Geodynamics Report: Exploiting the Earth Sciences Revolution

The concept of an active earth that is being continually and drastically rearranged by unknown forces has only recently gained wide acceptance among earth scientists. Even a decade ago few believed that whole oceans could disappear or that continents could migrate so far that the earth's climate and the course of biological evolution would be affected. Now there is evidence for all of these phenomena and a tentative hypothesis—the plate tectonic model—that explains the present positions of most of the world's major mountain ranges, volcanoes, earthquake zones, and subsurface ocean ridges. To test the plate tectonic model, to refine it, to exploit it for practical purposes, and to discover the forces within the mantle that drive the plate motion are the purposes of a new international research effort, the Geodynamics Project. A recent report summarizes current understanding of geodynamic phenomena, singles out a number of outstanding problems, and outlines a program for U.S. participation in the project.* So central is the plate model to the revolution under way in the earth sciences that the report is by implication a forecast of future directions in research.

Anytime a new paradigm appears in science, it is likely to bring together many studies that had not been thought to be related and many researchers who previously had no professional activities in common. The geodynamics report, published by the National Academy of Sciences, was the product of more than 200 scientists ranging from geologists and geochemists to seismologists and paleontologists. Under the leadership of Charles Drake of Dartmouth College, Hanover, New Hampshire, the U.S. committee prepared a document oriented around the ideas of plate tectonics, rather than strictly subdivided according to research disciplines. One measure of its effectiveness was the exchange of ideas that took place during its preparation. As one member of the report committee noted, "When you convince a vertebrate paleontologist to subscribe to the *Journal of Geophysical Research*, you know you've had some effect."

Another measure, more of the sweeping nature of transformation now taking place in the earth sciences than of the report's effectiveness, is the consensus that emerged among those involved in its making. Even those few geologists and geophysicists who question plate tectonics are agreed on the need to adequately test the model. By contrast, when well-established schools of scientists gather to forge a report on their future needs, the result is often a bloody battle between competing research enclaves, with little chance for improved communication or cooperation.

The geodynamics report is thus a refreshing change from the pattern, being neither the result of an intramural rugger match nor primarily a plea for more funds. Instead, it is a straightforward discussion of the most sweeping scientific theory of the decade and a concise summary of the many facets of crustal motion that are still unresolved. The emphasis is put on the intellectual challenges and the opportunities for a better understanding of the earth. A careful reading of the report reveals that it also calls for an additional $12 million per year for research and instrumentation by the 12 funding agencies that support geodynamics research. Current U.S. expenditures for geodynamics research are estimated to be $48 million per year (excluding the costs of operating ships). For a science that has obvious practical potential, that seems to be in a perfect position to capitalize on a conceptual revolution, and that has a history of producing excellent research with small budgets, the request for an additional $12 million per year seems unusually modest.

At the basis of the plate tectonic model is the concept of plates—huge pieces of the earth's outer shell that move around, split apart, and collide. The boundaries of the plates are defined by the earthquake belts of the world (Fig. 1). When two plates move apart, material from the hotter region beneath the plates (the mantle) wells up to the surface, cools, and forms new plate material at features known as ridges, which are found in many ocean basins elevated as much as 3 km above the ocean floor. As the rock cools, it becomes magnetized in the prevailing direction of the earth's magnetic field. Past reversals of the magnetic poles of the earth have established a chronology by which the magnetic records in the sea floor can be dated, and from the dates the motions of the plates are determined. The two most prominent ridges are oriented roughly north-south in the mid-Atlantic and eastern Pacific oceans.

