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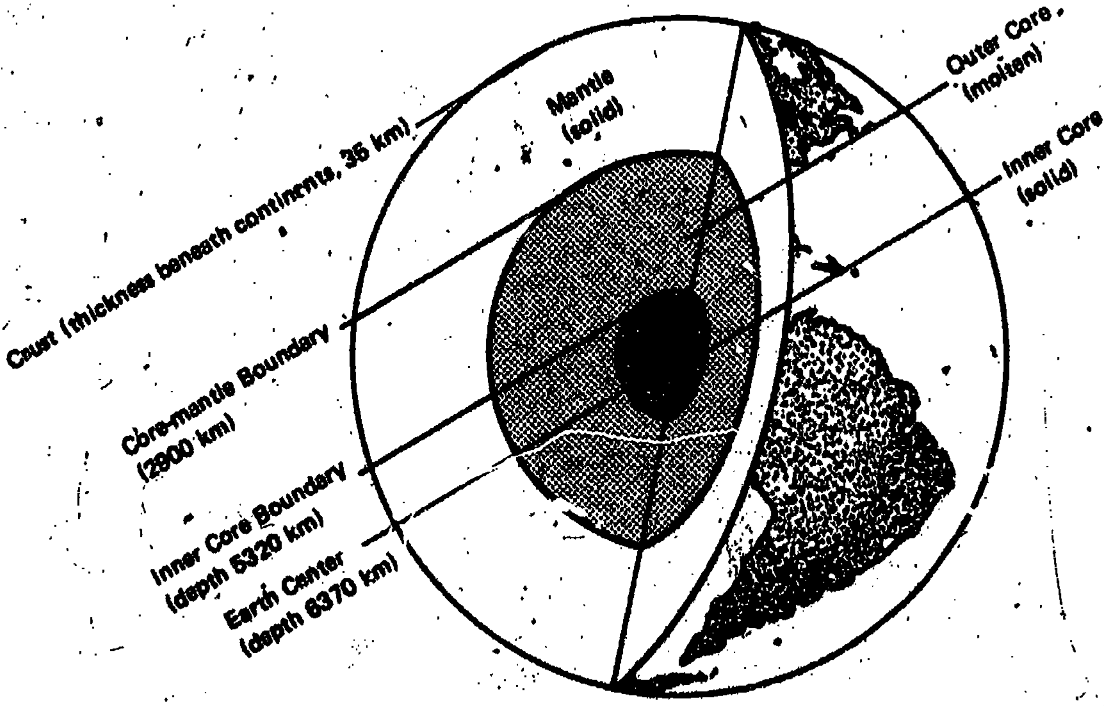
ABSTRACT

Various research studies designed to enhance knowledge about the earth's core are discussed. Areas addressed include: (1) the discovery of the earth's core; (2) experimental approaches used in studying the earth's core (including shock-wave experiments and experiments at high static pressures), the search for the core's light elements, the possible presence of potassium in the core, and use of the diamond cell for investigating the core; (3) seismic explorations of the core; (4) inhomogeneities at the core-mantle boundary; (5) terrestrial magnetism and the outer core; and (6) theories of inner-earth structure from the perspective of solar system history. Studies of the earth's mantle which may provide additional information about the earth's core are also discussed. They include laboratory experiments with mantle materials and modeling of mantle structure at the Carnegie Institution's Department of Terrestrial Magnetism. It is pointed out that although many questions about the earth's core are still unanswered, the promise of new research tools is vast. Favored by advances in computer modeling and in techniques for experiments at very high pressure, today's scientists seem well-positioned to address these questions about the deep earth. (JN)



The Earth's Core: How Does It Work?

The Earth's Core: How Does It Work?

An essay about basic research from
The Carnegie Institution
of Washington

Perspectives in Science
Number 1
1984

PREFACE

Our fast-growing understanding of the center of the earth is one of the most exciting happenings in science today. Questions about the deep interior are attracting scientists of several disciplines, and remarkable advances in laboratory instruments and in computers are opening new research possibilities. Driving the process of discovery is that combination of human curiosity, ingenuity, and resolve that equips certain men and women for a life's work in research. It is to such explorers of tomorrow that this booklet is dedicated.

Contents

Earth scientists George Wetherill and Alan Boss at Carnegie Institution's Department of Terrestrial Magnetism in Washington, D.C., 1984.

> And yet, as we progressed, the temperature increased in the most extraordinary degree, and I began to feel as if I were bathed in a hot and burning atmosphere. Never before had I felt anything like it. I could only compare it to the hot vapor from an iron foundry, when the liquid iron is in a state of ebullition and runs over. . . .
>
> Jules Verne
> *A Journey to the Center of the Earth* (1864)

Jules Verne's imaginary descent into the earth remains a classic of science fiction. The book's appeal reflects a curiosity among readers about the mysteries of the deep earth, a fascination evident in the work of poets and scientists for hundreds of years. But though our curiosity has been strong, our knowledge of the earth's interior has come slowly. It was only in our own century, for example, that the very existence of a distinct central region, or core—a region very different from the rest of the earth in composition and property—was confirmed.

The core occupies 16 percent of the earth's volume and more than half its radius. Temperatures in the core are thousands of degrees, and pressures are enormously high because of the weight of the earth's material above. The deepest region, or inner core, is composed of solid material several times the density of surface rocks. Surrounding the inner core is an ocean of liquid material—a molten outer core. Though conditions inside the core are utterly unlike the environment in which we live, the core is surprisingly close to us—its upper boundary is only 2900 kilometers beneath us, a distance less than that from New York to Salt Lake City.

But beyond this most basic kind of information, we have very little definitive understanding of the core. Scientists are handicapped in that they have no way of obtaining core material for study. (Unaltered earth material has been raised by natural eruptions from at most about 200-kilometer depth, while our deepest drillings reach into the earth only about ten

Are volcanos at the earth's surface related to deep-earth phenomena? Shown here, eruption at Heimaey in Iceland, 1973.

kilometers.) It can be argued that we know more about the surfaces of the Moon, Mars, and Venus, which we explore by spacecraft, than about the deep interior of our own planet. Talented scientists have devised clever methods for studying the core indirectly, but the evidence has been thin, and reaching conclusions from it, one writer has noted, is like trying to re-create the inside of a piano from the sound of its crashing down stairs.

In other areas of the earth sciences, however, ours has been a time of rapid discovery. The "New Geology" of recent years tells us that oceans spread, continents drift, and great plates near the earth's surface collide with or rub against one another. Every week, new studies of the outer earth bring fresh evidence supporting and refining the grand synthesis known as plate tectonics.

But what of the deep earth? When and how did the core separate from the mantle above it, and what is the core made of—iron, surely, but with what other major component or components? What are the properties of its regions, and how is it related to the earth's magnetic field? Finally, is heat from the core in some way a driving force contributing to the changing geology of the outer earth that we inhabit?

Today, scientists of several breeds in dozens of research centers worldwide are seeking answers to questions like these. Studies in related areas are also enhancing understanding of the core—studies of the earth's mantle, for example, or how the earth and solar system formed. But even the finest research of today seldom gives conclusive answers. One thing seems clear: fundamental understanding of the earth's core will come not from some single kind of inquiry but instead by combining results from many. Seismologist, laboratory experimentalist, geochemist, planetologist, computer-oriented theoretician—all will contribute to the future synthesis.

All these disciplines are strongly represented at the Carnegie Institution's Geophysical Laboratory and Department of Terrestrial Magnetism. At both centers, established scientists share with postdoctoral fellows and graduate students the challenges and satisfactions of basic research. Their investigations of the core are only part of the total activity at both centers, and only a part (albeit a major one) of the worldwide effort on this topic. But in their varied studies, the Carnegie scientists are showing how the different disciplines can and must avoid isolation in approaching this remaining frontier of knowledge.

THE DISCOVERY OF THE EARTH'S CORE

Until a few decades ago, most of what scientists knew about the core came from two sources: (1) analyses of whole-earth properties and (2) seismology.

Knowledge of certain whole-earth properties—the earth's mass, average density, and moment of inertia (a value expressing distribution of mass)—came from measurements of variation in gravity and the earth's rotation. It became clear early in the 20th century that the average density of the earth's central region was 2–3 times greater than the known value for the whole earth, and that materials of the deep interior must therefore differ drastically in property and composition from rocks of the crust.

Further understanding came from seismology—the study of the wavelike vibrations within the earth caused by earthquakes or underground explosions. These "seismic waves" are something like the vibrations in a metal bar struck by a hammer. Seismic waves travel through the earth, and their speed and strength at various vibrating frequencies are altered by properties of the regions through which they travel. Thus, seismic waves from earthquakes—recorded by sensitive seismographs at the surface—can reveal something of the composition, density, and rigidity of regions within the earth.

