The Whole-Earth Syndrome

As the inner earth comes into focus, geoscientists are beginning to see the ties that bind together the different sections of the planet

By RICHARD MONASTERSKY

There's no buttered popcorn, no music to accent the images on screen. Nonetheless, a dozen geophysicists and a few reporters stand captivated before the color television monitor, as 2 billion years of drama unfold before their eyes.

They are watching the newest earth-science video – starring the continental plates, moving at a film speed of about 700 million years a minute. In real life, the continents move too slowly to provide entertaining viewing material. If pitted in a race against a growing fingernail, the continents would just about tie.

But in the movie, it is possible to watch the plates through the eyes of an earth scientist, who is accustomed to letting the mind fly through billions of years in a blink. On screen, the continents drift about, floating raft-like on a partially melted portion of the earth's mantle. Driven by convection currents in the mantle, the individual pieces ram together to form supercontinents, then rip apart into smaller bodies that head toward opposite ends of the frame.

The video, which played last month at the American Geophysical Union meeting in Baltimore, is really a computer simulation called "Supercontinent Aggregation and Dispersal," created by Michael Gurnis and colleagues Bradford Hager and Arthur Raefsky of the California Institute of Technology in Pasadena. Gurnis developed the numerical model to study the interplay between the movement of the continents and the flow patterns of rock in the mantle.

Although still a crude approximation of the real thing, the model successfully mimics many of the events from the earth's history, he reports in the April 21 NATURE. And so far, the reviews on the model have been mostly thumbs up. "It's not the first simulation, but it's the closest approach yet to what are considered the conditions inside the earth," says Peter Olson, a geophysicist who works on numerical and physical simulations at Johns Hopkins University in Baltimore.

While Gurnis' work marks a technical achievement in computer modeling, it also exemplifies a new conceptual movement among those seeking to understand the inside of the planet. Geophysicists are beginning to examine the interrelations among the different sections of the planet: the core, the mantle and the much smaller crust. In the past, most scientists viewed these as isolated entities, but it is now clear that the separate regions are engaged in a multichannelled conversation. Across major boundaries and thousands of kilometers, these sections exert profound effects on one another.

"More people now are starting to appreciate that you have to treat the earth as a system; you can't just look at a part of it," says Don L. Anderson, a seismologist at Caltech. "Geomagnetic people [who study the earth's magnetic field] used to just look at the core and not worry about the mantle, but we know now that they are interconnected. Likewise, until recently, the interrelationship between the buoyant, continental lithosphere and the mantle had been ignored, except in a few older papers."

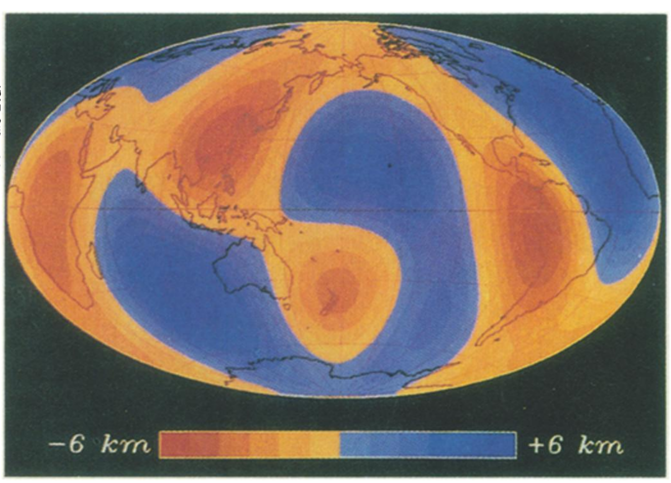
Since the introduction of plate tectonic theory 20 years ago, it has been a working assumption that convection within the mantle drives the motions of the plates. Until recently, however, few scientists had explored the opposite side of the situation: How do the continents affect the mantle?

Geoscientists view the almost immortal continental crust as a breed apart from oceanic material, which goes through a full life cycle in a few hundred million years. Born from molten mantle rock that rises to the surface at the midocean ridges, the oceanic crust travels in conveyor-belt fashion to subduction zones, where it plunges back into the mantle. Conversely, the continental cratons – stable regions in the center of continents – are thicker and more buoyant, which keeps them from remixing into the mantle. Although it is difficult to trace the origins of the cratons, scientists believe at least some parts formed within the first 1.5 billion years of the earth's 4.6-billion-year history.

Throughout their long stay on earth's surface, the continents have been a peripatetic lot. While now relatively spread out over the globe, all of the continental plates were joined together 200 million years ago into a singular land mass, called Pangaea. Some evidence also suggests that a similar supercontinent developed more than 400 million years ago.

