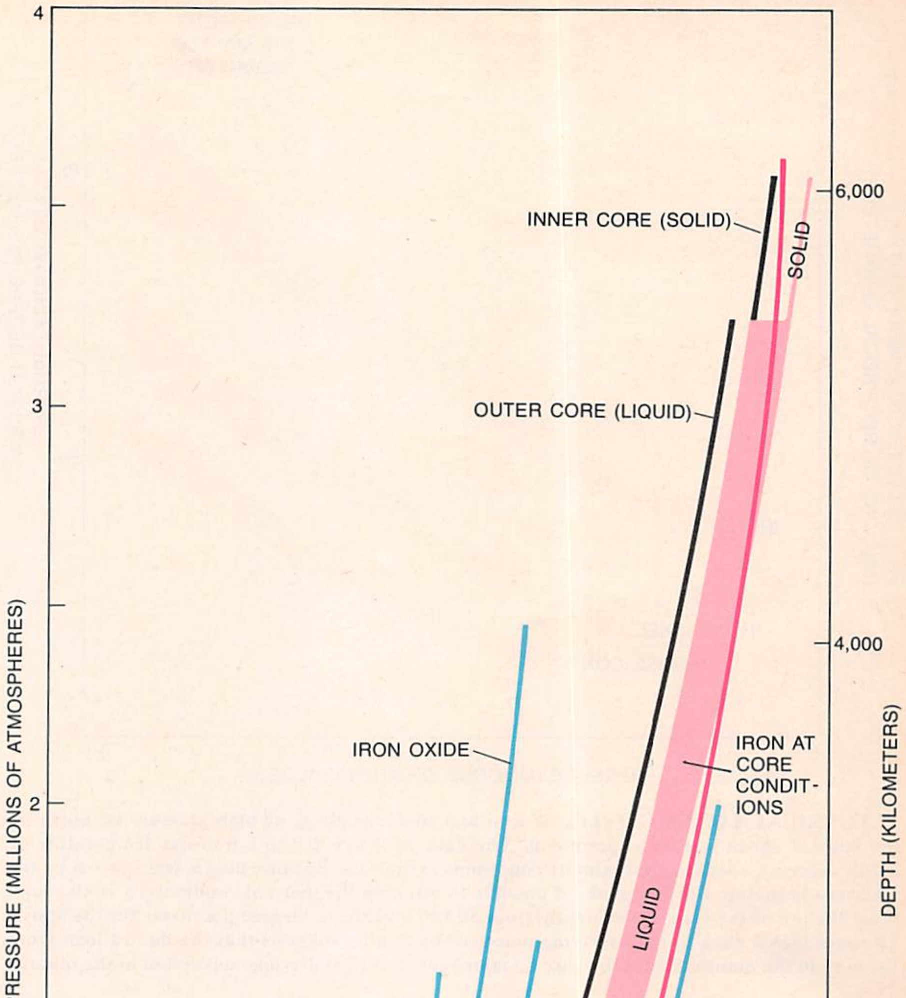
ACOUSTIC PROPERTIES OF THE CORE as revealed by changes in the velocity of seismic waves are shown as a function of depth from the surface of the earth and of pressure at each depth. One atmosphere is the pressure at the surface of the earth. The experimentally determined acoustic velocity of molten iron at core conditions (the pressures and temperatures of the core) closely matches the observed velocity. The seismic data also suggest the presence of an anomalous zone (*vertical shading*) at the top of the inner core. The zone is characterized by a relatively high attenuation of seismic waves. This is thought to be a partially molten region.

According to Fourier's law, heat is conducted down a temperature gradient with a flux (thermal energy passing through a surface of unit area in unit time) given by the value of the temperature gradient times the thermal conductivity. No one has measured the thermal conductivity of iron alloys at the temperatures and pressures of the core, but R. N. Keeler and G. Matassov have determined the electrical conductivity of alloys at core conditions by means of shock-wave experiments done at the Lawrence Livermore National Laboratory. In these metals the electrons carry the thermal energy as well as being responsible for the electrical conductivity. Thus one can employ the data to estimate the thermal conductivity of the outermost core; values between about 60 and 110 watts per degree C. per meter seem appropriate. Multiplying them by the adiabatic gradient of .8 degree per kilometer, one finds the surprising result that the predicted heat flux out of the core (70 milliwatts per square meter, plus or minus 25 milliwatts) is the same as the average heat flux at the surface of the earth.