The existence of a central core had been theorized since the 1600's, but its "discovery" from seismic waves occurred in 1906. A few years later, its depth beneath the earth's surface was accurately calculated (2900 kilometers). Meanwhile, the apparent inability of one kind of wave to pass through the core strongly suggested that the core was liquid—a view generally accepted upon later evidence from studies of the earth's rotation and its effects. Then in 1936, from the bending of certain waves at what appeared to be some sort of deep discontinuity, the woman scientist Inge Lehmann discovered the probable presence of a distinct inner region, inside the molten outer core. Later evidence showed that the inner core was solid.

THE EXPERIMENTAL APPROACH

Laboratory experiments to study the core were hindered by two circumstances: (1) the difficulty of attaining the inner-earth's pressures and temperatures in the laboratory, and (2) the lack of actual specimens of core material. In recent years, scientists have partly overcome at least the first problem, so that experimental results at high pressures have increasingly supplemented data from the older methods. A leader in experimental work has been Carnegie's Geophysical Laboratory, located on a hilltop in northwest Washington, D.C., not far from the National Zoo. Founded in 1905 as a center for applying experimental methods to questions about the earth, the Geophysical Laboratory is sometimes called the "gee-whiz lab" for its reputation in pace-setting innovation.

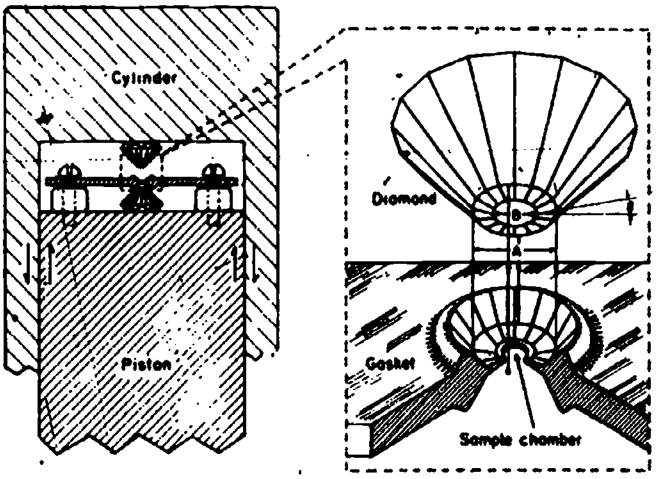
There are essentially two methods for studying materials at very high pressures—pressures comparable to the 1.3 megabars of the core-mantle boundary. (1.3 megabars is about 8500 tons per square inch; a megabar equals 1000 kilobars and is roughly a million times atmospheric pressure at the earth's surface.)

One method is by shock-wave experiments, where measurements are obtained in the few milliseconds after a high-speed projectile strikes a sample under study. Shock-wave studies have been conducted by Thomas Ahrens and colleagues at Caltech, as well as by other scientists in several government laboratories. There are disadvantages—pressures and temperatures change radically during measurements—but important results have been obtained, and more are emerging.

The second method consists of experiments at high *static* pressures. A sample is held between two diamonds, which are squeezed together mechanically to produce very high pressures. Diamond is the hardest known material, and its transparency to x-rays and other kinds of radiation facilitates its use in experiments. Devices featuring diamonds to transmit high static pressures appeared at the National Bureau of Standards in 1962; some of the most remarkable advances in their design have come at the Geophysical Laboratory. There, in 1978, static pressures were generated and accurately measured exceeding that of the core-mantle boundary. The Laboratory's diamond-window cell is hand-portable, can be modified for special experiments, and can hold a sample under pressure for days or weeks if needed.

The Search for the Core's Light Elements

A logical target for experimental work was to learn what the core was made of. Several lines of evidence made it clear that a principal component was iron. Only iron had roughly the properties needed to fit the density calculations and seismic data, and calculations of possible atomic arrangements in crystals tended to confirm its presence in the core. Further evidence came from the supposed abundance of iron in the whole earth, as inferred from samples of early solar system material (i.e., meteorites) and from studies of stars. (Iron is especially abundant in the universe, as the protons and neutrons of the iron nucleus are arranged in a highly stable way.) Inasmuch as iron appeared to be deficient in the earth's crust and mantle, a substantial presence in the core seemed likely.



Cross section of the diamond-window cell. Inset shows expanded view of the upper diamond and the sample chamber. (A = 370 microns, B = 175 microns; 1 micron = 1 micrometer = 10^{-6} meters.)

A diamond-window cell, held by Ho-kwang Mao at left. The unit was designed and built at the Geophysical Laboratory for conducting experiments at ultrahigh pressure. At right, Peter Bell.

But it was also evident that at least one other material—besides iron—was present in the core, as the density of pure iron at core temperatures and pressures is slightly but unmistakably greater than the known density of the core. Some other element or elements, mixed in or alloyed with iron, was needed to reduce the overall density to the known value.

It seemed possible that another core component was nickel, which like iron was otherwise deficient in its overall earth abundance and which was often present with iron in meteorite samples. Could it be that an iron-nickel alloy at very high pressure could have a *lower* density than pure iron? Experiments at the University of Rochester by Ho-kwang Mao (now of the Carnegie Geophysical Laboratory) and others, however, showed that nickel compressed almost identically to iron at high pressures and that an iron-nickel core would be at least as dense as a core of pure iron. Thus, although nickel could not be ruled out as a major core component, it was clear that a different element or elements must be present to reduce the average density. The foremost remaining candidates were lighter elements—sulfur, oxygen, hydrogen, carbon, silicon—any of which at very high pressures might alloy with or coexist with iron or iron-nickel to yield the known average core density. Still another possible core component was potassium, whose radioactivity could conceivably account for the generation of heat in the core.

Several of the light-element candidates have in turn enjoyed favor among scientists, but no theory has been conclusively verified. At the Geophysical Laboratory, investigators have for several years been studying what now seem the most-likely components—oxygen and sulfur. The approach has been highly systematic—properties have been studied at gradually increasing pressures with the goal of establishing a definitive base of data. The work with oxygen stems from Ho-kwang Mao's Ph.D. studies at Rochester, and has included studies to about 700 kilobars with various compounds of iron and oxygen. Work at the Laboratory with sulfur, which includes some of the most recent work, goes back some years to studies at the Laboratory by Staff Member Peter Bell and Robin Brett, then a postdoctoral fellow at the Laboratory and now of the U.S. Geological Survey.

Sulfur was scarcely a new possibility—geophysicists widely realized that its density and melting properties made it a good core candidate and that the rest of the earth was deficient in sulfur. In earlier shock-wave experiments at other centers, pressure-density relations had been determined for pure iron (Fe) and for two iron-sulfur minerals—pyrite (FeS_2) and pyrrhotite ($Fe_{0.9}S$). The Carnegie workers, therefore, began diamond-cell experiments first with pure iron (Fe) and then with troilite (FeS). Their results permit further evaluation of the

Peter M. Bell

Ho-kwang Mao

Guang-tien Zou of the People's Republic of China, who recently spent over two years as a visiting investigator at the Geophysical Laboratory.

possible presence of sulfur in the core.

Three principal investigators have been involved in the Carnegie work. Staff Members Ho-kwang Mao and Peter Bell had worked together for nearly ten years in developing the cell and using it in geophysical studies. The third collaborator in the recent FeS work was Guang-tien Zou, a Visiting Investigator at the Laboratory from Jilin University, People's Republic of China. Zou spent over two years at the Geophysical Laboratory before returning to China in 1982.

Mao, Zou, and Bell have obtained x-ray diffraction photographs of Fe and FeS crystals at pressures up to about 900 and 600 kilobars, respectively. In x-ray diffraction work, an x-ray beam is applied to a small sample. The x-rays are reflected at the atomic planes within the crystals, and if the crystal structure of the sample is regular, the reflected x-rays may reinforce one another to create a "diffracted" pattern when recorded on photographic film. When interpreted by a skilled crystallographer, the diffraction pattern gives details about the sample's atomic structure and crystalline dimensions. Techniques for such experiments with the diamond cell had been developed in previous years and were now routine, though demanding and slow. In the recent work with FeS, Mao, Zou, and Bell discovered changes in crystal structure at several pressures, and they revised the previously understood structure at pressures greater than 130 kilobars. Most importantly for studying the core, they obtained reliable values of density (measurable by observing how closely the atoms are packed within crystals) at given pressures.

Figure 1 shows the significance of these experiments for studying the possible composition of the core. Four curves (solid lines) plot pressure vs. density for materials of distinct iron-sulfur composition. The Fe and FeS curves are from Mao, Zou, and Bell's diamond-cell data; the FeS_2 and $Fe_{0.9}S$ curves are from shock-wave experiments.

