Geodynamics in the 1980's (1980)

Pages
67

Size
5 x 9

ISBN
0309332222

U.S. Geodynamics Committee; Geophysics Research Board; Assembly of Mathematical and Physical Sciences; National Research Council

Geodynamics in the 1980's

Basic objectives, ongoing activities and new directions, with emphasis on the origin and evolution of continental and oceanic crust, the continent-ocean transition, the relation of mantle dynamics to crustal dynamics, and a geodynamic framework for understanding resource systems and natural hazards.

U.S. Geodynamics Committee

Geophysics Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1980

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This report is based upon work supported in part by the National Science Foundation under Grant No. EAR 79-01089. Opinions, findings and recommendations expressed in this publication do not necessarily reflect the views of the National Science Foundation.

The U.S. Geodynamics Committee is pleased to acknowledge the support of the National Science Foundation, Department of Energy, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and U.S. Geological Survey.

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Preface

The U.S. Geodynamics Committee was established (under another name) in 1970 to foster and encourage studies of the dynamic history of the earth. In response to the request of ICSU for national participation in the Geodynamics Project, the President of the National Academy of Sciences changed the name of the Committee to U.S. Geodynamics Committee (USGC) and stated that its responsibilities should include development of a program of U.S. participation in the Geodynamics Project. The activities of the USGC in the following years are reviewed in an appendix.

In 1976, the Geophysics Research Board (GRB) requested the USGC to develop a statement of the objectives of geodynamic studies in the 1980's, and the corresponding research directions – continuing and new. *Geodynamics in the 1980's* is the result of three years of planning efforts by the USGC. The GRB has formally requested the USGC to continue providing guidance to U.S. geodynamic activities in the 1980's in a manner analogous to the guidance provided in the 1970's.

The cooperative efforts among geophysicists, geologists, geochemists and geodesists that were encouraged by the Geodynamics Project were considered to be exceptionally fruitful. Therefore, IUGG and IUGS began developing plans for a new cooperative program of continuing collaboration between the two unions to follow the formal end of the Geodynamics Project in 1979. A joint effort by Task Groups of the two unions led to the report "The Lithosphere: Frontier for the 1980's." The objectives set forth in that report were endorsed by the executive bodies of both unions early in 1979. These actions were reported to the ICSU Executive Committee in July 1979; shortly thereafter, the unions jointly established a Steering Committee to develop more precise guidance for the new program, and a recommended title. The Steering Committee held its first meeting during the IUGG General Assembly in Canberra, December 1979; it is expected to complete its work prior to the International Geological Congress in Paris, July 1980. The new program was formally approved by the Council of IUGG in December 1979. It is expected to be presented to the Council of IUGS in July 1980 and to the General Assembly of ICSU, September 1980.

By December 1979, it became well known that many countries were taking steps toward developing national programs corresponding to the new international program. The objectives set forth in *Geodynamics in the 1980's* and the objectives of the international program as set forth in "The Lithosphere: Frontier for the 1980's" and the discussions at the special conference "Geodynamics Problems: Outlook to the 1980's" (held in Zurich, February 1979), and the discussions at the meeting of the Steering Committee in December 1979 are all in good harmony. The USGC looks forward to active participation in the new international program.

The USGC has an established pattern of rotation of members in accordance with the general practice of committees of the National Academy of Sciences-National Research Council. Thanks are expressed to those former members who contributed to the preparation of *Geodynamics in the 1980's,* to the USGC reporters, and to many other participants in the meetings of the USGC. Such participation has included representatives of many federal agencies that are actively concerned with geodynamics, officers of the Inter-union Commission on Geodynamics, IUGG and IUGS, and chairmen of national committees for geodynamics of several countries, in particular our immediate neighbors, Canada and Mexico, with whom we share an interest in the geodynamics of North America. The program of geodynamics during the 1970's, and preparation of the report, *Geodynamics in the 1980's,* directly benefited from this assistance and participation, and from the activities of other NAS-NRC committees and national scientific societies. The USGC hopes that this pattern will be continued for Geodynamics in the 1980's.

February 1980

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I. Summary

During the past two decades, the concept of earth dynamics has changed from that of a sluggish planet characterized by slow, oscillatory, vertical movements to that of an earth in constant tectonic ferment. In this new concept of a dynamic earth, the crust is segmented into a small number of rigid plates, apparently moving essentially independently of one another. Where the plates move apart, new crust is formed, and where they collide, older crust disappears downward or is thickened to form great mountain ranges. Earthquakes and volcanoes are reminders of the continual interaction of the plates as they collide or slide past one another in response to forces that are dimly understood; these forces may be related to convective motions within the earth's mantle. These same distinctive forces create conditions which lead to the formation of mineral deposits and other natural resources.

