3 July 1981, Volume 213, Number 4503 SCIENCE

Geodynamics—Where Are We and What Lies Ahead?

Charles L. Drake and John C. Maxwell

John Walter Gregory, in the preface to his great work on the rift valleys of East Africa, noted that "pioneer geology has to choose between the rashness of using imperfect evidence or the sterility of uncorrelated, unexplained facts" (*1*). Geologists have rarely been attracted to sterility but rather have tended to push their data to the limits or even beyond in speculating about the nature, the origin, and the development of the earth and its visible surface features. In early epochs of geological speculation the data base was very thin, the degrees of speculative freedom were many, and the intellectual battles were savage.

Summary. The introduction and evolution of the plate tectonics hypothesis during the past two decades has sparked the current renaissance of research in the earth sciences. An outgrowth of active geophysical and geological exploration of the oceans, the plate tectonics model has come under intense scrutiny by geologists, geochemists, and geophysicists who have attempted to apply the model to the origin and growth of continents, the generation of oceanic and continental crust, and the nature of the lithosphere, asthenosphere, and underlying mantle with respect to their evolution through time and to the driving mechanism or mechanisms for plate tectonics. The study of other terrestrial planets and moons has been helpful in understanding the earth model. The unequal distribution of geological features, both in the continents and oceans, emphasizes the need for ongoing studies of international scope such as the recently completed International Geodynamics Project and its successor, the International Lithosphere Program, both stressing studies related to the dynamics of the lithosphere.

Early attempts to synthesize the geology and history of the earth were severely handicapped by an almost complete absence of information about the nature of the sea floor. At the turn of the century, Suess (*2*) and Haug (*3*) in their masterful syntheses implied that the oceans represented sunken continents, differing from the continents principally in elevation. Alfred Wegener, best known for his theory of drifting continents, had doubts about this since even the very crude marine gravity measurements of his day did not support the premise (*4*). Rather, the measurements suggested that the ocean crust was qualitatively different from the continental crust. This question persisted for another 40 years (*5*) until it was demonstrated conclusively by geophysical observations at sea that the ocean crust was indeed very different from the crust of the continents. It took another 20 years to explain why it was different.

The nature of the earth's interior was similarly a mystery until the first half of the 20th century. A separate crust and mantle were identified by Mohorovicic (*6*) in 1909, and the seismic velocity discontinuity between the two that bears his name was assumed to be worldwide and of fundamental significance (*7*). The fluid core was found through the seismological studies of Wiechert (*8*), Oldham (*9*), and Gutenberg (*10*), and the solid inner core by Lehmann in 1936 (*11*). Deep-focus earthquakes were first noted by Turner in 1922 (*12*), and Wadati showed in 1935 that in the area of Japan they fell on a plane dipping from the Nippon Trench to beneath the Asian continent in China (*13*). The idea of an outer, rigid lithosphere overlying a more plastic asthenosphere was suggested on the basis of geodetic observations (*14*). Gutenberg concluded from amplitude studies of body waves from earthquakes that there was a low-velocity, and by implication, low-rigidity layer beneath the lithosphere (*15*), but the data were not completely unambiguous and acceptance of this concept hinged upon later analysis of the dispersion of earthquake surface waves.

The development of geochemical and high-pressure techniques to define the properties and discover the processes characteristic of the earth's interior is similarly recent, most of these developments postdating World War II. The technique of radioactive dating of rocks goes back to the turn of the century, but many of the methods used today are of much more recent origin. These techniques gave rise to a new and not well-recognized discipline, paleogeophysics. Geophysics deals with the here and now, the present characteristics of the rocks and the currently active processes. Geochemistry provides evidence of past processes and permits speculation about earlier properties and thus provides an important link between geology and geophysics if members of these various research communities are able to communicate with each other. Communication is not always easy, since each community has its own native tongue and each investigator seeks approval from his own community of specialists.

Dr. Drake is professor of earth sciences at Dartmouth College, Hanover, New Hampshire 03755. Dr. Maxwell is professor of geological sciences at the University of Texas, Austin 78712.

 0036-8075/81/0703-0015$01.75/0

International Programs in Earth Sciences

Progress in the earth sciences depends not only on the individual discovery but also on the integration of information from different disciplines and disparate areas into a compatible common model. One of the principal functions of major national or international programs is to draw together the different communities probing the mysteries of the earth and to encourage communication among them.

The International Geophysical Year (IGY) of 1957–58 was a model for such programs. It followed International Polar Years of 1882–83 and 1932–33 but differed from them in that it incorporated strong research programs dealing with the oceans and the solid earth. The first worldwide seismograph network with matched instruments was established during the IGY, and oceanographic vessels ranged the seas to many places that had never before been examined scientifically. Equally important for the earth sciences, mechanisms for international and interdisciplinary scientific communication and data exchange were developed during the IGY that have persisted to this day.

The success of the IGY in promoting international cooperation in the geosciences prompted the initiation of a program in the 1960's sponsored by the International Union of Geodesy and Geophysics (IUGG). This program, the Upper Mantle Project (UMP), focused on the outer 1000 kilometers of the earth, the part in which identifiable tectonic activity takes place.