It can be seen that the positions of the four curves depend on iron-sulfur composition. The more sulfur present (as a percentage of atoms in a given molecule), the lower the density at given pressure and the farther left the plot. (FeS_2, with two atoms of sulfur per one atom Fe, is the least dense and plots farthest left; Fe, with zero S, is the most dense and plots farthest right.) We are, in effect, seeing how the presence of sulfur reduces overall density, just as it might lower the density of a primarily iron core in the earth.

Meanwhile, we know from seismology the pressure-density values of the actual earth's core, which are shown on Figure 1 in heavy dashes. This is an important curve, because it defines what must be seen in the laboratory in establishing the true core composition.

The plots in Figure 1 appear to show that sulfur can indeed be an important core component. It is evident that an intermediate sulfur composition—somewhere between that of pure Fe and FeS—could approximate the pressure-density values of the actual core. A value of 7–9% sulfur by weight appears to be required.

The Carnegie investigators note, however, that 7–9% sulfur by weight would still leave some sulfur unaccounted for under the whole-earth "sulfur budget" concept, and they warn that they have not proven that sulfur is the only or indeed the principal light element of the core.

Bell and Mao plan to continue systematic studies of iron sulfides and oxides, to include work with a 7–9% sulfide. They expect to extend the pressures to perhaps 1 megabar (1000 kilobars) in the next year. Their work has shown the need for

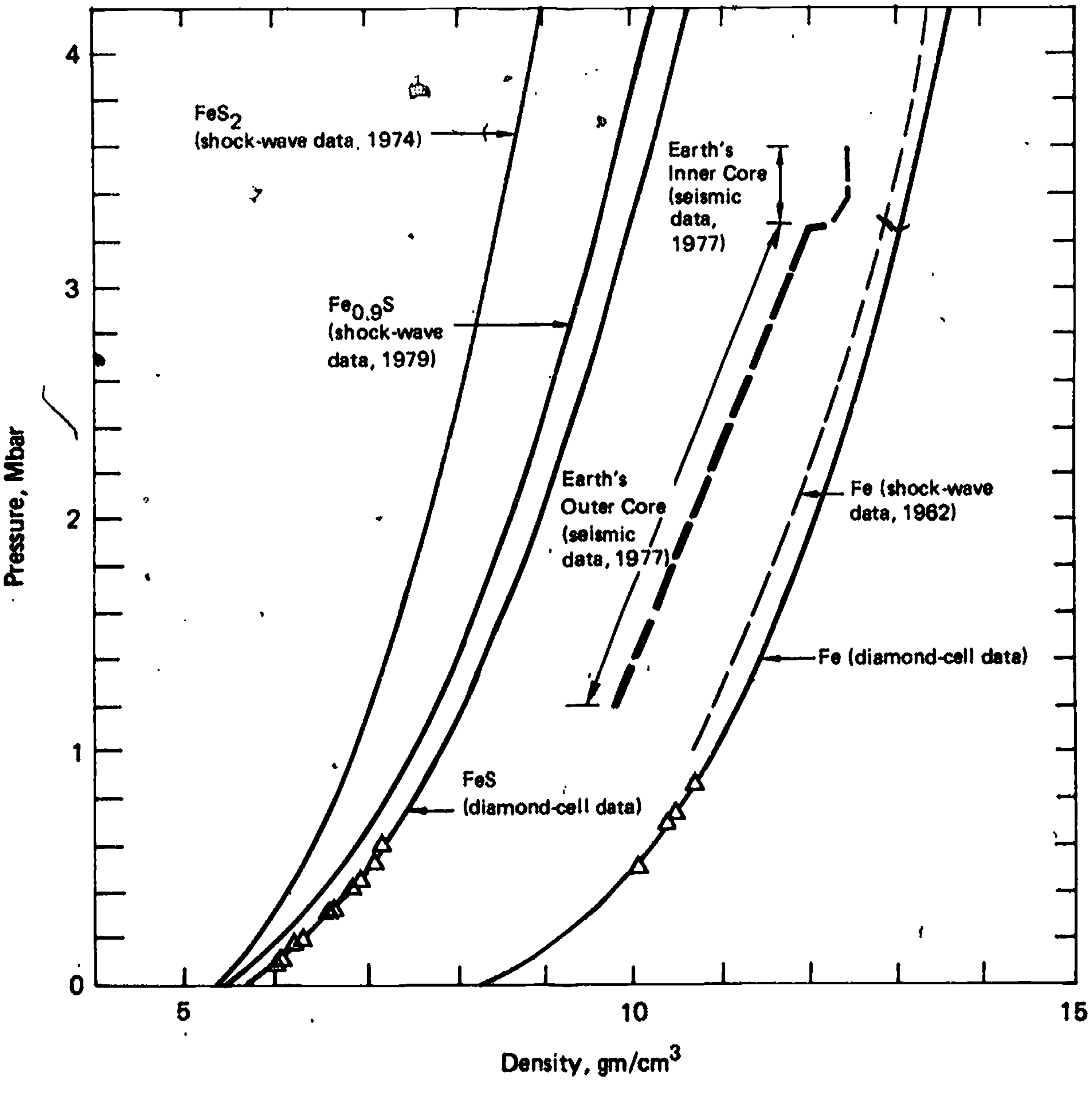


Figure 1. Experimentally determined plots of pressure vs. density for materials of varying iron-sulfur composition, and a plot for the actual earth's core known from seismic information. It is evident that the pressure-density relation of an iron-sulfur material having 7–9% sulfur would approximate that of the actual core. (Sources of data for the above plots are given at the end of this essay.)

further experimentation at higher pressures and with other candidate materials. Any future theoretical model of the core must be accommodated to their results.

The Geophysicists

The remarkably productive collaboration between Ho-kwang Mao and Peter Bell began soon after Mao's arrival at the Geophysical Lab in 1968. Born in mainland China, Mao had been raised on Taiwan and had earned the Ph.D. at the University of Rochester, where he worked with Professor William Bassett and other mentors in developing diamond-cell devices for experiments at high pressure. Peter Bell had come to Carnegie in 1963, fresh from doctoral work at Harvard under the geophysicist Francis Birch, whose earlier calculations of arrangements in crystals had shown iron to be a principal component of the earth's core. Bell warmly remembers the exhilaration of his early months at the Geophysical Laboratory at the chance to work with instrumentation designed for the most advanced kinds of experiments—"to do work possible nowhere else."

An important stimulus came in 1974, when Bassett told Mao and Bell that the government was removing restrictions on use of certain powerful laser equipment. (Lasers offered a way of heating samples inside the diamond-window cell.) Mao and Bell now "really went to work" stepping up the experimental pressures. A period of friendly competition with workers elsewhere ensued, and in 1978 Mao and Bell attained a static pressure of 1.7 megabars, equivalent to well inside the earth's core. One of the diamonds became plasticized at that intense pressure—a remarkable event but a disappointing one, as it suggested that higher pressures would not be achieved easily. The year 1984 brought a fresh surge of excitement at the Laboratory, when Mao and Bell (with newcomer Kenneth Goettel) found new techniques for overcoming the 1.7-megabar limit, and in fact reached pressures exceeding 2 megabars.

Over the years, a succession of younger investigators have come to the Geophysical Laboratory as fellows and visiting investigators to do research on the deep earth. This year, temporary staff member Kenneth Goettel and predoctoral fellow Andrew Jephcoat are addressing questions about the core.

Is Potassium a Component of the Core?

Several years [illegible], a graduate student at MIT, Kenneth Goettel, became interested in the possibility that the element potassium was present in the core. He noted that, like sulfur, potassium seemed depleted in earth rocks; especially interest-

A recent seminar-discussion of high-pressure experiments at the Geophysical Laboratory.

ing was the thought that the radioactive isotope of potassium could represent an important heat source in the core. In theoretical calculations, Goettel showed that at the high pressures of the core-mantle boundary, potassium ~~plausibly could~~ partition out of the solid silicate mantle to enter a molten iron-sulfur core. His laboratory experiments were limited to relatively low pressures, but his results indicated that potassium solubility in iron-sulfur melts increased with temperature and pressure.

His Ph.D. degree in hand, Goettel then spent several years as a faculty member at the University of Washington in St. Louis. Knowing of the diamond-cell work at Rochester and Carnegie, Goettel set out to develop a diamond-cell laboratory of his own. The venture was naive, Goettel now says, for he failed to appreciate the experience needed to make these seeming simple mechanisms function effectively.