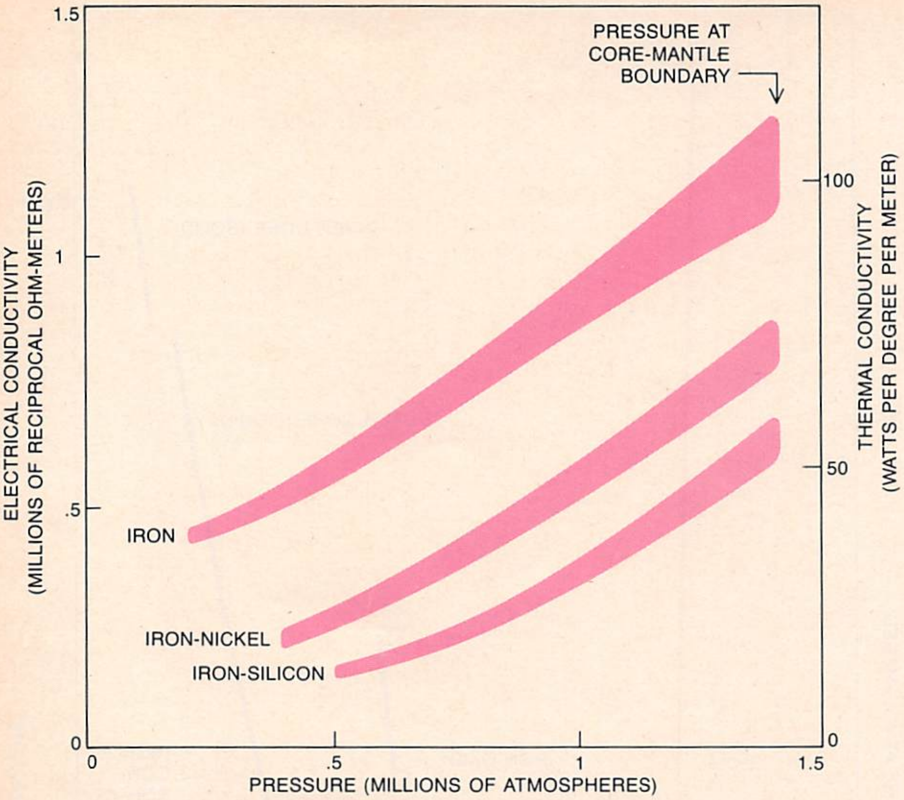
In fact, as most investigators currently believe, if thermal convection occurs, one would expect much more heat to be transported with the fluid than conducted. Therefore the heat flux from the core into the mantle would be higher still. The core thus becomes one of the major sources of heat driving convection in the mantle. Hence there may be not only an indirect but important link between the dynamics of the core and the earth's magnetic field but also one between the dynamics of the core and the large-scale tectonic motions observed at the earth's surface. Alternatively, lower temperature gradients in the core and a lower heat flux into the mantle are possible to the extent that the dynamo is compositionally driven. A low heat flux would imply the core exerts little influence on the dynamics of the mantle.

If a thermally driven geodynamo would need no compositional difference, a compositionally driven one would need no thermal difference. Therefore if no heat sources are invoked and the convective motions in the outer core are assumed to originate in the separation of dense crystals from the core fluid, the core could theoretically be isothermal: it would show essentially no change in temperature with depth. This is an extreme case, and it seems more plausible that heat sources are at work in addition to the compositional mechanism. Hence even for the compositionally driven dynamo temperature would be expected to increase with depth in the core. The core must still be considered an important source of heat for the overlying mantle.