Although the International Geodynamics Project was scheduled to end in 1979, investigations of earth dynamics are likely to dominate solid-earth research for decades to come. It is timely, therefore, to assess objectives with respect to ongoing research and to consider changes in direction of emphasis to exploit promising new opportunities. The Geophysics Research Board has therefore requested the Geodynamics Committee to develop a program of activities for the next decade. This document, *Geodynamics in the 1980's,* sets forth a program of continuing and new activities which the Committee believes to be of first order importance during the opening years of the coming decade.

Internationally, the Unions of Geodesy and Geophysics (IUGG) and Geological Sciences (IUGS) set in motion planning for a continuing cooperative program of solid-earth studies to go forward after the formal close of the International Geodynamics Project at the end of 1979.

Both internationally and domestically the experience of the past decade has clearly pointed the way to new directions and emphases for the future. For the United States activities, the following principal focus emerges for the studies of Geodynamics in the 1980's:

Crustal dynamics, with emphasis on

- the origin and evolution of continental and oceanic crust
- the continent-ocean transition

- relation of mantle dynamics to crustal dynamics
- a framework for understanding resource systems and natural hazards

Exploration of the continents is a major priority for the coming decade. The proposed Continental Scientific Drilling Program can be a significant contributor to this effort.

To implement the program of Geodynamics in the 1980's, the following activities are proposed (the sequence of listing has no significance regarding relative priorities):

– Studies of ancient and modern plate boundaries, with emphasis on boundaries between oceanic and continental crust, associated earthquakes, volcanism and geothermal phenomena.

– Studies of plate interiors, especially the study of the structure, lithology, and genesis of the North American continent; origin and localization of minerals and other natural resources; isolation of toxic wastes.

– Fine structure of the continental crust and upper mantle, primarily by reflection and refraction seismic techniques, controlled by other geophysical studies and by drilling where feasible.

– Crustal strain and crustal movements, especially within North America and adjacent oceanic areas by diverse techniques including space laser ranging and very-long-baseline interferometry.

– Generation and evolution of the oceanic lithosphere; hydrothermal circulation and mineralization of ocean bottom rocks.

– Utilization of deep drilling for scientific purposes:

Continental – proposed Continental Scientific Drilling Program emphasizing the greater return of scientific information from holes drilled by government agencies or industry for narrowly defined objectives

Continent-ocean margins – drilling in the deep water and thick sediments of the continental slope and rise, or trench margin and accretionary prism, to investigate the nature of the continent-ocean crustal transition

Oceanic – especially to investigate the generation, alteration, mineralization and aging of oceanic crust

– Studies in geomagnetism, especially those relating to the origin and nature of the magnetism associated with oceanic crust; also the study of paleomagnetism in Paleozoic and older rocks, including modification of initial magnetism in rocks, and plate reconstructions in pre-Mesozoic time.

– Geological and geophysical mapping, with priority given to completion of an aeromagnetic map of the United States.

– The earth's internal processes and properties, especially: thermal regimes; electromagnetic properties; origin of magmas; and equations of state of the mantle as determined from earthquake seismology, isotope geochemistry and phase petrology. Investigations of thermal and physical regimes within the earth will be given high priority.

– Geodynamics in the Caribbean area – a poorly understood "Mediterranean Sea" dividing and connecting North and South America.

– Comparative planetology of the earth, moon, and planets (and their satellites) of similar size within the solar system, to gain insight into the varied composition and histories of such bodies, and of the evolution of the earth and solar system.

– Geodynamic modeling, both as a guide and as an end-product of crust and mantle investigations.

– Geodynamic syntheses, including regional maps and reports, to focus attention on activity and problems in priority areas.

– Geodynamic data collection, storage, retrieval, emphasizing the necessity for planning for data handling in projects where large quantities of data will be generated.

– Instrumentation; advances in science and in applications of science to societal needs will depend to a large degree on the availability of instruments – existing, under development, and as yet undesigned – capable of meeting the requirements for a wide range of analytical and experimental investigations.

The U.S. Geodynamics Committee considers that its proposed program of Geodynamics in the 1980's is completely consistent with the international planning being developed by IUGG and IUGS, and looks forward to collaboration in the new international program. The USGC intends to emphasize cooperative efforts with scientists of other countries to study selected areas and phenomena of special importance to geodynamics.