Realizing that experiments under high pressure were essential to test further his thoughts on the core, Goettel in 1982 applied for and received an appointment at the Geophysical Laboratory. There, in a small office in an outlying building

Andrew Jephcoat, a Johns Hopkins graduate student, who is doing his doctoral research at the Geophysical Lab.

Kenneth Goettel, who is investigating potassium as a possible core component.

once used in wartime for testing machine-gun barrels, he planned a serious assault on the candidacy of potassium as a core component.

He began with x-ray diffraction experiments on potassium, looking for changes in atomic structure as pressure was increased. Such changes would suggest that at the pressure of the core-mantle boundary, potassium would behave not as in its normal, alkali-metal state but rather like iron or nickel. He worked with potassium in the metallic form, which readily oxidizes and is therefore difficult and indeed hazardous to handle; Goettel therefore devised special techniques for preparing and loading samples under inert mineral oil.

Experiments with potassium were not entirely new at the Geophysical Lab. Even before Goettel arrived, Zou, Mao, and Bell had done diamond-cell experiments with potassium thioferrite, or $KFeS_2$. The manufacture of this material for laboratory use is difficult (and dangerous), requiring controlled oxidation reactions at very high temperatures. The Carnegie workers were able to obtain samples from Thomas Ahrens at Caltech, who had previously conducted shock-wave experiments with the same material. The Zou, Mao, and Bell results, conducted at intermediate pressures, conformed well with Ahrens' shock-wave results, except that a sharp transition in density was discovered at about 274 kilobars.

Since 1982, Mao and Bell have studied $KFeS_2$ up to about 600 kilobars, while Goettel has obtained initial results with metallic potassium to similar pressures. Their data suggest that experiments may some day confirm whether or not potassium could be maintained in an iron-sulfur structure at core pressures. Meanwhile, potassium remains a potential candidate—neither confirmed nor refuted—as a core component. Its main role, however, must be as a heat source; calculations verify that it cannot alone be present in sufficient amount to bring the density of the predominantly iron core to the known value.

Using the Diamond Cell

Graduate students sometimes make important contributions at research centers. Andrew Jephcoat grew up in England but came to America to study at Johns Hopkins University. Since mid-1982, Jephcoat has worked several days each week at the Geophysical Laboratory under the guidance of Mao and Bell. The routine has not been easy; he sometimes commutes by rail and subway from Hopkins in Baltimore—two hours each way. The regime entailed long workdays at the Laboratory and an occasional overnight stay.

In his first months at the Laboratory, Jephcoat learned from Mao the demanding techniques for working with the diamond-window cell. Diamond-cell experiments can be trying, he soon discovered. A month or more can be required in preparing a diamond-cell unit and sample for observations; the diamonds must be aligned slowly and with great care. Once observations begin, each x-ray diffraction photo requires about a week of film exposure in order to gather enough x-ray photons. The pressure is then increased (or reduced) for another round of exposures until, inevitably, one of the diamonds finally breaks. Then the procedure starts again with new diamonds and a new sample.

Jephcoat's early observations were with FeS_2 samples at pressures up to about 250 kilobars. (Bell explains that it is important to work gradually toward the pressures of the core, because interpretation of x-ray and other observed data depends on understanding the behavior of atoms and ions at lesser pressures.) After his first year, Jephcoat had accumulated several series of x-ray diffraction photographs, of which some were obtained using Mao's recently developed "hydrostatic" techniques. In a hydrostatic experiment, the sample is enveloped in fluid, and pressure is applied evenly from all directions thereby reducing distortions when there is a single axis of compression. One of Jephcoat's goals is to discover differences in results from the two methods, thereby pinning down the corrections necessary when using data obtained by the older method.

Jephcoat's studies with S_2 are, in effect, adding data to the known pressure-density plots of Figure 1. He has now reached 400 kilobars with FeS_2 toward a goal in his thesis re-

Carnegie Institution's Department of Terrestrial Magnetism.

search of about 800 kilobars. He also plans to study at least one iron oxide, probably FeO wüstite, as well as pure iron, in order to develop comparisons between oxygen and sulfur as possible core components.

SEISMIC EXPLORATIONS OF THE CORE

A mile or so north of the Geophysical Laboratory, in a neighborhood of splendid woodland and residences, lies the Carnegie Institution's Department of Terrestrial Magnetism (DTM). There, in wide-ranging work in the earth sciences and astronomy, scientists continue the Department's tradition of exploring in promising directions without regard to traditional disciplinary boundaries. Members of DTM and the Geophysical Lab share computer facilities, sometimes collaborate in research, and periodically renew rivalries in softball and soccer.

The work at DTM has for several decades included a strong program in seismology. In 1962, a new individual joined the seismology group, whose members were then engaged primarily in studying the earth's crust by means of man-made explosions. Selwyn Sacks arrived fresh from doctoral studies in South Africa and with a background in studying mining-induced earthquakes. Sacks' interests soon turned to the deep earth, however, and in the late 1960's, from his analyses of certain earthquake waves traveling along the core-mantle boundary, he published new values of core radius, core rigidity, and other properties.

In 1969–1970, Sacks began exploring the deep earth by studying the attenuation, or weakening, of seismic waves in passing through given regions. A region's attenuation properties are expressed numerically as its anelastic coefficient, or Q. A very high Q value typically indicates a molten region; an intermediate Q is usually associated with solid matter, while a very low Q can signify partially melted, soft material.

To determine Q, comparisons are made between waves taking different paths through the earth. The *direct* compressional wave, or P wave, travels directly through the earth from earthquake to a given station. Another wave from the same earthquake might be "reflected" at the earth's far surface and reach the same station many minutes later. Other waves can be received after being reflected or bent at certain inner-earth discontinuities—at the core-mantle boundary, for example. Seismologists, by comparing the recorded signals from different waves, can make comparisons between the different regions of the earth traversed.

For studying Q of the *outer core*, Sacks needed to compare a pair of waves *differing mainly in their extent of travel through the outer core.* (Consider: if both waves travel through the mantle an equal distance but only one travels through the outer core, then the differences between the recorded waves will represent the effects of travel through the outer core.) Unfortunately for Sacks, there are no wave pairs having this ideal geometry. Instead, Sacks was forced to work with (1) the direct P wave and (2) a reflected wave, *PKPPKP* in Figure 2, which traverses the core twice. Sacks could compare the attenuations of the two waves, but because the two path-

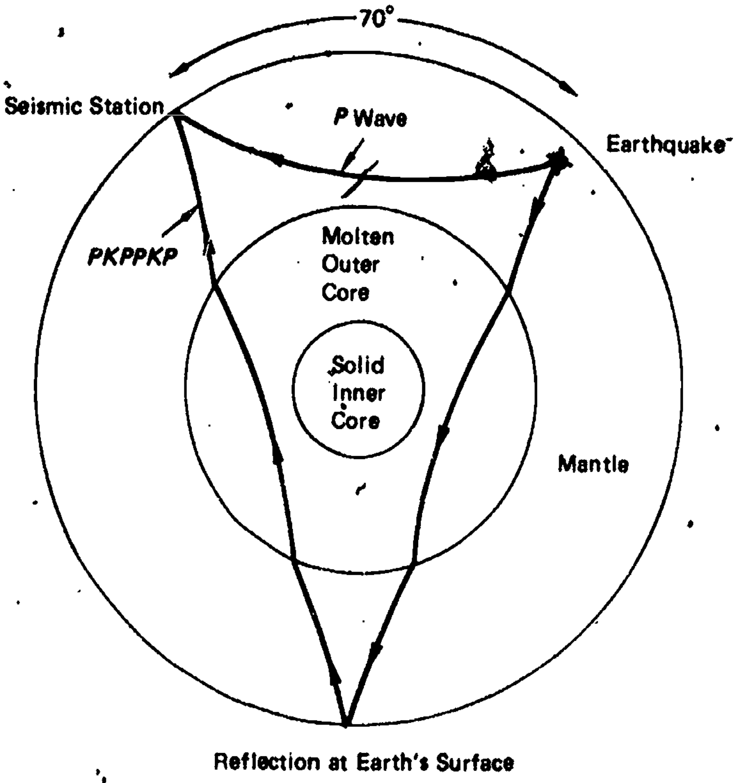


Figure 2. Wave paths used to study the outer core. The *P* wave travels directly through the mantle to the seismic station. The *PKPPKP* wave, which reaches the station after being reflected at the earth's distant surface, travels through the mantle four times and the outer core twice. The determination of outer-core *Q* thus depends heavily on correcting for mantle *Q*. To receive this wave pair, the locations of earthquake and station must be about 70 degrees of earth circumference apart.

ways differed considerably in extent of mantle travel, a major correction for mantle *Q* was required. Unfortunately, scientists in 1970 had not reached an agreed value for mantle *Q* (although Sacks himself had previously published measurements). Sacks, therefore, did not feel justified in stating a unique numerical value for outer-core *Q*. He conclusively showed, however, that "the *Q* of the outer core is much higher than that of any other region in the earth." This result was consistent with the known liquid nature of the outer core.