The compositional dynamo does have



DENSITY AS A FUNCTION OF PRESSURE is charted in a comparison of the observed values for the earth's mantle and core with experimental data on iron and iron alloys that may exist in the core. The shock-wave experiments were done at the California Institute of Technology and at the Los Alamos National Laboratory. The comparison is improved by correcting the experimental data for the temperature within the earth and for the liquidity of the outer core, as is shown for iron by the shaded band. The width of the band corresponds to the uncertainty in density at each pressure. The "mystery transition" in iron oxide is a rapid increase in density with pressure that is seen in the experiments. The reason for this densification is not known, but it may indicate that the oxide becomes metallic at core pressures. If this is the case, oxygen may be the alloying element that modifies the observed density of iron in the core.



ELECTRICAL CONDUCTIVITY of iron and two iron alloys at high pressure is shown on the basis of shock-loading experiments. The data are corrected to a uniform temperature of 3,200 degrees Celsius to approximate conditions in the core. Because heat is transported by the electrons in metals, the data make it possible to estimate the thermal conductivity in the core. Near the top of the core it is evidently from 50 to 70 watts per degree per meter for the alloys, 10 times higher than in the overlying mantle. The finding suggests that the flux of heat from the core to the mantle makes the core a major source of heat driving convection in the mantle.

the simple requirement that the liquid of the outer core can separate into two phases (presumably solid and liquid) of significantly different composition, so that they can have significantly different densities. After separation the remaining liquid must be less dense than the original liquid, which makes up the rest of the outer core.

A liquid with a composition different from that of a solid is exactly what would be expected for a partially frozen alloy under equilibrium conditions. This is why an alloy melts and freezes at slightly different temperatures. Here, of course, the presumption is that the solid inner and liquid outer parts of the core are at equilibrium and that accordingly they differ in composition. Certainly the presence of a seismic attenuating zone at the top of the inner core—possible seismological evidence for a crystal-liquid mush—supports the idea.

On the other hand, one should bear in mind that the magnetization of rocks suggests the basic structure of the core (for example the presence of an inner core) may have been unchanged for most of geologic history. If the geodynamo is powered by the separation of the inner core from the outer one, it may be difficult to avoid accepting the contradictory assertion that the structure of the core has changed drastically over geologic time.

A stronger test would be to see whether the inner core is significantly denser than what would be expected for solidified outer-core material. The present seismological evidence is not sufficient to answer this question unambiguously. What seismic waves show is that the jump in density across the boundary between the inner core and the outer one is quite similar to the change in density of iron solidifying at the same pressure without a change in composition. This finding does not support the compositional-dynamo model because it implies that the solidified part of the outer core has essentially the same density as the inner core. Geophysicists are tantalizingly close to being able to evaluate this model, but more data are needed from both seismology and experiments at high pressure.

I return now to the question of primordial heat because it bears on the questions of how and when the core formed and in what way the process was related to the birth of the planet. Two extreme scenarios can be identified. One is that the earth assembled first and then separated into distinct iron and silicate fractions: the core and the mantle. The other is that the core aggregated first and then the remaining silicate-rich material was added.

The first of these pictures is called homogeneous accretion. It is mechanically analogous to the compositional model of the geodynamo, entailing a separation of dense material from less dense material after the earth had accreted. This model is well entrenched in the geophysical literature.

The second picture is heterogeneous accretion. It is a more recent and somewhat less well defined model. The reason is that different rationales have been proposed for the core metal to accrete before the silicates of the mantle do.

In order to distinguish between models of accretion one must consider the timing of three separate (but not necessarily temporally distinct) events in the earliest history of the solar system: (1) the condensation of solids out of the gaseous, cooling solar nebula; (2) the accretion of the entire earth, and (3) the accretion or formation of the core. This is the order of events for homogeneous accretion, with the key factor in the model being that all solids are condensed before accretion begins. Thus the growing planet accumulates both silicate and metal at the same time.