On the basis of paleomagnetic evidence, scientists believe Pangaea was probably centered where Africa lies today. At that time, the giant continent was sitting over a hot area in the mantle, a region where partially molten rock rises upward from the depths. Since Pangaea's breakup, almost all of the individual continents have centered themselves over relatively cool spots in the upper mantle, which are believed to correspond to downflows of mantle rock.

Gurnis and many other scientists think this pattern suggests the continental cratons work as insulators that trap the heat of the mantle. His model is the first to examine what role these insulating con-



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Undulations on the core? From the seismic data, scientists conclude there are irregular spots at the boundary between the core and mantle, 2,900 kilometers below the earth's surface. One possible interpretation is that the core surface is composed of elevated (blue) and depressed (orange) areas.

tinents may play.

In his simulations, Gurnis found that individual continents tend to congregate into a large mass, situated over a cool spot in the mantle. With time the insulating power of the supercontinent drives up the temperature of the underlying mantle material and causes it to rise.

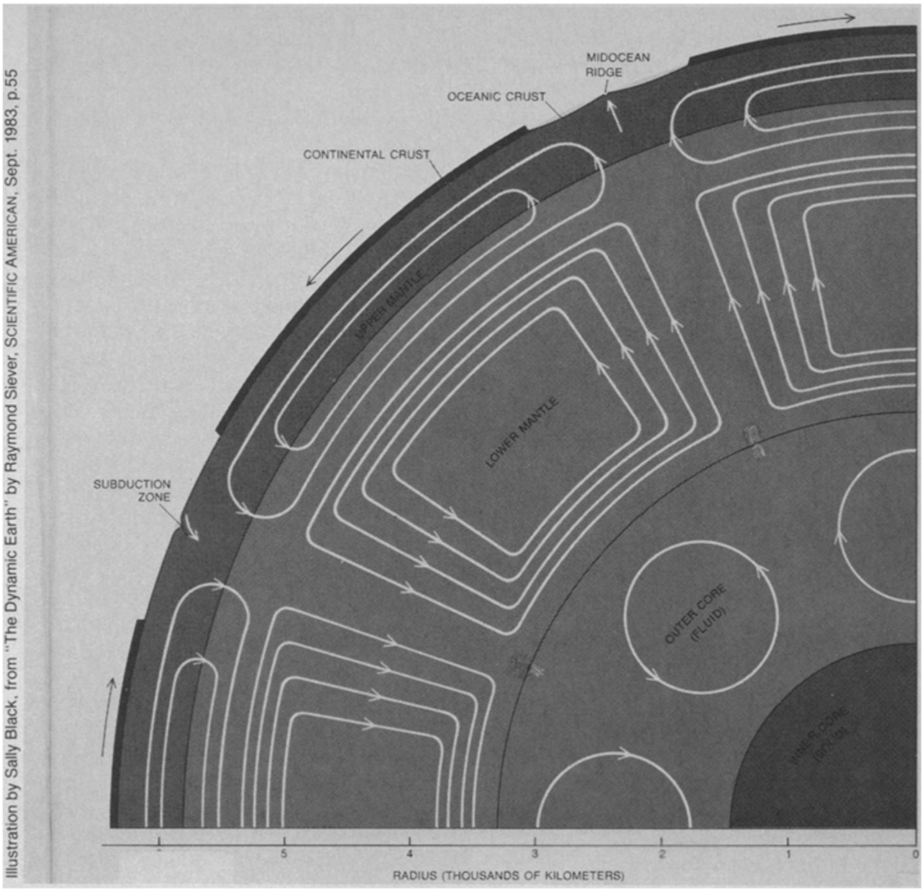
Beneath the interior of the continent, this rising material builds tremendous pressure. The climax occurs when the upwelling mantle finally breaks apart the supercontinent, sending individual pieces toward cooler regions on the surface.

After the breakup, single continents become trapped over separate, cool downflows. However, as the convection patterns shift, the land masses may join again into a supercontinent over a large downflow. And a new cycle begins.

"The interesting thing about the numerical models is that it's not so clear cut," says Gurnis. "We've seen some nice cycles on the order of 500 million years, but sometimes the continents never came back together."

In general, he says, the model demonstrates how the position of the continents can alter the pattern of mantle convection, an old idea that earth scientists are only now beginning to explore in earnest. "The most important part of this study is that now, for the first time with the methods of computational fluid mechanics, we can understand the two-way dynamic feedback between how continental plates move and their effect on the underlying convection and vice-versa."

Illustration by Sally Black, from "The Dynamic Earth" by Raymond Siever, SCIENTIFIC AMERICAN, Sept. 1983, p.55



Simplified diagram of the earth's interior shows some major features. Convective motion in the fluid outer core is believed to generate the earth's magnetic field. Convection of rock in the mantle governs the movement of the lithospheric plates, which float on a partially melted region of the upper mantle. Scientists now are studying how the slow convection of the mantle may help determine flow patterns in the outer core. Others are examining how the continental crust affects mantle convection.