Wave-path geometry is more favorable for studying the inner core. A pair of waves can be received, one of which passes inside, the other just outside the inner core. The two are similar in their mantle and outer-core travel, so that Sacks could compare attenuation properties and compute *Q* for the inner core without making major corrections (see Figures 3 and 4).

In a significant and largely unexpected result, Sacks determined that *Q* values in the outer part of the inner core were extremely low. The change from the high values of the outer core was extremely abrupt (see Figure 5). Sacks conjectured that a zone of partially melted, relatively soft material extended 100–150 kilometers into the inner core. Within this soft region, *Q* increased with depth, indicating that the solidity of the material gradually increased. Below the transition region, Sacks found that *Q* increased slightly with depth—a result confirming that the inner core was solid. These results are still cited in scientific literature, and Sacks is often asked questions about the work at professional meetings.

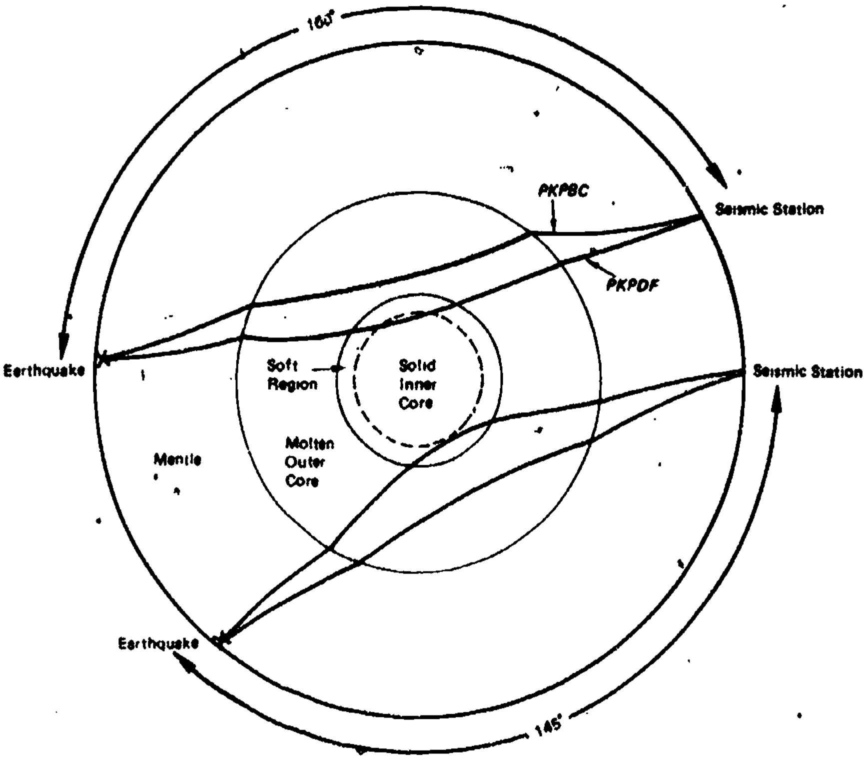


Figure 3. Wave paths used to study the inner core. The wave pair at bottom is used to study the upper part of the inner core, where a soft, transition region has been found. Earthquake and station are separated by about 145 degrees. The upper pair, where earthquake and station are about 160 degrees apart, is used to study a deeper part of the inner core. Waves of each pair have near-identical travel distances through the mantle and outer core, facilitating wave comparisons.

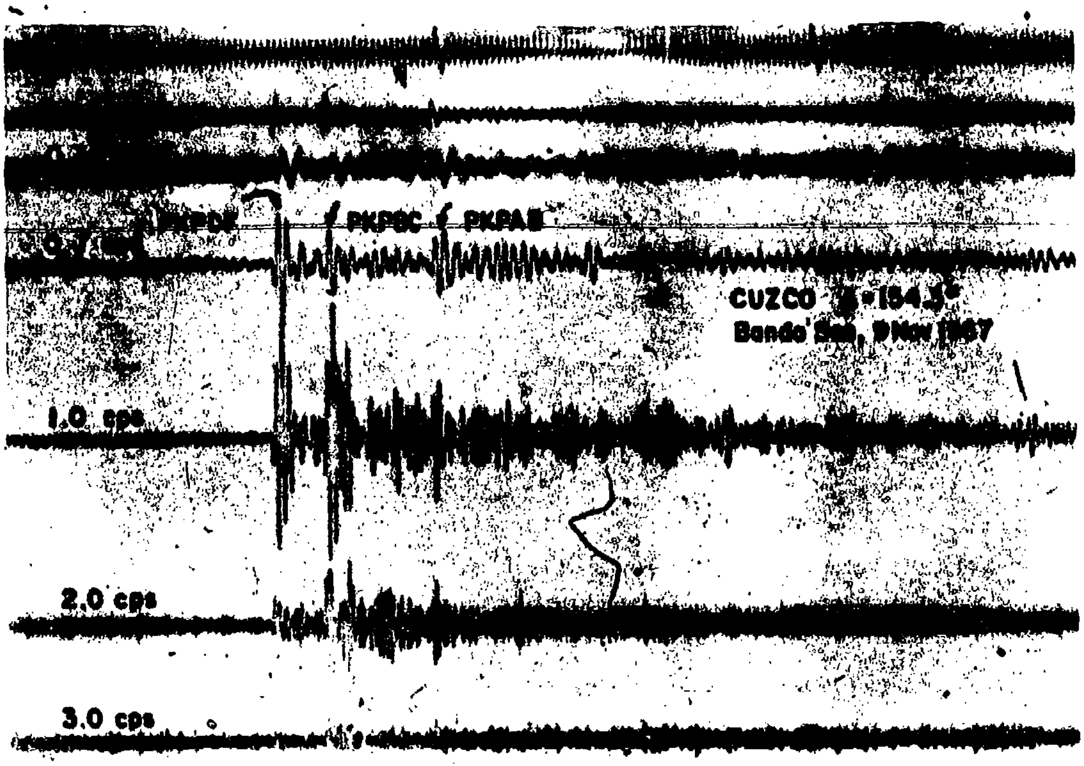


Figure 4. Seismic-wave traces used in studying the inner core; recorded at Cuzco in Peru from a 1967 earthquake in the Banda Sea, Indonesia. The station and earthquake were 154 degrees apart on the earth's circumference. The *PKPDF* has traveled through the solid inner core; *PKPBC* and *PKPAB* have not. (The wave paths are shown on Figures 3 and 6.) Comparisons of the signal heights, or amplitudes, at the several frequencies (cps) allow determinations of inner-core *Q*.