Subsequently the core separates from the mantle. According to Francis Birch of Harvard University, the separation leads to the release of an enormous amount of gravitational energy as the dense iron settles to the center of the planet. The amount of energy involved is comparable to the total thermal energy that would leave the earth over 4.6 billion years, given the present heat flux at the surface. It would have been enough to heat the entire planet by a few thousand degrees, which would presumably initiate substantial melting.

The best-known model of heterogeneous-accretion, proposed by Karl K. Turekian and Sydney P. Clark, Jr., of Yale University, visualizes the core material as condensing early and accreting before condensation is complete, indeed before the mantle silicates can condense and begin to accrete. Hence by the time the mantle has accreted the core is already in place because of the prior chemical separation of iron and silicates during the condensation process. The result is that the planet is relatively cold once it has formed. The reason is that little heat is retained as the earth accretes small particles condensing out of the solar nebula; most of the heat can be efficiently radiated back into space.

With no heat released by the separation of the core and the mantle, high temperatures would not be reached in this model. Yet the chemical separation of iron and silicates during condensation is no longer thought to be plausible. Calculations of the temperatures at which minerals would condense out of the cooling solar nebula indicate that the mantle phases appeared at about the same time as the core materials and maybe earlier. Therefore chemical heterogeneous accretion is now considered to be an unacceptable model.

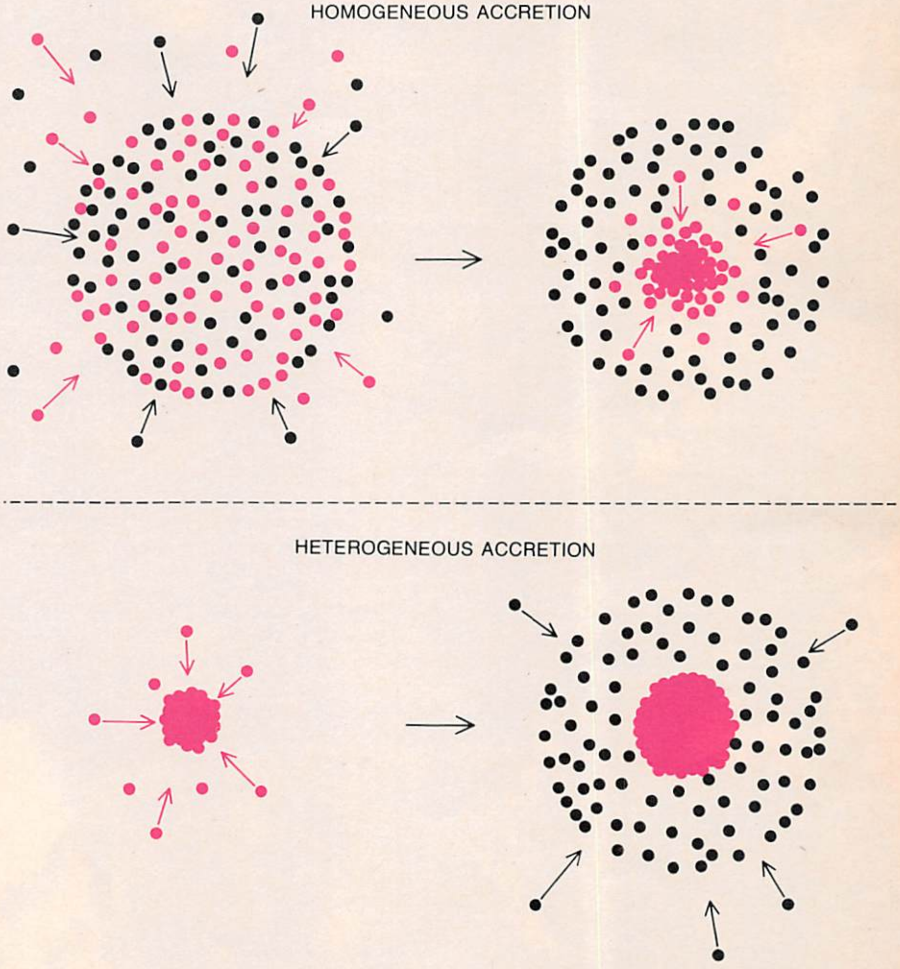
An alternative, physical mechanism could lead to heterogeneous accretion after condensation is complete. As proposed by Egon Orowan of M.I.T. and Hitoshi Mizutani and Takafumi Matsui of the University of Tokyo, after the materials of the core and the mantle have condensed one would expect metallic (core-forming) grains to accrete preferentially. In this view, because of the brittleness and rigidity of silicate and the relative ductility and high density of iron-rich phases, one would expect a rapid agglomeration of metal and a much slower accumulation of silicates. With increasing size the growing protoplanet can accumulate silicates more readily as the gravitational attraction increases. Thus most of the mantle could be accreted after the core has assembled. In this model one can think of planetary growth as being nucleated by the formation of a metallic core.