A second type of boundary occurs when two plates slide past each other (a strike-slip boundary). One example of this is California's San Andreas fault, where the edge of the Pacific plate is moving northwesterly at the rate of a few centimeters per year and

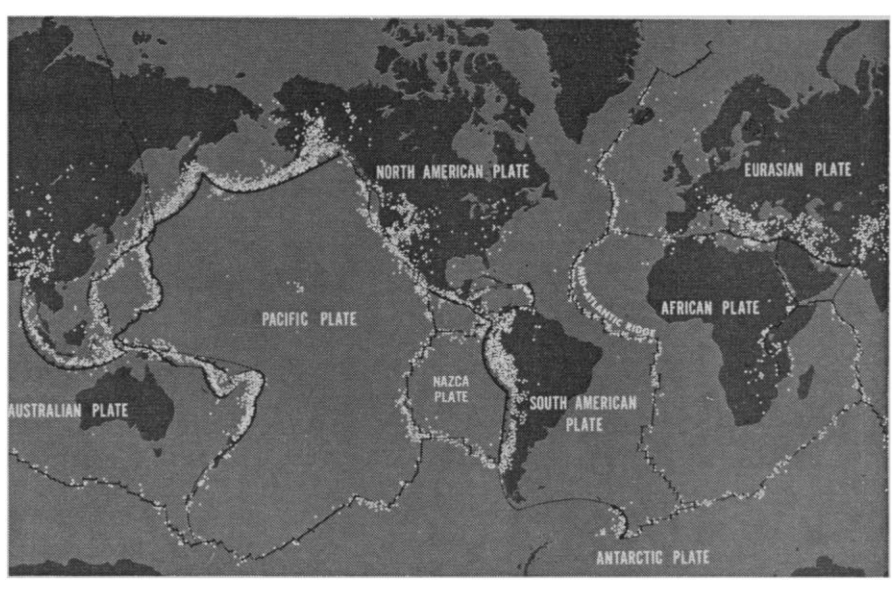

Fig. 1. Earthquake epicenters (dots) indicate plate boundaries and coincide with major geological and geophysical features (lines).

* U.S. Program for the Geodynamics Project, available for $3.25 from the Printing and Publishing Office of the National Academy of Sciences, Washington, D.C. 20418.

carrying with it past the mainland a narrow strip of the California coast. The third and most complicated type of boundary occurs when two plates converge and one plate overrides the other and pushes it deep into the mantle where it is heated and assimilated. Because continental rocks are generally lighter than the rock of the sea floor, the plate with continental rock tends to be the overriding plate, and the one with ocean floor tends to be thrust downward. A deep ocean trench is usually formed where a plate descends.

Since the revolution in the earth sciences is now accepted by most U.S. investigators, the authors of the report took considerable care to differentiate those aspects of plate tectonics that seem established from those still not understood. (Interestingly, Russian geodynamicists, who generally have devoted more time to continental than ocean studies, are about evenly divided between those who accept plate tectonics and those who reject it.)

The best known aspects of plate tectonics are the shapes, locations, and relative movements of the major plates at the present time. (By geological reckoning, the "present time" is approximately the last 10 million years.) But many phenomena in the interior regions of plates are difficult to explain by plate tectonics, and the processes that occur at plate boundaries are seldom understood in detail. The configurations and motions of plates at times further in the past are much more difficult to determine, and perhaps the greatest puzzle for any epoch is why plates move at all. Many scientists think that the most important questions remaining to be answered are, When did the plates begin to move? and What are the driving forces that keep them going?

Of all the types of plate boundaries, the ridges where new crust is formed (diverging boundaries) are probably the best understood, according to the report, although variations along the world's ridge zones are still puzzling. Converging plate boundaries seem to be much more complex. The primary process that occurs, underthrusting, takes place at such a great depth that it is extremely difficult to measure. Furthermore, the intense deformation of crust produced by two plates colliding results in very complex geological features, such as island arcs and mountain belts. When the collision occurs between two continents or bits of continental crust, the interaction seems to be still more complicated. The Himalayas, for example, are thought to have been formed when the Indian subcontinent collided with the Eurasian plate, probably after breaking away from Australia 100 million years ago, and the geology of the Himalayas and ad-

Speaking of Science

Frontiers of Research in Atmospheric and Marine Science

The dedication of new academic buildings is traditionally an occasion for taking stock of past accomplishments and future prospects. Ceremonies held last November at Texas A & M University in celebration of a towering new oceanography-meteorology building included such a look at research areas of growing importance to atmospheric and marine scientists. The subjects ranged from paleo-oceanography to long-range weather forecasting and—not to ignore topical themes—even to the potential role of the oceans in solving the energy crisis.