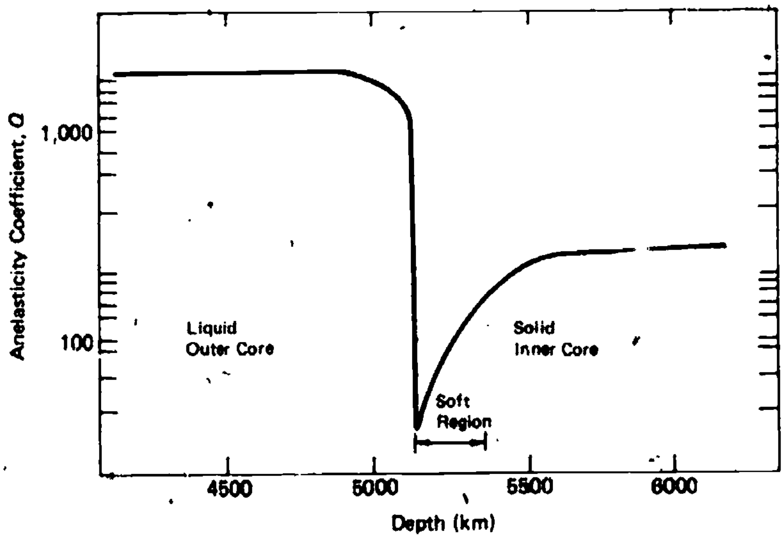
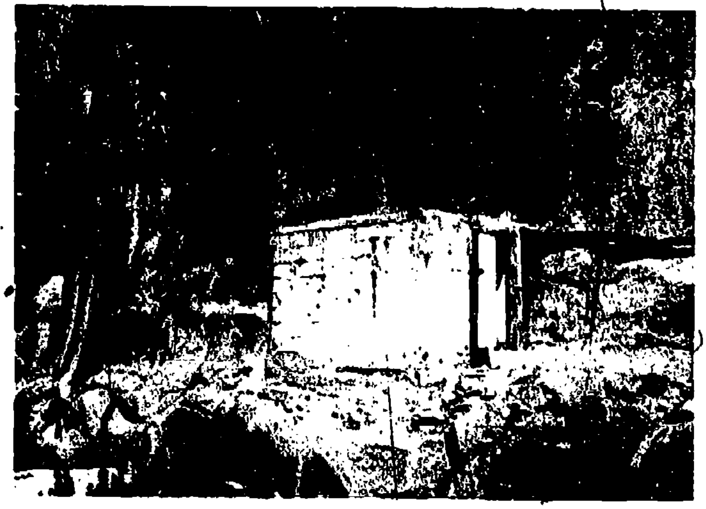
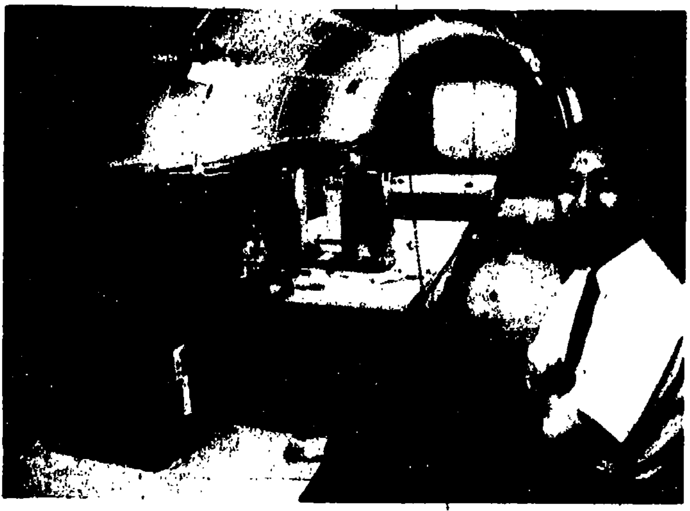


Figure 5. The probable attenuation properties of the core; from Sacks' 1970 investigations. Values of *Q* change markedly at the outer part of the solid inner core, showing the presence of soft, partially molten material.

Selwyn Sacks describing his seismic investigations before a group of scientists at DTM.



Vault containing recorders for seismic information in the Andes Mountains of northern Chile.



The DTM-developed broadband seismograph installation 50 feet beneath the surface at Matsushiro, Japan; geophysicist Ziro Suzuki of Tohoku University, shown above, was a postdoctoral fellow at DTM in the early 1960's.

Inhomogeneities at the Core-Mantle Boundary

Sacks next turned to a puzzle left from previous work. Several years earlier, he had observed an unusual scattering among seismic waves that had traveled along the core-mantle boundary. One possible explanation was that the core-mantle boundary was not a perfect sphere but that it was physically irregular, having severe topographic relief. Sacks at first favored this view, but by 1974, researchers elsewhere had ruled it out.

Another possibility remained—that the mantle closest to the core is not everywhere the same, that different places are different in composition, temperature, and other properties. If this was the case, Sacks realized, such inhomogeneities might be evidence of nonuniform heat flow from the core beneath. "In some way," he wrote, "the elastic properties of this region are affected by the core."

Sacks and Liselotte Beach, a technical assistant at DTM and an expert in working with seismic records, set out to pin down whether or not the region just outside the core is, in fact, nonhomogeneous. They worked with two waves that crossed the lowermost 150 kilometers of the mantle at different places and at very different angles. One wave traveled through the lowermost mantle at an oblique angle, while the second wave crossed the region almost squarely (see Figure 6). A comparison of the two waves from a single earthquake, Sacks reasoned, would exaggerate properties of the place where the region was traversed obliquely. Then, by analyzing *many* pairs of waves from *many* earthquakes recorded at *many* stations, the properties of many different places could be compared and a kind of horizontal map of the lowermost mantle could be developed.

To receive the desired waves, it was necessary that the seismic stations and the earthquake source be located 155–175 degrees of earth circumference apart. Sacks and Beach worked with records from stations throughout South America, where the necessary waves were received from the frequent earthquakes of the northern and western Pacific. A good part of the lowermost mantle could be studied, especially the part directly under the eastern and southeastern Pacific. Computers greatly facilitated the analysis.

In their results, Sacks and Beach found much inhomogeneity in the lowermost mantle. Further, the patterns of inhomogeneity that they found strongly suggested that heat and material were slowly circulating within the lowermost mantle, in a process known as convection.

Convection is an important concept in studying the earth. In convection, warm material, being lighter, moves upward; cooler material descends. Cells of circulation are formed. We can see convective movement when water is heated in the kitchen. In solid material like the earth's mantle, convection is much slower than in a fluid, but the basic principle is the same—

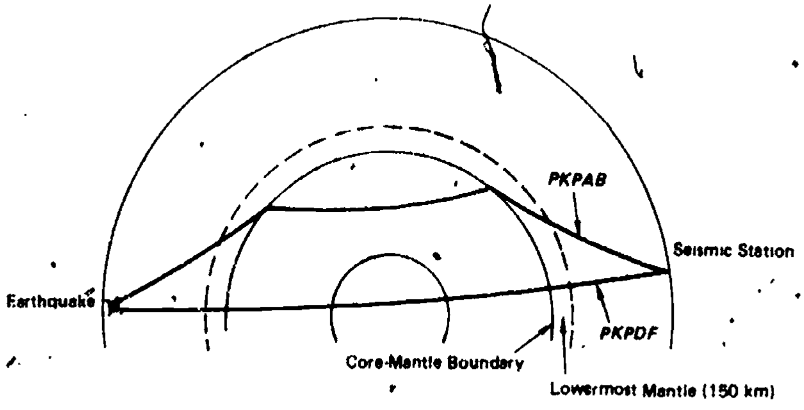


Figure 6. Wave paths used to compare properties of different places in the lowermost mantle. The *PKPAB* wave traverses the lowermost 150 kilometers of the mantle obliquely, while the *PKPDF* crosses the region radially at a different place. The lowermost mantle thus affects *PKPAB* maximally, *PKPDF* minimally. The measured difference between the two waves, then, is primarily an indication of the properties of the places in the lowermost mantle traversed by the *PKPAB*.

heated material rises and cooled material descends, forming cells of circulation and transporting heat.

Do the lowermost-mantle inhomogeneities found by Sacks and Beach indicate convection *below* the core-mantle boundary as well as above?

Sacks believed that the answer was yes. The inhomogeneities, he wrote, were most likely produced by uneven heat flow across the core-mantle boundary—strong evidence of the existence of convection in the molten core. Moreover, the transfer of heat across the boundary suggests that convection in the core could be related to convection in the mantle: a hot (rising) sector in the molten core, for example, could encourage formation of a hot (rising) sector in the mantle immediately above.

TERRESTRIAL MAGNETISM AND THE OUTER CORE

The name of Carnegie's Department of Terrestrial Magnetism comes from its early work in surveying the earth's magnetic field by land and sea. For many years, the Department's nonmagnetic sailing vessel conducted scientific voyages to far corners of the world. But starting in the 1920's, DTM's activities gradually shifted to other matters. The current DTM director, George Wetherill, passes on a good-natured comment by a prominent British scientist, that "the last director of DTM to know anything about terrestrial magnetism was the first one." Still, Wetherill notes that consideration of the earth's magnetism and its magnetic field must not be neglected in any discussion of the core.

Scientists early in our century realized that the earth, in a very rough way, resembled a simple electromagnet. In an electromagnet, wires are coiled to form a helix around an iron cylinder. When electric current is passed through the wires of the coil, a magnetic field is induced through the iron core and the medium outside. In the earth, fluid motions of electrons in the molten outer core may perform the role of the coil; a magnetic field could thus be induced whose lines of force extend through the solid inner core, and through and around the whole earth (see Figure 7).

But it was also apparent from changes in the earth's magnetic field—changes rapid enough to be evident to seagoing navigators from year to year—that the field and the mechanism that produced it were scarcely simple. Indeed, it has been said that the behavior of the earth's magnetic field is comparable in its complexity to the behavior of the earth's weather.