During the UMP the plate tectonics model was introduced, a model that incorporated the movements of the continents in the time and space frame predicted by Wegener half a century earlier. This model came as a revelation to many but was not accepted with grace by others. It was philosophically difficult for some to accept the idea that the observed deformation on the continents was of almost trivial scale as compared with the creation of whole oceans, that the earth was a much more intensely active body than had previously been recognized, and that perhaps Wegener was right after all. Some objected that Wegener's model lacked an adequate driving mechanism to explain the mind-boggling movements of the continents. It is paradoxical that acceptance of the model was based not on discovery of a driving mechanism, the details of which still elude us, but on evidence for the formation of new crust at oceanic ridges and on better and stronger evidence that large-scale horizontal motions had indeed taken place. The model revolutionized geological thinking and greatly enhanced communication in the geosciences, because data of almost any description from almost any location could be fitted into or used to test it. It was a heady experience for geoscientists to have such an elegant, viable, and comprehensive theory.

As the UMP drew to a close, many of the leaders in the geosciences recognized the need for continued international cooperation. Professor Jean Coulomb of France, then president of the IUGG, was quick to appreciate the importance of the new model and encouraged the formation of a new project to develop it. This new project, the International Geodynamics Project (IGP), jointly sponsored by the IUGG and the International Union of Geological Sciences (IUGS), operated as an interunion commission under the auspices of the International Council of Scientific Unions (ICSU). More than 50 countries participated in the IGP, and meetings and symposia were held in many countries, including Nepal, Iran, Brazil, Peru, New Caledonia, Czechoslovakia, Canada, Japan, and the United States. Perhaps the most important aspect of the project was its ability to bring together scientists from many countries and disciplines to exchange ideas and data. But it also provided a focus for planning and a rationale for support of research activities that proved useful to those charged with the responsibility for the disbursement of public funds.

The IGP came to an end at the International Geological Congress in Paris during the summer of 1980. The results of scientific efforts were published in a series of symposium reports during the project, and a multivolume final report is now being published by the American Geophysical Union in collaboration with the Geological Society of America. The individual volumes are being prepared by the Working Groups of the Interunion Commission on Geodynamics. They reflect the progress made during the life of the project in understanding the dynamics of the earth and its regional manifestations.

Progress and Problems

The oceans. It is sometimes said that we know more about the sea floor than we do about the continents. This observation is somewhat misleading, however, because we are not speaking to the same body of knowledge or the same history in both of these areas. The sea floor is geologically young and has typically been affected by only one tectonic process. Thus, in contrast to the much older continents, the tectonic history of the oceans is relatively straightforward, lending itself well to rather simple thermal modeling. It might therefore be concluded that we have solved the major problems of the origin and geological history of the oceans and should direct our total attention to the continents. Talwani and Langseth (page 22) argue otherwise, noting that we have only a broad reconnaissance knowledge of the geology of the sea floor, gained through geophysical measurements, sediment coring, dredging, deep-sea drilling, and underwater photography. At no location in the oceans do we know the details of the geology as we do for many parts of the continents. Our acceptance of the simplicity of the geology of the ocean may reflect the broad-scale coherence of the available geophysical data rather than an inherent simplicity of the system.

We know that modern continental margins contain major supplies of hydrocarbons and hold many of the clues to the processes of continent formation. Most mountain systems began their history as continental margins. We recognize that modern continental margins represent fundamental but poorly understood crustal discontinuities and that ancient margins, now represented by sutures in mountain systems within the continents, contain whatever history remains of old ocean basins eliminated when continental fragments merged. The continental margins are difficult places in which to work because many properties of the rocks change simultaneously. We have not yet done the experiments, nor have we even developed the techniques required to discover all of the secrets of continental margins.

Recently we have acquired tools—multibeam sounding systems (see cover), ocean bottom seismographs, deep-towed instruments, submersibles, multichannel reflection seismograph equipment, and others—with which to examine in detail the properties of the ocean ridges and rifts and the processes by which they were created. Ballard *et al.* (page 31) discuss major questions concerning the tectonics and origins of ocean ridges and the findings of recent investigations based on the use of these tools. Of special note is the discovery of active deep hydrothermal circulation of seawater through hot, newly formed crustal rocks. This circulation is accompanied by extensive alteration of these rocks, and locally by the formation of deposits of metallic sulfides. These deposits have much in common with ore deposits now being mined.

We have a reasonably good understanding of the first-order tectonics of the sea floor, but we are only beginning to explore the basic geology, including the distribution of rocks at the ocean surface, changes in rock type at depth, the details of tectonic processes affecting the oceanic rock, and the geochemistry of the seawater-rock interactions with resulting formation of metal deposits.

The continents. On the continents the situation is reversed. After two centuries of geological mapping, we have at least a reconnaissance knowledge of most of the surface geology. The hundreds of thousands of wells drilled in search of energy resources have given us a picture of the sedimentary cover in many basins as well as tantalizing glimpses of the underlying crystalline basement. We have determined the surface structure and have attempted to project its behavior at depth, with mixed results. Our knowledge of the deep crust is poor and is based primarily upon broad-scale geophysical measurements. The continental crust contains a record of time approximately 20 times as long as does that of the oceans. Most of the continental rocks have been subjected to multiple tectonic processes, and the crust does not exhibit the same broad-scale geophysical coherence that we find in the oceans. Because of the history of the continents, the rocks are complex; simple thermal effects are no longer dominant, and we do not yet understand the first-order tectonics.