Jerome Namias of Scripps Institution of Oceanography (and a former head of the Weather Service's long-range forecast group) spoke on the problems of predicting weather patterns months, and even years, in advance. Anomalous weather such as the cold winters of the eastern United States in the 1960's or the record number of tornadoes in the Midwest in 1973 is blamed on many things, from solar activity to lunar influence (neither explanation had, at last report, gained many adherents in the meteorological community).

Namias pointed toward another extra-atmospheric influence—the oceans, whose high heat capacity makes them excellent sources and sinks of energy for the atmosphere. He reviewed evidence that thermal anomalies (hot and cold spots) in the upper layers of the oceans can persist for several seasons and suggested not only that wind patterns may help generate such anomalies, but that storm systems may intensify by drawing energy from the sea. The mechanism of the interaction is still unknown, but since the ocean changes less rapidly than does the atmosphere, it may be possible, Namias speculates, to monitor the oceans and hence to predict shifts in atmospheric patterns. In any case, the investigation of how the ocean and the atmosphere are coupled, Namias concluded, is an increasingly important research frontier.

Air-sea interaction on a smaller scale—the exchange of heat, momentum, oxygen, and carbon dioxide across the surface layer of the ocean—was also singled out as an important area. Owen Phillips of Johns Hopkins University spoke on breaking waves in the open ocean, which he characterized as one of the most widespread but least understood processes occurring at the sea surface. He pointed out that interaction among short waves, long waves, and wind-induced drift can markedly increase the chances that a wave will break and hence disrupt the surface layer that can otherwise be a barrier to air-sea exchange.

Jule Charney of the Massachusetts Institute of Technology spoke on predicting turbulent flows in the atmosphere. Turbulence is poorly understood—there is no acceptable theory of turbulence—and its irregular, aperiodic character makes it difficult to model. The question of whether turbulent flows such as those in the atmosphere are predictable even in principle is thus a key one for atmospheric scientists (Charney called it as fundamental a question as there is in all of science). Both numerical and theoretical calculations done to date indicate that atmospheric motions become essentially random (that is, unpredictable) when forecast more than a week. It happens, however, that large-scale fluctuations in the atmosphere are more energetic than small ones, and energy seems to propagate from large to smaller scales of motion while uncertainty propagates from small to larger scales. The distribution of energy among the differing scales of motion therefore deterjacent regions from Tadzhikistan to Mongolia is exceedingly complex. But the Himalayas are one of the more recently formed mountain belts in the world, and it is clear, say many geophysicists, that to unravel the tectonic details of an older mountain belt like the Appalachians would be even more difficult. Even when small bits of continental crust collide, such as along the Alpine fault in New Zealand, the processes at the boundary became much more complicated than when oceanic crust is involved. As one researcher noted, "It's clear that things get much more complicated when you get to continents, and it's also clear that it's not just because you can see them better."

If plates are moving, it seems easy —at least in principle—to explain active geological features at plate boundaries, but active features within plates appear to be inconsistent with the simple plate tectonic theory now in use. Vertical motions are sometimes almost as rapid as horizontal motions. The Rocky Mountains and the Appalachian Mountains are rising a few millimeters per year, and the very mountainous region of Tadzhikistan is moving upward at 1 to 2 centimeters per year. To a geologist, that is a huge velocity, described by one as "shooting up," and no one knows whether plate tectonics or some other process will be required to explain it. Other mid-plate phenomena that may not be consistent with plate tectonics are mid-ocean volcanism, such as in the Hawaiian islands, and the occurrence of large underwater ocean ridges that do not seem to be plate boundaries because they are free of earthquake activity. On land, the largest earthquakes in North America in modern times occurred in the Mississippi Valley in 1811, far from the boundaries of the Americas plate. So there are many phenomena that occur in the interior regions of plates that do not easily fit into the plate tectonic model.