Seismologists quickly credit their field for the current concern with understanding the relationships among the core, mantle and crust. Although this may sound self-congratulatory, colleagues in other realms of the earth sciences often join in lauding recent work within seismology.

The key to the development of these new ideas, say scientists, is seismic tomography — a technique that uses earthquake waves to map out structures deep within the planet. The process is akin to computerized axial tomography, or CAT scan, which uses X-rays to image the interior of the human body.

As a seismic wave from a strong earthquake spreads through the earth, its speed depends on the temperature and chemistry of the rock through which it travels. For example, waves pass more quickly through colder, denser rock than through warmer areas. By analyzing the travel times of these waves to approximately 1,000 stations positioned around the world, seismologists are producing tomographic maps of previously uncharted regions within the planet (SN: 7/5/86, p.10).

Scattered all through the earth's mantle are so-called heterogeneities — patches that either speed or slow the traveling seismic waves. The regions, according to interpretations, indicate that the mostly solid mantle behaves much like a boiling liquid, albeit on a time scale of tens of millions of years. Its slow but turbulent convection drives hot, buoyant mantle material toward the surface and sucks down cooler, denser rock.

The tomographic maps also have revealed what appear to be heterogeneities at the boundary between the liquid outer core and solid mantle. One interpretation is that these spots are wave-like features in the surface of the core. Alternatively, the heterogeneities may sit within the boundary layer itself as "anticontinents" — or thick, irregular regions in the layer. While the data are still ambiguous, it is clear that the discovery of these irregularities has led to an explosion of interest in the boundary itself.

As the core-mantle boundary comes into better focus, scientists find they must revise their thoughts about the regions on either side of the boundary. "That's something that we've begun to realize in the last two years — the extent to which the core is interacting with the mantle," says Harvard geophysicist Jeremy Bloxham. "We really can no longer treat the core and mantle as being systems in isolation of each other."

Such concepts are influencing thinking on one of the deepest problems in the earth sciences: the attempt to understand the planet's magnetic field. Although there is much that scientists do not understand about the behavior of the field, they believe it arises in the liquid outer core of the earth from moving molten rock that generates electrical currents.

Using magnetic observations spanning almost 300 years, Bloxham and colleague David Gubbins from Cambridge University created geomagnetic maps of the outer-core convection patterns responsible for the magnetic field (SN: 4/4/87, p.222). These can be matched against maps of the lower mantle based on seismic tomography. "It's through looking at these maps that you can see that there are similarities between where particular things are happening in the core and in the mantle," says Bloxham.

In general, hot material in the outer core seems to flow toward cold regions in the lower mantle, which convects much more slowly than the liquid core. If true, this means the mantle draws most of its heat from selected locations along the boundary, says Bloxham. In this fashion, the mantle is directly influencing the flow of the inner core and, in turn, the earth's magnetic field.

The proposed anticontinents along the boundary may be key to this relationship, he adds. "If you have continents at the core-mantle boundary, they will serve as blankets, suppressing the flow of heat from the core."

Hand in hand with the new inner-earth discoveries come some important theoretical questions that remain unanswered. Scientists wonder in particular whether the anticontinents would be thermal or chemical structures — a distinction with important implications. These areas might be cool patches of rock, or they might be composed of unique material that has accumulated at the boundary, in a manner analogous to what has happened at the earth's surface.

Thomas Jordan, a seismologist at the Massachusetts Institute of Technology, is one of many scientists who believe unique material must have accumulated at the interface between core and mantle, because there is a density difference between the two regions.

"If you have a density interface, material just gets stuck there. It can move around on the boundary, but it doesn't really get remixed," he says.

If this chemical boundary layer does exist between core and mantle, some scientists suggest it formed early in earth's history, when a (theoretically) homogeneous planet began to separate itself into distinct regions. Alternatively, some say chemical reactions between the mantle and core continue even today. In this case, they would be constantly adding to an ever-growing boundary layer.

Another outstanding question is whether material from the core-mantle boundary reaches the earth's surface. Many scientists think extremely hot areas along this boundary spawn plumes of material that rise to the surface, thereby forming the so-called hotspots of the earth's crust. Over tens of million of years, hotspots eat holes into the traveling plates, creating linear tracks of volcanoes and seamounts such as the Hawaiian Island chain (SN: 10/17/87, p.250).

If hot regions along the core-mantle boundary are the source of the material erupted at hotspots, this would indicate an interaction between the core and the earth's surface — a long-distance communication crossing thousands of miles of mantle, says Olson, who has created models to study mantle plumes.