The Consortium for Continental Reflection Profiling (COCORP) deep seismic reflection studies performed thus far have yielded important and unexpected results. Of particular interest are indications that the crystalline rocks of the Appalachian Piedmont and Blue Ridge have been thrust far westward over flat-lying sedimentary rocks of presumably late Precambrian and early Paleozoic age (*16*). The data suggest that the thrusting is related to multiple opening and closing of a proto–Atlantic Ocean accompanied by one or perhaps two continental collisions. Deep seismic reflection exploration across the bounding fault on the south side of the Wind River range of the Rocky Mountains in Wyoming shows the fault to be a great thrust continuing downward at an angle of about 40° to a minimum depth of 24 kilometers. Such a major low-angle thrust, contrary to earlier interpretations, indicates the existence of very strong compressive stress at the time of its generation. Should continuing studies indicate that other related crystalline uplifts are bounded by similar faults, as now seems probable on the basis of COCORP work across the Laramie Range, then we will be faced with a dilemma (*17*). It has been widely assumed that such great thrusts within continental crust, for example, those characterizing the Himalayan Mountains, require the collision of continental masses for their generation. No such collision has yet been recognized for western North America at the time of the uplift of the great basement blocks of the Rocky Mountains and concurrent subsidence of associated basins. Another observation of great interest is the delineation of probable magma chambers within the Rio Grande Rift of New Mexico (*18*). The implications are that this rift is still active and that further volcanic activity is to be expected at some unknown time. Obviously the existence of relatively shallow magma chambers also has implications for the development of geothermal energy resources.

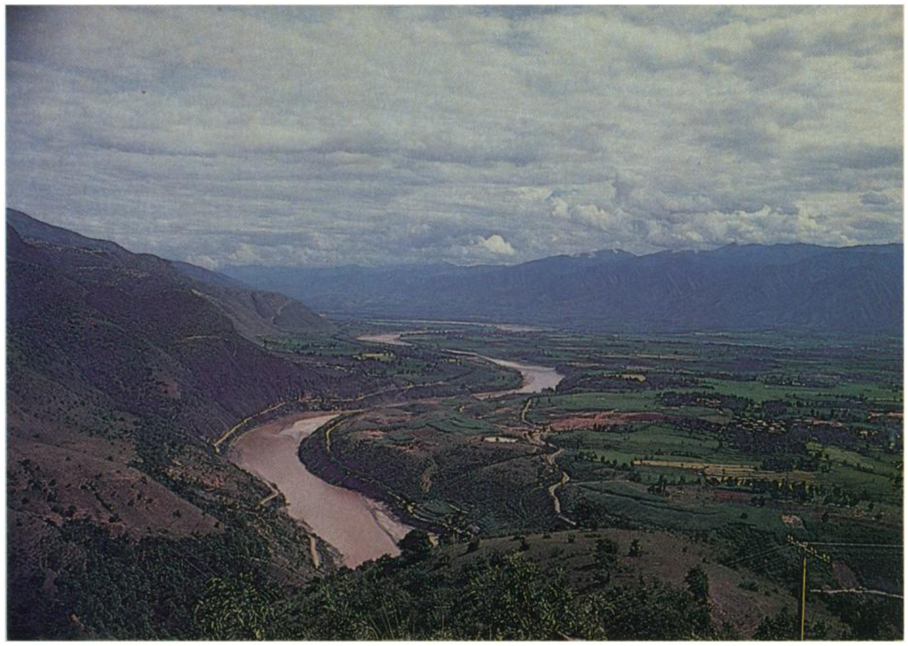

Fig. 1. The mantle beneath the continents is usually buried beneath many kilometers of continental crust. In the Ivrea zone of northern Italy, geological and geophysical data indicate that the rocks have been thrust upward and exposed to view. These ultrabasic rocks outcrop here in the mountains near the town of Finero.

A particularly puzzling problem is the nature of the lower boundary of the continental crust, the Mohorovicic discontinuity (Fig. 1). At this boundary refraction and earthquake seismology indicate an abrupt increase in velocity to that characteristic of the mantle. Deep seismic reflection work, however, commonly fails to detect a significant event at the expected depth of this discontinuity. Where reflections are obtained, they characteristically indicate discontinuous zones several kilometers thick of parallel to subparallel reflectors (*18*). A related quandary was encountered in the Soviet Union where deep drilling in the Kola Peninsula penetrated the mid-crustal Conrad discontinuity but failed to reveal geological evidence to explain its presence.

Although the seismic data suggest the general character of deep crustal structure and put some constraints on possible lithologies, the actual identification of rocks and interrelation between rock units depends ultimately upon direct observation. Deep mines and especially deep exploratory drill holes locally provide a glimpse of the top 10 kilometers or so of the continental crust. Unfortunately, much of the data potentially obtainable from such drill holes either is not observed at all or is not readily available to the scientific community. In an effort to capture some part of the vast amount of useful data potentially available from deep holes drilled for other purposes, a program of Continental Scientific Drilling has been instituted (*19*). The principal objective of this program is to apprize the scientific community of opportunities for obtaining samples and for performing various types of geophysical observations, such as regional stress determinations, in drill holes of opportunity. A vast amount of critical data could be obtained at relatively small additional cost from drilling that will be initiated for purposes other than purely scientific. Exploration drilling by the petroleum and mining industries and by various