In 1973, the USGC issued its report, *U.S. Program for the Geodynamics Project: Scope and Objectives,* which included a chapter "Initial Priorities." Shortly after the issuance of that report, the Federal Council on Science and Technology announced that the Interagency Committee on the International Geodynamics Project would be established to coordinate the activities of the federal agencies. The USGC then designated 10 reporters corresponding to the topics identified in the chapter "Initial Priorities." The duty of these reporters was to determine what steps needed to be taken by the U.S. Geodynamics Committee to encourage implementation of its recommendations. In the following years, new topics were identified and additional reporters appointed correspondingly. (A few of the tasks were considered completed and the corresponding reporters retired.) This system of reporters of the USGC and the diverse ways in which they carried out their responsibilities, including the communication links between the USGC and Geodynamics Correspondents in some 175 geoscience departments in colleges and universities throughout the United States with nine national scientific societies is discussed briefly in Part IV and in some detail in Appendix B.

Part II provides an overview of the objectives proposed by the U.S. Geodynamics Committee for Geodynamics in the 1980's.

Part III is a brief discussion of international planning; Part IV briefly reviews the relation of Geodynamics in the 1980's to various domestic activities.

Part V of this report contains brief discussions of the main themes for Geodynamics in the 1980's; Part VI discusses implementation.

The USGC will continue its system of reporters to develop recommendations for actions by the USGC to implement the topics identified for emphasis in Part VI in this report. As in the past, implementation will depend in large part on the enthusiasm of the scientific community; the topics for emphasis themselves will be subject to review in the light of new developments, with the addition of new reporters as appropriate.

For the proposed U.S. program in the 1980's, the USGC recommends as the most fruitful approach continued emphasis on basic sciences, but with increased awareness of applications to societal needs. This philosophy is expressed in the subtitle of this report.

II. Directions for the Future

Background

In the last three decades, the earth sciences have undergone a revolution of major scope and importance. To the long-held model – a static earth dominated by slow, rhythmic vertical motions – has been added the concept of comparatively rapid and independent horizontal motions of large slabs of the earth's crust, a concept encompassed in the plate tectonics hypothesis. In this model the earth has an everchanging surface; continents enlarge by accretion of new material, divide, and reassemble in new patterns, and new oceans form as old ones are destroyed by subduction beneath the continents. The resulting strains developed within the crust are evidenced by devastating earthquakes and volcanic outbursts, but phenomena associated with the dynamism also create the conditions necessary for the formation of mineral deposits and other natural resources.

The plate tectonics hypothesis is ocean centered. Virtually all the data and inferences on which the hypothesis rests were derived by observations within the oceans and along their margins. These critical observations were, however, one part of a pervasive scientific ferment, an era of earth exploration following World War II, embodied in the solid-earth exploration activities of the International Geophysical Year program and the Upper Mantle Project. The decade of the International Geodynamics Project coincided with the widespread acceptance of the plate tectonics hypothesis. Although the International Geodynamics Project was scheduled to end in 1979, investigations of earth dynamics are likely to dominate the thinking of solid earth scientists for several decades. Therefore, it is timely to reassess our objectives and to define the opportunities and challenges of the future. To this end, the Geophysics Research Board requested the U.S. Geodynamics Committee to develop a rationale for geodynamic studies in the 1980's. Much of the past three years of Committee activity has been devoted to this effort. A draft working document entitled "Crustal Dynamics: A Framework for Resource Systems" was widely circulated, both domestically and internationally. As a result of reviews of "Crustal Dynamics," the USGC decided to prepare the present report, *Geodynamics in the 1980's,* which is essentially a condensation of "Crustal Dynamics," some sections of which had become extremely detailed. (The USGC does not plan to issue the more detailed version.)

It is difficult to predict where major advances in the earth sciences will occur. In the past, advances have come from unexpected directions. The U.S. Geodynamics Committee considers that it is appropriate for the 1980's to invoke a program that supports and encourages fundamental research bearing on the principles governing the evolution of the earth's crust, its natural hazards, and the distribution of the resources of the solid earth, and that provides a bridge between the geoscience community and the public.

The development of *Geodynamics in the 1980's* was greatly aided by a large number of scientists and by reports of other committees and workshops (see Appendix A).

Focus of New Program

From the review of progress to date and assessment of objectives for the future the following principal focus emerged for the program of Geodynamics in the 1980's:

Crustal dynamics, with emphasis on:

- the origin and evolution of continental and oceanic crust
- the continent-ocean transition
- relation of mantle dynamics to crustal dynamics
- a framework for understanding resource systems and natural hazards

With the knowledge base accumulated during the International Geophysical Year, Upper Mantle Project and Geodynamics Project, we can attack one of the most fundamental questions in earth sciences: What are the physical and chemical processes that have controlled the generation and distribution of continental and oceanic crust and what are their rates? Major advances will require a broadly based, focused and persistent effort of large scale. To study the continents and ignore the oceans and continent-ocean interaction will be insufficient, because crustal evolution, in the plate tectonics model, begins at spreading centers located mostly in the oceans. Continents and oceans have not stayed fixed and immobile through time. Oceanic crust may be converted into continental crust, and continental crust may become oceanized. An overall understanding will demand complementary studies of both continents and oceans.