Traditionally, the inner earth has attracted the scrutiny of only a small minority of earth scientists, largely because near-surface processes are so much more accessible. But as researchers begin to tie together the core, mantle and crust, more scientists are turning their gaze toward the distant interior.

Particularly intriguing is new research suggesting earth's surface may actually reveal signs of motion in the core. This work falls under the aegis of geodesy — the field that precisely measures the habits, shapes and size of the planet.

At the geophysical meeting last month, geodesist Marshall Eubanks of the U.S. Naval Observatory in Washington, D.C., reported that fluid moving in the outer core should produce swells and other features that would be visible at the surface through such measuring techniques as Very Long Baseline Interferometry (VLBI), which uses radio signals from quasars to determine distances. On the basis of sketchy calculations, he proposes that large patches of the earth's surface may rise or fall by a full centimeter over several decades, which is technically within the resolving power of VLBI. These deformations, perhaps several thousands of kilometers in area, should be noticeable on land and in the oceans, says Eubanks, who is working on the project with Coerte Voorhies of the NASA Goddard Space Flight Center in Greenbelt, Md.

A second potential method of tracing core motion involves the earth's rotation axis. Since changes in the core would affect the inertia of the planet, scientists should also be able to discern these core processes through shifts in the rotation axis, says Eubanks. Working independently of Eubanks, James B. Merriam of the University of Saskatchewan in Saskatoon also proposed recently that motion in the rotation axis may lead to insight about the core.

At present, scientists interested in this part of the earth have only limited access to their quarry, mostly through seismic and geomagnetic studies. "It's so hard to get information about the core that any way you can get information, you're likely to provide some real science," says Eubanks. "Even if you could just get a crude idea, the knowledge of the core is so crude that you could make a very great gain for science."

Scientists have only recently focused on the earth as a whole rather than as a patchwork of autonomous, unrelated sections. But as the idea of an interconnected earth develops, researchers say it is drawing together the disparate parts of the geosciences. "It's generating if not interdisciplinary research, at least an interdisciplinary attitude because of the complexity of these interactions," says Olson. "The fact that there are physical problems and chemical ones, the fact that the data are seismological while the inferences are geodynamical, [means] no one person can handle the whole thing." □

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Archimedes' Revenge: The Joys and Perils of Mathematics — Paul Hoffman. In readable essays the author sketches for the nonmathematician the range and scope of mathematics. Gives a glimpse of some of the things that mathematicians, pure and applied, actually do. Attempts to convey a sense of the limits of mathematical knowledge. Sometimes, says the introduction, knowledge is limited because a field is young; in other cases it is because the mathematical problems are extraordinarily difficult. Norton, 1988, 285 p., illus., $17.95.

The Dark Matter: Contemporary Science's Quest for the Mass Hidden in Our Universe — Wallace Tucker and Karen Tucker. Not all the mass of the universe can be accounted for by the luminous matter observed in the galaxies. This book describes for the general reader scientists' search for the solution to the mystery of missing mass or dark matter. Discusses the possible sources of dark matter that scientists are investigating. Morrow, 1988, 254 p., illus., $16.95.

In Praise of Imperfection: My Life and Work — Rita Levi-Montalcini, translated by Luigi Attardi. An autobiography of this fascinating woman who won the Nobel Prize in Medicine in 1986. In scientific research she feels the factors essential for attaining personal success and fulfillment are total dedication and a tendency to underestimate difficulties, which causes one to tackle problems that other, more critical and astute persons opt to avoid. A volume in the Sloan Foundation Science Series. Basic, 1988, 220 p., illus., $18.95.

Interactions: A Journey Through the Mind of a Particle Physicist and the Matter of This World — Sheldon Glashow with Ben Bova. According to this 1979 Nobel Prize winner, "My greatest discovery was that science can be more than a mere hobby. . . . People would actually pay me to do what I most wanted to do: to satisfy my own curiosity." This book, he goes on to say, is about "the search for the ultimate portrait of the universe, as seen through the eyes of one of the searchers." Traces for the general reader the history of modern physics from the discoveries of Einstein and Bohr in the early 20th century to the most recent advances in particle physics. In special sections set apart from the text are detailed discussions of the more complex concepts of physics for those who wish to probe deeper into the mysteries of subatomic physics. Warner Bks, 1988, 345 p., illus., $19.95.

The Science of Structures and Materials — J.E. Gordon. A beautifully illustrated, readable, interdisciplinary examination of the strength of structures and materials by this leading materials scientist. Shows how the same mechanical principles that underlie the strength of natural structures like tendons and muscles apply to human-made structures like skyscrapers, bridges, ships and aircraft. Provides an introduction to biomechanics, the study of mechanical behavior of living things, and points out how this new science benefits areas ranging from heavy construction to orthopedic surgery. Sci Am Bks (W H Freeman), 1988, 217 p., color/b&w illus., $32.95.