Fig. 2. The Red River near Yuanjiang in Yunnan, China, flows along a marked crustal discontinuity between undeformed late Precambrian rocks to the north (left) and deformed and metamorphosed Mesozoic rocks to the south. Geological discontinuities of this sort can be used to identify ancient plate boundaries.

unidirectional evolution of processes. Some rocks, such as komatiites, have melting temperatures much higher than lavas commonly extruded at the present. They are relatively abundant in early Precambrian rocks but rare in modern ones. These and other observations suggest a hotter, thinner lithosphere in early Precambrian times. Many lines of evidence suggest an early reducing atmosphere which began to contain significant amount of oxygen in Proterozoic time after the development of shallow continental shelves and a resulting explosive growth of algae. Oxidation of the iron-rich ocean waters produced the major iron formations of the world. Many of the rock assemblages, such as ophiolites and blueschists, that are associated with modern converging plate boundaries are absent from early Precambrian terranes. Goodwin suggests that the present-day plate tectonics pattern may have emerged after a major thermal event that produced extraordinary bodies of anorthosite, a rock type that formed the early crust of the moon and possibly other planets. Many questions remain to be answered about the generation of lithosphere and of continental crust under the early conditions of the earth. There remains considerable difference of opinion about the timing of the evolution of this crust as well as the nature of the evolutionary processes.

agencies of the federal and state governments is expected to contribute significantly to our knowledge of the continental crust in the next decade or two.

Plate boundaries, present and past. The boundaries of the present tectonic plates are defined by their seismicity and, in the case of converging plates, by deep earthquakes and subduction. Moores (page 41) points out that we lose the seismicity indicator very quickly as we go back in time so that the recognition of older plate boundaries becomes increasingly difficult. Because it now appears that all of the present ocean crust was created during the last 200 million years, we must rely on the record of the continental rocks to indicate the location of earlier plate boundaries. In some cases remarkable success has been achieved in determining these boundaries through paleomagnetic studies. Such studies have recently demonstrated that our original concept of a limited number of very large plates moving relative to each other was itself limited. Small slivers of continental crust and of unusually thick oceanic crust have been identified that were accreted to the continental portions of plates in the recent past (Ben-Avraham *et al.*, page 47). These movements result in changes in latitude, tectonic environment, and climate that are important to the generation of resources of economic significance. In other cases we can recognize ancient plate boundaries now within the continents as marked geological discontinuities or as deformed zones that were originally on plate margins (Fig. 2). The deformation associated with presently active orogenic belts can be identified, and we find that structures and rock suites generated during the last 700 million years show strong similarities. Especially significant are ophiolites, the remnants of ancient deep oceans, now trapped along sutures in the continents and elevated above sea level. When we look at older terranes, we find similar rocks in some instances and different ones in others, back to about 2500 million years. Still older rocks show significant departures from those of modern plate margins and suggest that tectonic processes were markedly different. We have some clues bearing on the recognition of ancient plate boundaries, but we lack the data required to completely define the nature of ancient plates or the nature of changes in crustal behavior through time. In view of the scarcity of information, it is not surprising that conflicting models have been developed.

Development of the Crust Through Time

That early tectonic processes should be different from modern ones is a reasonable conclusion since both the heat sources and their magnitudes have changed with time. Goodwin (page 55) suggests that the Precambrian continental crust, representing 85 percent of the earth's history, contains the record of a

The record of continental rocks extends back for about 3.8 billion years, although the radiometric ages of the oldest moon rocks and of meteorites suggest an age for the earth of close to 4.6 billion years. To date, despite much searching, we have found no record of this first 800 million years of the earth's history. When we consider that Phanerozoic time, the interval in which fossils with hard parts were preserved in the sediments, includes only the last 600 million years of the earth's history, the magnitude of this missing record becomes obvious. Isotopic evolution studies of samarium-neodymium ratios suggest that we will not find this missing record, for the dynamic processes in the earth have acted to erase it (*20*). We may, however, find some important clues through studies of neighboring planets, which have been less dynamically altered.

Space programs and manned missions have given us many insights into the character of the rocks and the tectonic behavior of the terrestrial planets and our moon. It has become apparent that these bodies were heavily bombarded by external objects, especially in the period from 4.2 billion to 3.9 billion years ago. It is unlikely that the earth could have escaped this bombardment although the record is missing, obscured or destroyed by subsequent tectonic activity and by weathering and erosion. Head and Solomon (page 62) point out that the tectonic histories of the terrestrial planets are quite varied. Although the lithosphere of the earth is broken into separate plates and characterized by the recycling of material into the interior, the lithospheres of the moon, Mars, and Mercury are continuous, spherical shells. It is not yet certain what tectonic style prevailed on Venus. The absence of recycling and the presence of the record of early bombardment suggest that the early record of planetary history may be preserved on these bodies, a suggestion that is supported by the ages of moon rocks brought back by Apollo missions. Thus, these bodies are natural laboratories that can provide exciting opportunities for studying the early evolution of planetary bodies and determining, by analogy, the nature of the earliest one-sixth of the earth's history. Similarly, our greater knowledge of the properties of the earth's interior will give us insights into the nature of the other terrestrial planets.