From the work of many scientists, it is now almost universally accepted (1) that the earth's magnetic field is strong evidence of convective movements of heat and material in the outer core and (2) that changes in the magnetic field are

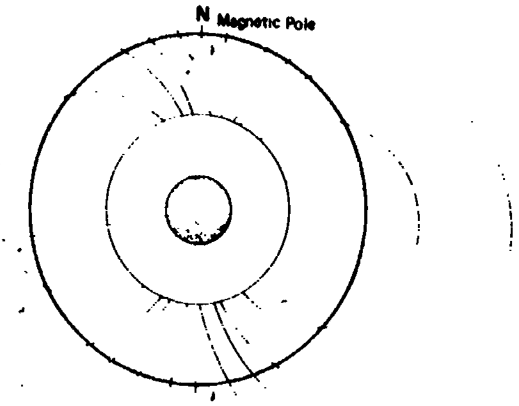
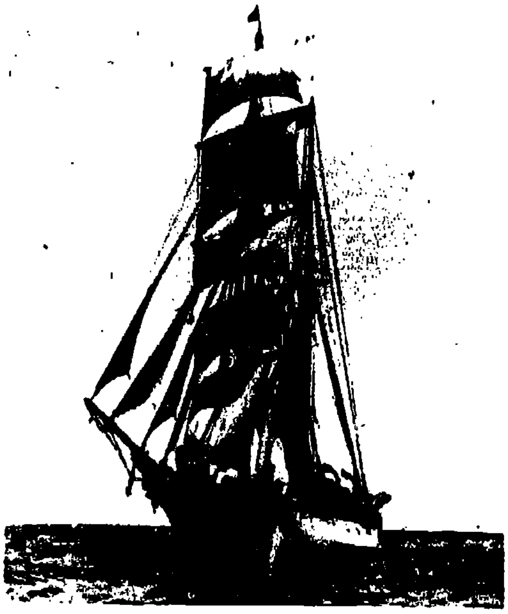


Figure 7. The earth's magnetic field.



The nonmagnetic vessel *Carnegie* was used for exploring the earth's magnetism until the ship was destroyed by explosion and fire in the Pacific in 1929.

caused by changes in this convection. But there are wide differences in explaining the causes of the convection and the nature of its changes. Perhaps convection in the outer core is primarily caused by the heat of radioactive potassium in the core itself, or perhaps by heat released as molten material of the outer core slowly solidifies to build up the inner. Or perhaps there are differential movements in the rotations of the solid inner core and the solid mantle, movements which dissipate energy and create turbulence in the outer core thus contributing to convection or constantly altering it. A concept recently being discussed at DTM is that molten material of the outer core cools and solidifies at the core-mantle boundary; the solid particles then descend by gravity through the molten core, and the gravitational energy is transformed into heat.

Something of the history of the earth's magnetic field is told by paleomagnetism—the study of magnetism remaining in ancient rocks. Evidence from paleomagnetism seems to indicate that the earth's magnetic field (and presumably the convecting core) formed early in earth history. But no theory of core convection and its role in producing the magnetic field has been conclusively proven. A phenomenon as basic and remarkable as the periodic 180-degree reversals in polarity of the earth's magnetic field, also known from paleomagnetism, remains very incompletely understood.

THE MANTLE AS A WINDOW ON THE CORE

Scientists realize that many questions about the earth's core can be answered only with greater understanding of the mantle. Indeed, at both DTM and the Geophysical Laboratory, scientists interested in the core are directing much of their immediate attention to mantle questions.

Laboratory Experiments with Mantle Materials

About four years ago, investigators at the Geophysical Lab began experimenting at high pressure with materials believed to predominate in the mantle. Peter Bell, Ho-kwang Mao, and Takehiko Yagi, now of the University of Tokyo, found an important change in mineral structure at pressures equivalent to 670-kilometer depth in earth. The discovery reinforced evidence from seismology, isotope geochemistry, and theoretical work, all suggesting the existence of some kind of discontinuity or change at that depth.

Increasing the experimental pressures, Bell, Mao, and Yagi discovered that at pressures corresponding to the lower third of the mantle, iron begins to shift from the silicate compounds over to the denser oxides, which would tend to descend in the actual earth. Then, at experimental pressures equival[illegible] to the core-mantle boundary, a small amount of metalli[illegible] is expelled. It remains speculative whether in the real [illegible] some such solid-separation process is taking place, thereby slowly influencing core structure.

Although most of the group's work today is at pressures of the mantle, the eventual objective, Bell explains, is to study the properties of iron and its alloys at pressures and temperatures of the core. "Once we know the melt properties of the molten core, the density relations, the convective possibilities, the drag properties and viscosities, then we can ask about the reactions between the solid silicate mantle and the molten outer core, about the composition of the inner core, and whether the inner core is growing. It could be an enormous breakthrough."

Mantle Models at DTM

The inhomogeneities in the lowermost mantle found by Sacks and Beach are, Sacks believed, caused by uneven heat flow from the core. The question inevitably followed: to what extent are the mantle inhomogeneities—themselves a reflection of events in the core— further related to structure in the upper parts of the mantle and at the earth's surface? (A dis-

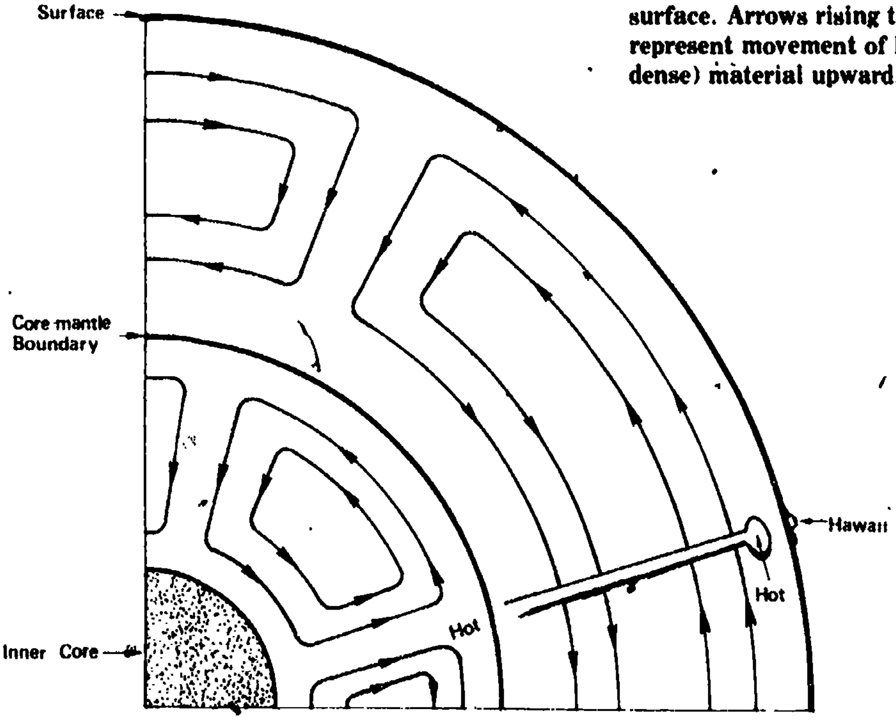


Figure 8. Sketch showing a possible relationship between a hypothetical convection pattern in the outer core and a plume of hot material extending through the mantle and underlying a volcanic hot spot on the surface. Arrows rising toward the surface represent movement of heated (i.e., less dense) material upward.

tinctive region identified by Sacks and Beach deep beneath the southeastern Pacific, Sacks noted, seems to be related to a bulging at the surface detected by satellite.) In particular, can certain hot places at the core-mantle boundary be linked to rising plumes of hot material in the mantle, like the plume apparently causing the volcanoes forming the Hawaiian Islands?

These are relatively new ideas, and scientists are only beginning to develop ways to test them. With such questions ultimately in mind, Sacks and J. Arthur Snoke, who now serves on the faculty at VPI, several years ago began computer studies of mantle convection. Later, DTM postdoctoral fellow Richard A. Lux prepared a computer code (i.e., a detailed software program) for use with the DTM computer in developing a two-dimensional model of the mantle. The code introduced known seismic and geochemical data along with equations from thermodynamics and fluid mechanics in an attempt to simulate mantle structure and dynamics. Currently, Alan Boss, a DTM Staff Member, is working with Sacks in adapting Lux's code for use with the more-powerful computer at the Geophysical Laboratory.

The computer code now in use is extremely detailed, and its running requires much computer time. Even so, the code produces a great simplification of the real mantle: specific geographic places are not represented, and the simulation is two-, not three-dimensional. In an important recent result, however, Boss and Sacks showed that a region of significantly high temperature at the core-mantle boundary could indeed disrupt the general convective flow of the mantle, to form a plume able to reach the surface in about 100 million years (see Figure 8).

The workers at DTM expect to continue improving their computer simulation of the mantle. Their venture, and similar ones elsewhere, serve to exemplify how modern data-processing technology can be applied in basic research.

THE PERSPECTIVE OF SOLAR SYSTEM HISTORY

Any theory of inner-earth structure must be consistent with what is known about how the earth itself initially formed, a matter of much uncertainty.