According to the report, it is essential to find out when plate tectonics started. Our present knowledge can only be extrapolated back about 200 million years to the end of the Paleozoic era, when the continents as we now know them were probably joined together in one large land mass, called Gondwanaland. All ocean floors that now exist were apparently formed out of the ridges that opened up when Gondwanaland split apart, so the ocean floors are too young to have any record of tectonics in the Paleozoic era. If old convergence boundaries could be found on land, they could prove tectonics to be older than 200 million years, but there are no agreed upon criteria for finding such boundaries.

No one knows how to answer the basic question of plate tectonics, but

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mines the predictability, according to Charney, and he proposed new methods of estimating energy transfer from one scale of motion to another. He believes that it will be possible to forecast some features of the atmosphere at times longer than a week.

Archie Kahan of the Bureau of Reclamation in Denver spoke on weather modification. He characterized it as a frontier involving more than just science—there is now a wide spectrum of opinion and intense public involvement in the question of whether or not to seed clouds. Selecting particular clouds to seed is increasingly done on the basis of numerical models, but the key problem, according to Kahan, is still in evaluating the results and in determining whether precipitation really was increased. Even experiments that are statistically designed and randomized have not settled all questions.

In oceanography, a growing area of research is the study of upwelling ecosystems—the interaction of winds and currents that bring bottom water and nutrients to the surface, thereby supporting vigorous biological communities. John J. Walsh of the University of Washington described numerical models of upwelling systems that are being used to sort out the relative roles of phytoplankton, zooplankton, and fish in the food chain, as well as the extent to which light, nutrients, and the time of year control the ecosystem. Better models of these systems, according to Walsh, may provide more accurate estimates of the anchovy production off the coast of Peru and an explanation of why a similar upwelling system off the coast of northwest Africa has not evolved a similar, harvestable species.

Karl Turekian of Yale spoke on the geochemistry of estuarine and deep-sea environments. He pointed out that uranium and thorium isotopes and the products of their radioactive decay can be used to study the effects of dumping hostile materials in the ocean. Sediments in Long Island Sound, for example, show a rise in the concentration of metals following the beginning of human habitation of the area. Uranium and a few other metals that form anionic complexes appear to find their way out of the sediments, but most do not, Turekian finds. He believes these estuarine results can be applied to deep-sea sediments, which are more difficult to study in detail, while other geochemical processes, such as those that regulate calcium carbonate, are more readily studied far from sources of continental debris.

Another growing field is that of paleo-oceanography, the study of the oceans, and, implicitly, of the climate in earlier times. James Hays of the Lamont-Doherty Geological Observatory described how analysis of sediment in the Antarctic has provided a picture of conditions 18,000 years ago. At that time, according to Hays, the cold polar water extended much farther north in the summers, as, probably, did the sea ice—in effect, the Antarctic endured winter conditions all year long. Similar events occurred in the North Atlantic—the sea extended as far south as the glacial ice that at the time covered much of the northern continents. These conditions of extreme cold have occurred about eight times in the past 700,000 years, according to Hays, in regular alternation with the periods of warmth (like the present climate). The study of the process seems important, if only, Hays indicated, because it seems very likely that a new glacial period will eventually recur—perhaps within a few thousand years.

Finally, Jacques Cousteau addressed the energy crisis and its relationship with the sea. He pointed out that nature concentrates energy in winds, currents, and tides, and he proposed that serious consideration be given to power plants operating on the tides, on the mechanical energy of ocean currents, and on the thermal gradient between surface and deep waters. In all, a selection of subjects indicative of the growing vigor of atmospheric and marine science.—ALLEN L. HAMMOND

Recommendations for Geodynamics

The U.S. Geodynamics Committee has singled out six areas in which new developments in instrumentation or new approaches to geodynamics problems can provide knowledge needed for understanding geodynamics and adjacent disciplines.

Recent developments in reflection seismology suggest the feasibility of a broad program of studies of deep reflections, such as observed from the Moho. If used systematically on land, this technique promises enormous advances in knowledge of the deep crust and the upper mantle.

Detailed study of the Mid-Atlantic Ridge, particularly by a cooperative program with France, is recommended.