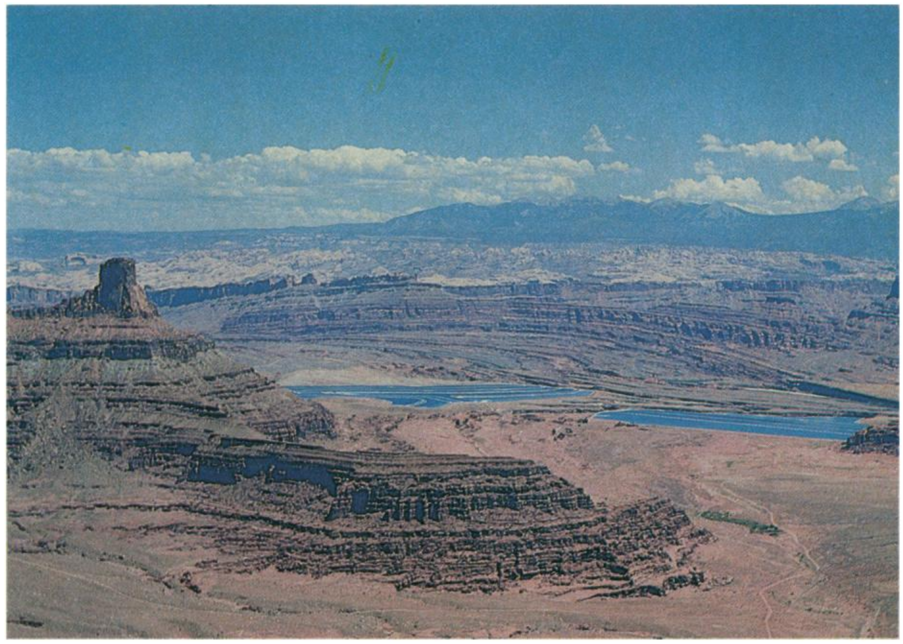

Fig. 3. Dead Horse Point, Utah. Large-scale vertical movements are clearly demonstrated in the western United States where major uplift has produced some of our most spectacular scenery. Other movements, often oscillatory in character with rates that sometimes are on the scale of centimeters per year, are less obvious. The relationship between these vertical movements and the simple plate tectonics model is not clear.

The tectonic style of a planet is closely related to its internal thermal history. O. L. Anderson (page 76) notes that in 1970 quantifying the internal temperature profile appeared to be essential in interpreting the thermal regime. With the general acceptance of mantle convection, this view is no longer commonly held since the boundary conditions can be tied to plate motions rather than to the initial conditions at the time of formation of the earth. Because viscosity varies greatly with temperature, convection is self-regulating and temperature is derivative rather than definitive. If the lithosphere is nonconvecting and radioactive heat production is similar on other planets to that on the earth, then one would expect the critical viscosity, or base of the lithosphere, to be at greater depth in a small planet than in a large one, and the tectonic style to be quite different. Thus it would be expected that Mars, Mercury, and the moon, being smaller than the earth, would have thicker lithospheres and a lower degree of melting and that the thermal conditions necessary to fragment the lithosphere and produce plate tectonics would not be reached.

In one definition, the lithosphere is described as a thin thermal boundary layer above the convecting cell in the earth's mantle. The question of whether convection cells extend through the whole mantle has received a positive answer from some investigators (*21*), but D. L. Anderson (page 82) argues on the basis of seismological data and element abundances that the mantle is chemically stratified and that there is no whole-mantle convection in the conventional sense, although whole-mantle convection at an earlier stage of the earth's history probably led to the current layering. Anderson's analysis goes against current dogma in a number of ways. He concludes that the lower ocean lithosphere is eclogite rather than pyrolite, richer in garnet than usually thought; that the low-velocity zone in the mantle is enriched rather than depleted; that the so-called primitive reservoir that provides magmas to a variety of tectonic settings is actually enriched; that the source region for the mid-ocean ridge basalts is eclogite rather than peridotite; and that subducted ocean lithosphere sinks no deeper than 670 kilometers. These conclusions, based on evidence from geophysics and paleogeophysics, appear likely to lead to healthy discussions about the nature of the interior in future publications and at meetings.

Stress and Strain

As we have come to view tectonics on a global scale, we find that there are inadequacies in our measurements and in our measuring systems. From the magnetic anomalies in the oceans we can obtain an integrated picture of plate motions for the last 200 million years. For earlier times, we rely on paleomagnetic data or paleoclimatic indicators. This information tells us what has happened but not how it happened. We accept the idea that motions have occurred, but we have few direct measurements of these motions. Flinn (page 89) points out that poor time discrimination prevents us from deciding whether plate motion is continuous or intermittent. We assume rigid plates without knowing whether or how they deform. We have an integrated view of the large-scale horizonatal motions that have taken place, but we lack data on the rates, directions, and continuity of both horizontal and vertical movements going on at present (Fig. 3).

Space technology has matured in the last decade to the point where it can be applied to geodynamical problems in a meaningful way (Flinn, page 89). The development costs of these techniques are significant, but the operational costs are moderate. They have the potential for determining the distribution and rate of strain at or near plate margins, or between continents, or between disparate parts of continents.