All the evidence suggests that the earth accreted after metal and silicate particles had condensed in the solar nebula. The model of homogeneous accretion and the model of physical heterogeneous accretion could accommodate this process. The present thinking is that not only particles but also small planetesimals, perhaps already differentiated into iron (core) and silicate (mantle) regions, may have been the building blocks of the earth. One line of evidence is that iron meteorites are thought to have been present 4.6 billion years ago. They exhibit textures characteristic of a slow cooling that could have occurred only in planetary bodies with dimensions of hundreds of kilometers or more. Protoplanetary bodies of substantial size therefore could well have been present at the time the earth formed. Computer studies show that if such bodies were accreted rapidly, the radiation of heat into space would have been relatively inefficient and the planet would have got hot as it grew.

Without rejecting the possibility that the nucleation of the earth may have been initiated by the accumulation of iron, one should consider what would have happened as the planet was growing. On the assumption that both silicate and iron were being accreted, as in the homogeneous-accretion hypothesis, one finds it is not possible to delay for long the settling of iron toward the center of the planet. As G. F. Davies of Washington University has recently pointed out, the force of gravity pulls increasingly on the denser iron-rich regions with time. The reason is that the gravitational force increases as the planet grows, which is to say as its mass increases. For reasonable estimates of the sizes of the denser regions Davies finds the iron can sink, without necessarily melting, after only about one-eighth of the final mass of the earth has been accumulated. The phenomenon is explained by the fact that rocks remain relatively weak even at the pressures existing deep inside a planet.

It therefore seems inevitable that the formation of the core began well before the earth was fully formed and that the differentiation of the planet took place at the same time as most of its accretion. This picture has features of both the homogeneous- and the heterogeneous-accretion models: the earth accretes after condensation is complete, but the core is present early in the growth of the planet. One implication is that the core probably started forming at a relatively low pressure. This implication may lead to difficulties with the hypothesis that the core is an alloy of iron and oxygen. Still, the relation between the composition of the core and the processes by which it formed is not well understood, and further work in this direction is needed.

In any case, once the differentiation of iron and silicates begins the planet would be expected to heat up rapidly as gravitational energy is released. This heating and the heating caused by the relatively rapid accretion of planetesimals are thought to be enough to trigger melting, which leads to an even more effective differentiation of the planet. In this way the formation of the core is seen as a self-perpetuating and possibly accelerating process. Evidently the core had a role in triggering the geologic processes that are still taking place, some 4.6 billion years later.



FORMATION OF THE EARTH is visualized as having been by one or the other of the processes depicted here. In the homogeneous-accretion model silicate (*black*) and iron (*color*) accumulate to form the complete planet (*top left*). Subsequently the core forms by the separation of the metal from the silicate (*top right*). During the formation of the core the iron sinks to the center of the planet and heat is generated by the release of gravitational energy. In the heterogeneous-accretion model the metallic core is accumulated first and the silicate mantle accretes around it. The sequence could occur during or after the condensation of solids out of the solar nebula, depending on whether chemical or physical processes are involved. In each model the accretion of the planet is viewed as resulting from the infall of meteoritic bodies.