The development of high-pressure technology via a number of steps is recommended. First, apparatus for rheology studies at pressures from 25 to 400 kilobars should be developed, then apparatus for ultrasonic, phase equilibrium, and other experiments later.

Special attention should be paid to the use of a new technique, the ion probe, for chemical analysis of magmas, which are among the few examples of material derived directly from the mantle.

Theoretical studies of the dynamics of the earth need further support, and "an intensive effort" should be made to draw mathematicians and geophysicists into the construction of realistic models. Additional large computing facilities may be necessary.

The Deep Sea Drilling Project should be given further support, and should be supplemented by drilling on land.

the geodynamics committee infers that a heat engine of some sort provides the power to drive the plates and suggests that fundamental research may help to find an answer. The section of the report on driving forces barely mentions convection by name, but nevertheless describes all the thermal properties of the mantle that should be studied to understand how convection may operate. Heat from radioactive decay in the earth's interior as well as heat from phase changes of the material in the mantle could produce thermal instabilities that would influence driving forces. Surface temperatures do not indicate the temperatures in the mantle faithfully because most heat comes up through the ocean ridges, but seismic measurements of shear waves could indirectly indicate temperatures in the mantle, the committee notes. Tests of the earth's minerals at the very high pressures (60 kilobars) characteristic of the mantle are needed to learn shear velocities and also many thermal properties, such as the heat released in phase changes and creep—the relative fluidity of the mantle. High-pressure facilities with a large enough volume to test these properties are not available. Other studies may ascertain what constraints can be placed on mantle motions by geological evidence—such as the distribution of trace elements, the patterns of volcanic activity, and distribution of mantle-type rocks on the earth's surface.

More explicit suggestions for driving forces have been made, such as convection cells, mantle plumes, and the force of gravity pulling the heavier plate down into a trench. Most of the studies of these ideas are theoretical, and many aspects are not known. Do convection cells cause the upwelling of ocean ridges? How big are convection cells and how many might lie under a large plate? Can convection cells drive a plate only if they act coherently? Are instances of mid-plate volcanism like the Hawaiian islands caused by mantle plumes? Clearly there are fascinating questions, and many of them can be examined by estimating properties of the mantle and testing numerical models of specific mechanisms.

In addition to spelling out the most important questions for geodynamics as a whole, the report lays out a detailed program of regional investigations centered on the Americas plate. As with the larger problem, the questions to be emphasized are boundary processes, past and present plate motions, and phenomena in the earth's interior. Hence, geological investigations are to be primarily aimed at resolving particular problems that bear on the question of plate movement while the geophysicists are to concentrate more directly on the driving mechanisms. Despite the focus on a common target, the research effort is neither to be highly organized nor centrally directed. "This is still," as one committee member put it, "a basic research effort."

The Americas plate is large enough to contain examples of nearly every type of tectonic process. The San Andreas fault system in California (that forms part of the western edge of the plate) is one of the few active plate boundaries exposed on land rather than concealed beneath the sea. The report proposes geological studies to ascertain the early history of the fault and to resolve two disparate estimates of how rapid the horizontal motion along the fault is (these estimates are important for determining the risk of earthquakes in the region). Geophysical studies of the mechanisms by which strain is built up and released along the fault and more accurate measurements of deformation in the region are also recommended. The Colorado Plateau–Rocky Mountain area contains the record of a somewhat different phenomena—large vertical motions and other events possibly caused by the Americas plate encountering and overriding a now extinct ridge.

Three other plates adjacent to the Americas plate will also be studied. The Nazca plate in the Pacific is a rapidly moving crustal segment that is small enough to be studied in considerable detail. The Caribbean plate is an anomaly that seems to include crust formed by other means than the mid-ocean ridge mechanism. (It is also an important area because its history is closely linked to that of the surrounding plates.) The Antarctic plate, because it is surrounded by oceanic ridges, seems to be a unique tectonic entity.