Coupled with strain is stress. Because the bulk of current earthquake and volcanic activity occurs along the plate margins, we sometimes forget that some of the largest earthquakes and some of the major volcanic events have occurred in plate interiors. These events are infrequent and this infrequency makes them

Fig. 4. New volcanic island in the New Hebrides. Although some volcanoes associated with young mountain systems or island areas, like Mount St. Helens, explode subaerially, others may erupt beneath the sea surface.

more difficult to analyze. One way to attack this problem is to determine the state of stress within a plate. Zoback and Zoback (page 96) have analyzed the available data within the conterminous United States. The data indicate that the country can be divided into provinces in which principal stresses are reasonably consistent. In addition, new geophysical data indicate the presence of buried structures to which stresses and the occurrence of intraplate earthquakes can be related. There are a number of possible sources for the observed variable stress fields, in all probability related to plate tectonics but equally probably not to the existing simple model. Both stress and strain measurements raise questions about the degree of rigidity of the lithospheric plates and the extent and nature of intraplate deformation.

Geodynamics and the Environment

The earth we live on is such a familiar place that we generally show very little curiosity about the peculiar conditions that created this planet. It is fortuitously located relative to the sun so that water can exist on its surface in liquid, solid, and gaseous forms and is of a size and mass that much of its volatile material has been retained. As far as we know, only this planet is a site suitable for life in our solar system. It seems to differ from similar bodies in the solar system, except perhaps for Io, a satellite of Jupiter, in being intensely energetic. For this we pay a price in earthquake, volcano, tsunami, and hurricane damage, but we also reap benefits of natural resources formed over the eons of the earth's existence and still forming today. The study of the dynamic earth, therefore, continues to be exceedingly important to humanity. Geodynamic data and studies are directly pertinent in three broad areas: (i) the anticipation and amelioration of natural disasters, particularly those related to earthquakes and volcanoes; (ii) the study and control of certain elements of our environment, especially those related to the geochemistry of dangerous chemicals and other natural and man-made pollutants; and (iii) the location and use of natural resources.

The recent eruptions of Mount St. Helens, although not unexpected by those most familiar with that volcano, came as a great shock to the people who lived nearby. Mount St. Helens is but one of a chain of volcanic cones, some considered "dead," others showing occasional signs of life in the form of hot springs and steam vents, but generally peaceful elements of a beautiful landscape (Fig. 4). Other volcanic edifices and very young lava flows are found scattered about much of the broad cordilleran belt of western North America. The most recent activity east of the Cascade mountains predates the arrival of the white man, and only a little is recorded in Indian legend. Nevertheless, as the discovery of probable magma bodies beneath the Rio Grande Rift (*18*), the Yellowstone area (*22*), and elsewhere suggest, there is reason to believe that some volcanoes may again come to life. The sudden appearance and growth of the new volcano Paricutin in Mexico in 1943 could very well be duplicated in the Cascade Range, or conceivably in Arizona, New Mexico, Colorado, or California, where very young cinder cones exist.

Much has been learned from the study of the active volcanoes in Iceland, Italy, Hawaii, Alaska, and, most recently, Mount St. Helens. In the last case, peculiar harmonic earth tremors were recognized, which anticipated many of the eruptions and disappeared with the cessation of the eruptions. This and other kinds of data now being collected may lead to a modeling of underground magma movements which may help to anticipate future eruptions with greater accuracy.

The time of occurrence of devastating earthquakes likewise can seldom be anticipated within useful time and space frames, even though their recurrence along certain great faults, such as the San Andreas and related fractures, can be confidently predicted. Much effort is now being expended in the study of phenomena that may signal activity along fractures leading to earthquakes. Although some success has been claimed in China and elsewhere, true predictability in real time still seems to be some distance in the future. Continued study of the nature of strain and stress within the earth's crust (Zoback and Zoback, page 96) and of local variations in both space and time, may eventually permit better identification of areas where major earthquakes are to be expected. In this respect the direct measurement of plate motions, both horizontally and vertically (Flinn, page 89), is perhaps now technically feasible and promises to become a reality during the 1980's. In the meantime it will be possible to learn much more of the local stress pattern throughout a country by measurements in wells drilled for other purposes, as envisioned by the Continental Scientific Drilling Program (*19*).

During the greatest part of their history, humans, like their fellow creatures, struggled constantly to protect themselves from their environment. For the last three millennia, however, as numbers have increased and humans became organized into agricultural, pastoral, and manufacturing communities, the environment has often been on the losing end of the fight. Fyfe (page 105) puts the matter in perspective by pointing out that if the average rate of production of garbage per person in North America (approximately 1 ton per year) were applicable worldwide, it would somewhat exceed the rate of production of volcanic materials above subduction zones, a process which built much of the mountainous terrains surrounding the Pacific Ocean. Not unexpectedly, the rate at which we use the resources of the earth is far greater than that at which they are being replaced.

Our capacity to measure the distribution of elements and compounds has greatly increased. We can estimate the quantities of valuable materials within the earth and note some of the kinds of processes that result in enrichment of these materials into deposits of commercial size and grade. We are, however, only beginning to understand the global geochemical, geophysical, and geological systems related to the formation of natural resources and, equally importantly, to the location of places for the safe storage or disposal of the wastes that are accumulating in troublesome quantities.

The Challenge of the 1980's

International Lithosphere Program. The fragmentary clues left by mother nature in her experiments in geodynamics are unequally distributed. Geologists in Zimbabwe, Greenland, and Brazil are presented with many opportunities to study the early history of the earth but lack the evidence of recent deformation that is so obvious in Switzerland, Japan, or Nepal. Marine geologists and geophysicists can study young ocean crust and lithosphere, but older sea-floor rocks are available only in the suture zones of the continents. Experimental petrologists and geochemists depend upon the seismologists to identify the physical constraints upon which to base their estimates of the composition of the earth's interior. Modelers can suggest one- or two-stage convection but look to the isotope geochemists for supporting evidence.