Most scientists agree that the Sun, earth, and planets all formed from a primitive nebula of gas and dust. The earth and the inner, terrestrial planets are rocky, unlike the outer "gaseous" planets which succeeded in retaining most of their hydrogen and helium. The earth now predominantly consists of elements much heavier than hydrogen and helium—mainly silicon, magnesium, and iron, along with oxygen in the form of oxides.

Essentially, there are two possible scenarios for initial earth formation. Our planet might have formed at about its present size very rapidly (in about 10,000 years) by direct condensation about a single region of gravitational instability. Or, it may have been assembled by the accumulation of smaller planetesimal bodies over a period of perhaps 100 million years—also a short time relative to the 4.5-billion-year age of the earth.

A foremost figure in addressing such matters is DTM's director, George Wetherill, whose wide-ranging scientific interests seem to typify the broad outlook of the Department. Wetherill, after four years in the Navy during World War II, attended undergraduate and graduate school at the University of Chicago, where he earned the Ph.D. in nuclear physics in 1953. For the next seven years at DTM, he worked in a cooperative program with the Geophysical Laboratory primarily on measuring the ages of rocks by isotopic measurements. Moving to UCLA in 1960, he became a leading figure in planning space missions and in research on lunar rocks; there he began investigations of solar system bodies and the origins of meteorites. Returning to DTM as director in 1975, he has since developed numerical techniques and computer simulations, exploring theories proposed by the Soviet scientist V. S. Safronov for the formation and heating of earth by the accumulation of planetesimals.

In explaining the formation of the earth, Wetherill strongly

Seismology, isotope geochemistry, planetology, and computer-oriented theoretic work all come together at DTM. Selwyn Sacks, David James, Alan Boss, and George Wetherill, 1984.

favors the accumulation mechanism, though he notes that direct formation from a single gravitational instability cannot be dismissed. But in either case, he points out, the internal temperature of the earth must have been very high during the period of formation—above the melting point of iron and close to that of silicates. (If formation was by accumulation, the energies of impacts produced the necessary heat.) The planet cannot have been formed cold. Thus, Wetherill continues, liquid iron must have migrated to the earth's center during earth formation, primarily because of density differences between liquid iron and molten (or partially molten) silicates. In effect, Wetherill holds, the largely iron core was formed with the earth itself.

Other planets probably have cores, almost certainly so if they formed at temperatures above the melting point of iron. Gravity measurements by spacecraft indicate that the outer planets Jupiter and Saturn have cores about 10–15 times greater in mass than the entire earth. The cores of these giant planets are most likely composed of carbon, nitrogen, and oxygen with a mixture of iron and silicon rocky matter. (Their outer regions are composed primarily of hydrogen and helium.) Mercury and probably Venus have iron cores at least half the size of the earth's. The Moon is believed to have a very small solid core, on the basis of evidence from possible faint moonquakes recorded by seismic instruments left by the Apollo crews.

Wetherill's studies of the earth's early history are closely related to the modeling of mantle structure at DTM and to research by the Department's isotope geochemists on material raised from the mantle in volcanic rocks. Wetherill, Boss, and Sacks, joined by the geochemists and those postdoctoral fellows currently in residence, often gather for wide-ranging discussions of one another's thinking. To an outsider, the discussions seem highly technical; to the scientists, the flow of ideas is often exhilarating.

WHERE ARE WE TODAY?

> Science—in the end unerring. . . .
> Science has fallen into many errors—errors which have been fortunate and useful rather than otherwise, for they have been the stepping-stones to truth.
>
> Jules Verne
> *A Journey to the Center of the Earth* (1864)

Ours is a time of ferment in studying the earth's deep interior. Scientists of varied discipline and outlook are continually advancing new ideas, new ways of interpreting the known evidence. Those ideas that withstand the tests of observation and experiment will remain alive, perhaps until fresh evidence causes them to be discarded and new ideas surely to be raised. This is the process of science—a self-correcting process, accurately glimpsed by the captain of Jules Verne's imaginary journey, quoted above.

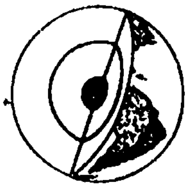
Diversity of approach is to be expected, indeed sought, as theory and experiment move toward accommodation. But with this diversity comes an important corollary—the necessity for regular and broad interactions among researchers of different specialty. In studying the deep earth, seismologists and high-pressure crystallographers must interact with theoreticians steeped in computer modeling, with planetologists, with astronomers. There is need, too, for interactions across institutional, indeed international, boundaries, of the kind exemplified by the recent return of Takehiko Yagi to the Geophysical Laboratory for a period of research on hydrogen as a possible core component.

Selwyn Sacks recently offered advice for deep-earth researchers of the future:

> Interpret data cautiously, and open up a lot of dialogue. There are so many fields of activity, you have to look broadly to judge, "Does what I'm doing make sense?" Because otherwise you may be going off in a direction that somebody else knows to be wrong. . . The more interactions, the better.

The story of the exploration of the core is far from over. Favored by advances in computer modeling and in techniques for experiments at very high pressure, today's scientists seem well-positioned to address questions about the deep earth. It would not be surprising if scientists of the next generation look back at 1984 mildly surprised that so little was known.

Research on the earth's deep interior remains a last, great frontier in the earth sciences—a frontier where many questions are yet unanswered but where the promise of new research tools is vast. Scientists of the Carnegie Institution studying the deep interior are only a part of a much larger family of such investigators worldwide. But in bringing talented and imaginative investigators of different specialty into a common environment favoring daily interaction, the Institution sets a unique example for the greater scientific community.



Additional Reading. Some other materials on the past exploration of the core and the present ferment in understanding it:

Don L. Anderson, A new look at the inner core of the earth, in *Nature*, Vol. 302, p. 660, April 1983.

Peter M. Bell, Core models, in *EOS: Transactions of the American Geophysical Union*, Vol. 64, p. 387, May 24, 1982.

Stephen G. Brush, Chemical history of the earth's core, in *EOS: Transactions of the American Geophysical Union*, Vol. 63, pp. 1185–1188, November 23, 1982.

Stephen G. Brush, Discovery of the earth's core, in *American Journal of Physics*, Vol. 49, pp. 705–724, September 1980.

Raymond Jeanloz, The earth's core, in *Scientific American*, Vol. 249, pp. 56–65, September 1983.

Raymond Jeanloz, Oxygen in the earth's metallic core?, in *Nature*, Vol. 299, pp. 108–109, September 1982.

Note to Teachers. Extra copies of this booklet can be obtained by calling or writing to the address given below. In addition, Carnegie Institution has produced a series of radio broadcasts featuring four-minute discussions with scientists whose research is described in this essay. The disks are available free to broadcasters for educational or public service uses. A teacher might encourage a campus radio station to obtain the broadcasts from:

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* * *

Sources of Data in Figure 1. FeS_2 shock-wave data from Simakov, G.V., M.N. Paulovskiy, N.G. Kalashnikov, and R.F. Trunin, Shock compressibility of twelve minerals, *Izv. Acad. Sci. USSR, Phys. Solid Earth*, *8*, 11–17, 1974. $Fe_{0.9}S$ shock-wave data from Ahrens, T.J., Equations of state of iron sulfide and constraints on the sulfur content of the earth, *J. Geophys. Res.*, *84*, 985–998, 1979. Fe shock-wave data from Al'tshuler, L.V., K.K. Krupnikov, B.N. Lednenev, V.I. Zhuchikhin, and M.I. Brazhnik, Dynamic compressibility and equation of state of iron at high pressures, *Zh. Eksp. Teor. Fiz.*, *34*, 1958. Seismic data for core from Hart, R.S., D.L. Anderson, and H. Kanamori, The effect of attenuation on gross earth models, *J. Geophys. Res.*, *82*. 1647–1654, 1977. FeS diamond-cell data from Mao, H.K., G. Zou, and P.M. Bell, High-pressure experiments on FeS with bearing on the composition of the earth's core, *Carnegie Inst. Wash. Year Book 80*, 267–272, 1981. Fe diamond-cell data from Mao, H.K., and P.M. Bell, Equation of state of MgO and epsilon-Fe under static pressure conditions, *J. Geophys. Res.*, *84*, 4533–4536, 1979, and from Mao, H.K., and P.M. Bell, Compressibility and x-ray diffraction of the epsilon phase of metallic iron and periclase (MgO) to 0.9 Mbar pressure, with bearing on the earth's mantle-core boundary, *Carnegie Inst. Wash. Year Book 75*, 509–513, 1975. All curves 23°C isotherm except Fe shock-wave data and earth's core.

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