Even though the majority of researchers agreed with the report's emphasis on plate tectonics, some were unhappy with the outcome. The committee tried to include something for everyone, and many good specific ideas were apparently lost. "The report tries to please everyone, no matter how conservative, and doesn't have a focus," says one of the 200 participants. "It's really a catalog of all the things you would like to know in an ideal world. But you don't make progress by tediously considering all the options." Another scientist, who is a structural geologist, was invited to help write an early draft of the report but saw no resemblance

(Continued on page 769)

RECENT DEATHS

Emory S. Bogardus, 91; dean emeritus, Graduate School, University of Southern California; 21 August.

Leonard Carmichael, 74; vice president, National Geographic Society, and former head, Smithsonian Institution; 16 September.

Nelson S. Fisk, 59; associate professor of civil engineering, School of Engineering and Applied Science, Columbia University; 2 October.

George Gold, 61; attending professor of psychiatry, College of Physicians and Surgeons, Columbia University; 29 September.

George D. Humphrey, 76; former president, University of Wyoming and Mississippi State College; 10 September.

Elmer E. Jukkola, 68; retired advanced systems materials engineer, Wright-Patterson Air Force Base; 15 June.

Frank D. Kern, 90; first dean, Graduate School, Pennsylvania State University; 28 September.

Laura A. Kolk, 82; former associate professor of biology, Brooklyn College; 11 August.

Beatrice G. Konheim, 64; dean, Institute of Health Sciences, Hunter College; 1 October.

Thomas B. Ledbetter, 53; professor of mechanical and aerospace engineering, North Carolina State University; 25 August.

Frank T. McClure, 57; deputy director, Applied Physics Laboratory, Johns Hopkins University; 18 October.

Robert E. Ohm, 55; dean, College of Education, University of Oklahoma; 14 October.

Frank E. Rice, 86; former professor of agricultural chemistry, Cornell University; 19 August.

Gordon L. Roene, Jr., 43; associate professor of physiology and health science, Ball State University; 7 September.

Karl Sax, 81; professor emeritus of botany, Harvard University; 8 October.

Madan M. Singh, 49; professor of medicine, State University of New York, Buffalo; 24 August.

***Erratum*: In the issue of 25 January, p. 291, *Science* reported that Representative Charles A. Mosher (R-Ohio), vice chairman of the Technology Assessment Board, would become chairman of the board in January 1975. However, by law, any House member of the board may become the chairman. It is likely that a member of the majority party, in this case a Democrat, will be chosen. Edward Wenk, Jr., is chairman of the Committee on Public Engineering Policy of the National Academy of Engineering.**

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between his program and the final form of the report. "I was just one of the infantry for the tanks to run over," he said. Geologists seem to have been particularly alienated during the preparation of the report, which took more than 2 years.

But the report of the U.S. Geodynamics Committee serves a useful function in drawing up a coordinated program for scientists from the many disciplines now involved in the earth sciences. There was no previous tradition of comprehensive earth science reports. The only obvious predecessor is the report of the Upper Mantle Project in 1962, which is just 36 pages long and much more limited in scope. In the view of some scientists, the report also comes at a time when better monitoring of the various funds spent for earth science research is badly needed. The committee made a hesitant attempt at monitoring by denoting the areas to which various federal agencies contributed research monies, although it did not publish the figures.

The report could also have the effect of making the importance of geodynamics much more visible to Congress and the public. The idea that North and South America split away from Africa and Europe has fascinated people for years. Unfortunately, the report is probably too technical for a nonscientific audience.

Much research in the earth sciences is also relevant to another important public concern—the availability of fossil fuels and minerals. Although the report underplays economic aspects, plate tectonics is clearly related to the formation of oil and mineral deposits. Long-term vertical movements have resulted in sediment-filled basins which are important sources of hydrocarbons, and the locations of minerals may be influenced by tectonic spreading centers. Geodynamic research may thus have a substantial economic impact. Geophysical exploration cruises are already followed quite closely by those hoping to find oil.

A comment by John Sclater, of the Massachusetts Institute of Technology, seems to sum up the view of many others. "We've got a nice model which works damn well for 70 percent of the world, but that's all ocean. How's it going to work for the continents?"

—WILLIAM D. METZ AND ALLEN L. HAMMOND