Even though interdisciplinary and international communication is important in all sciences, the unequal distribution of geological features and the interdependence of biological, physical, and chemical phenomena make communication doubly important in the geosciences. If we want to understand how the heat engine that is the earth really works, not only must we identify the connecting rods and the spark plugs, but we must also understand how they function in the engine. Much of geological evidence consists of the emissions and the products resulting from past operations of this engine. The geophysical evidence, on the other hand, deals largely with the present and can tell us principally how the engine is running currently. Geochemical evidence provides a link between the two, relating the current operation to that of the past, and can help us to understand changes in operating mode over the past 4 billion years.

Geoscientists in the IUGG and IUGS clearly recognize the need for continuing international and interdisciplinary cooperation in studying the earth, its properties, and the processes that affect it. They have agreed that there should be a new venture for the 1980's based on the findings of the IGY, UMP, and IGP which would encourage continuation of the most important ongoing activities and would add new ventures that promise to yield significant insights into the workings of the solid earth. This new project, the Inter-Union Lithosphere Program (ILP), has now been approved by the ICSU (*23*). It will focus on the dynamics of the lithosphere, with increased emphasis on the nature and origin of continents and continental margins and on the applications of geodynamic data and concepts to human needs.

The lithosphere is the rigid outer shell of the earth that overlies a more plastic interior region. We have come to realize that the differences between continental and oceanic areas, once thought to be limited to the crust, in fact extend to depths of hundreds of kilometers. There is some evidence that these differences are related to the age of the overlying crust, with the thickest lithosphere being found where the crust is the oldest. This observation creates problems for the current simplistic plate tectonics model, and modifications of the model are needed. Therefore, an intensive study of the thermal regimes and chemical and physical properties of the earth's materials below the lithosphere is also an important objective of the ILP.

The presence of a relatively rigid lithosphere over a more plastic layer has been recognized for many years, but its nature is poorly known and its definition is ambiguous. Clearly a lithosphere defined by its rigidity is not the same as one defined by other commonly cited properties such as seismic velocities or thermal structure. The problem of definition was recognized by the architects of the new program as a justification for a thorough scientific study of this outer portion of the earth, which plays such an important role in global geological processes. A desirable product of the program would be a rigorous definition of the term "lithosphere" acceptable to the different disciplines and encompassing the finding of the program with regard to composition, thermal state, physical properties, internal processes, and thickness.

U.S. Geodynamics Committee in the 1980's. After a 4-year study directed toward an anticipation of the most fruitful directions for geodynamic research during the next decade, the U.S. Geodynamics Committee (USGC) issued its report, "Geodynamics in the 1980's" (*24*). As the members of the committee see it, geodynamic studies during the next decade will emphasize crustal dynamics, particularly the origin and evolution of continental and oceanic crust, the nature and development of the continent-ocean transition, the relation of the dynamics of the earth's interior to crustal dynamics, and the development of a framework, based on the use of geodynamic principles, for the understanding of natural resource systems and natural hazards. These objectives are compatible with those of the newly organized ILP (*23*), and it is anticipated that the USGC will participate actively in the ILP.

It is the appreciation of the need for international and interdisciplinary cooperation that encouraged the formation of international geoscience programs, such as the just completed IGP and the ILP that has sprung, like the phoenix, from its ashes. As we have become more concerned about the capacity of the earth to supply resources to its population, about the protection of this population from natural hazards, and about providing it with a tolerable environment, so has the need for international cooperation increased in order that we might understand the earth's properties and its dynamics. It would be unrealistic to think that we will have a complete understanding of the earth's geodynamics by the end of the ILP, but we should have made progress. It is unrealistic to expect the need for international geoscience projects to disappear upon completion of the ILP. Rather, we anticipate that by the end of this program many of the current priority objectives will have been realized and new, more advanced, priorities will have been identified.

References

1. J. W. Gregory, *The Rift Valleys of East Africa* (Seeley, Service, and Co., London, 1921).
2. E. Suess, *The Face of the Earth (Das Antlitz der Erde)* (Clarendon, Oxford, 1904–1924).
3. E. Haug, *Traite de Geologie* (Librairie Armand Colin, Paris, 1908–1911).
4. A. Wegener, *Die Entstehung der Kontinente und Ozeane* (Vieweg, Braunschweig, 1929).
5. B. Gutenberg, *Geol. Soc. Am. Bull.* **62**, 427 (1951).
6. A. Mohorovicic, *Jahrb. Meteorol. Obs. Zagreb* **9**, 1 (1909).
7. For example, K. E. Bullen, *An Introduction to*

the Theory of Seismology (Cambridge Univ. Press, Cambridge, ed. 3, 1963).
8. E. Wiechert, *Nachr. Ges. Wiss. Gottingen Math.-Phys. Kl.* (1897), p. 221.
9. R. D. Oldham, *J. Geol. Soc. (London)* **62**, 456 (1906).
10. B. Gutenberg, *Nachr. Ges. Wiss. Gottingen Math.-Phys. Kl.* (1914), p. 1; *ibid.*, p. 125.
11. I. Lehmann, *Bur. Centre Seismol. Int. A* **14**, 3 (1936).
12. H. H. Turner, *Mon. Not. R. Astron. Soc. (Geophys. Suppl.)* **1**, 1 (1922).
13. K. Wadati, *Geophys. Mag. Tokyo* **8**, 305 (1935).
14. J. Barrell, *J. Geol.* **22**, 655 (1914).
15. B. Gutenberg, *Geol. Soc. Am. Bull.* **65**, 337 (1954).
16. F. A. Cook, L. D. Brown, J. E. Oliver, *Sci. Am.* **243** (No. 4), 156 (1980).
17. S. B. Smithson, J. A. Brewer, S. Kaufman, J. E. Oliver, C. Hurick, *J. Geophys. Res.* **84** (B11), 5955 (1979).
18. L. D. Brown, C. E. Chapin, A. R. Sanford, S. Kaufman, J. E. Oliver, *ibid.* **85** (B9), 4773 (1980).
19. Continental Scientific Drilling Program (Geophysics Research Board, National Academy of Sciences, Washington, D.C., 1979).
20. D. J. De Paolo, *Eos* **62** (No. 14), 138 (1981).
21. W. M. Elsasser *et al.*, *J. Geophys. Res.* **84** (B1), 147 (1979).
22. R. B. Smith and R. L. Christiansen, *Sci. Am.* **242** (No. 2), 104 (1980).
23. *Dynamics of the Lithosphere: the Framework for Earth Resources and Reduction of Hazards* (Interunion Commission on the Lithosphere Report 1, International Lithosphere Program, c/o Geodynamics Program Office, Mail Code ERG-2, National Aeronautics and Space Administration, Washington, D.C. 1981).
24. U.S. Geodynamics Committee, "Geodynamics in the 1980's" (National Academy of Sciences, Washington, D.C., 1980).

Ocean Crustal Dynamics

Manik Talwani and Marcus Langseth

Summary. The study of oceanic crust continues to be important because of the presence of economic resources in oceanic areas and because many fundamental problems of geologic evolution are best solved from studies of the ocean. Although modeling and syntheses of existing data remain important, key breakthroughs in the future will come from the application of new technology such as multichannel towed seismic arrays, deep-towed side scan sonars, improved thermal probes, deep drilling, and satellite altimeters.

Much current research in earth science is based on applying the plate tectonic model to problems as diverse as continental orogeny, paleoceanography, and metallogeny. Plate tectonics, developed in large part from geophysical and geological information gathered from the world's oceans, is now playing a key role in explaining the geological events and processes that shaped the continents.

The growth in interest in continental geology has led some in the earth science community to consider geophysical and geological research in the oceans to be less important now than research on land. Among the reasons given are that the first-order problems of the geological development of the oceanic basins are solved, whereas those of the continents are not, and that continental geologic research will better serve society and its need for natural resources.

We suggest, however, that marine geological research continues to be important, for the following reasons.

1) Important economic resources reside in the deep-sea and submerged margins.

2) Subduction of the oceanic lithosphere plays an important role in shaping the continents, and the major zones of active underthrusting occur mostly beneath the sea. The processes that occur in subduction zones are poorly understood, and the relative ease and smaller expense of using geophysical techniques at sea offers the best hope of unraveling these processes.

3) There remain many important problems in the evolution of the oceans, such as the role of hydrothermal circulation in the chemistry of seawater and the alteration of the crust, the origin and deep structure of backarc basins, and their relation to subduction.

4) The fundamental problem of what drives plate tectonics is best investigated over the oceanic plates.

The directions that research in marine geology and geophysics will take was the subject of a series of workshops sponsored by Joint Oceanographic Institutions. In summary of the report of this group's Ocean Crustal Dynamics Planning Committee, Hussong (*1*) states that new technology will be extremely important for research in earth sciences at sea. During the past decade new tools, such as the deep-sea drilling ship *Glomar Challenger*, multichannel seismic profiling, deep submersibles, and satellite altimeters, have allowed scientists to sample and sound deeper and with greater resolution and discrimination than the standard tools of marine geology and geophysics that opened the door to modern research in the oceans. These standard tools, largely developed in the 1950's, still have a role to play in rapid surveys and reconnaissance work; but to attack current problems, more powerful and incisive techniques are needed.

At the same time that new techniques were being developed, a change in philosophy has occurred in the research community. This change results in part from the success of plate tectonics and its simple kinematic models for testing observations, which altered the thrust of earth science research, turning it away from exploration and fieldwork toward review and synthesis of existing data and the formulation of successful earth models. One effect of this change is that today relatively few students in geoscience have an interest in the exploratory phase of research.

The emphasis on synthesis and modeling has helped us understand processes that shape and change the face of the earth. But progress may be slow in the 1980's if new data and techniques that would allow a more profound look into the earth go undeveloped.

To illustrate the importance of the role of new technologies, we discuss some outstanding geological problems in areas familiar to all geologists—passive margins, convergent margins, and the oceanic crust—and show how new techniques might help solve these problems.

M. Talwani is professor of geological sciences and M. Langseth is senior research associate and adjunct professor, Lamont-Doherty Geological Observatory, Palisades, New York 10964, and Department of Geological Sciences, Columbia University, New York 10027.

0036-8075/81/0703-0022$02.00/0