A coordinated international effort bringing together information from many parts of the world and the facilities and talents from diverse disciplines and from many countries will be required. The United States is in a position to make major contributions to such a program, contributions that will not only complement international efforts but also offer a foundation upon which the solutions to national problems can be constructed.

Societal Needs – Framework for Investigations of Resource Systems and Natural Hazards

A major objective of the program of Geodynamics in the 1980's is to develop a basic understanding of geodynamic processes that will provide a frame of reference to which specific societal needs can be related. Among important needs are the identification of: habitats favorable for hydrocarbon accumulation and preservation and for concentration of valuable minerals; methods for prediction of earthquakes and volcanic eruptions, and perhaps eventually for modification and control of these events; and sites and controls for safe subsurface containment of dangerous waste materials.

Mineral and Energy Resources

The major sources of useful minerals are highly enriched deposits. Some of these, to our good fortune, exist in outcrop or in the near subsurface where they can be discovered by direct observation or simple exploratory procedures. Other deposits are concealed; their discovery will depend largely on an understanding of their genesis. The environment in which these deposits form is established by the same large-scale processes that determine the behavior of the crust. These include climatic processes related to the atmosphere, hydrosphere, and cryosphere (weathering, erosion, sedimentation, groundwater circulation, sea level variation); marine processes involving the chemistry and circulation of the oceans (chemical precipitation and dissolution, production of organic matter, sedimentation, erosion); tectonic processes that control the movement of rock masses; and thermal processes that control the metamorphism of rocks (such as conduction, hydrothermal convection, magma intrusion, devolatilization).

Although the currently exploitable resources are largely confined to the continents, understanding of genetic processes must be gained through studies in both continental and oceanic areas. Hydrothermal and magmatic processes that have produced exploitable resources of heavy metals within the continents are now known to occur on an extensive scale beneath the oceans. Similarly, the conditions for the generation, preservation, and maturation of organic materials to form oil and gas and the conditions that lead to their subsequent accumulation in deposits that can be produced economically are best studied offshore in the continental shelf, slope, and rise areas. Scientific understanding of the processes involved appears to be achievable.

The search for and interpretation of scientific data bearing on the origin and localization of natural resources, especially minerals and hydrocarbons, will be a principal priority during the coming decade. The potential of geothermal energy resources is receiving increased attention. The proposed continental drilling program should significantly increase basic understanding of geothermal systems.

Natural Hazards

Natural hazards such as earthquakes and related tsunamis, and volcanic eruptions are directly related to crustal strain and resulting differential motions within the crust. During the last decade, useful hypotheses have been developed regarding the mechanisms causing earthquakes and volcanic eruptions associated with plate margins. Increased accuracy of prediction of events in some areas is foreseeable. The occurrence of such events in the interiors of the plates is less well understood, largely because little is known about intraplate tectonics or even intraplate basement geology. Improved global, national, and regional earthquake-recording networks and increased emphasis on the regional and local studies of crustal strain variation in intraplate areas are important for progress in understanding earthquakes.

Waste Disposal and Waste Management

An unavoidable characteristic of an industrial society is the generation of waste, some of which is highly toxic, either indefinitely, or, in the case of radioactive materials, for tens or hundreds of thousands of years. The management or permanent disposal of such long-lived dangerous wastes requires underground containment in rocks of the proper physical and chemical characteristics and stability. A fundamental understanding of crustal dynamics and crustal composition is essential to proper decisions regarding potential areas for waste management and disposal. Decisions regarding site selection for isolation and management of radioactive wastes require a knowledge of the various factors, including the following: crustal structure; state of stress and evidence for long-term stability of the site area; the reaction of the rock to local stress; the chemical characteristics of both the waste and the containing rock; the possible effects of water accessibility to the storage area; and identification of geological conditions that will provide multiple, redundant containment features. Thus, both crustal composition and crustal dynamics play major roles in the choice of areas for waste isolation, management, and disposal.

Crustal Dynamics and Crustal Evolution

Because the plate tectonics hypothesis and many of its important corollaries evolved from geophysical and geological observations in oceans, it is not surprising that the hypothesis has been more successful in providing explanations for phenomena in oceanic areas than in the continents. If the present model is even approximately correct, the ocean basins are of Mesozoic age or younger and represent a relatively simple single-cycle episode of crustal formation. The continents, on the other hand, reflect multiple cycles of addition of material, orogeny, and uplift and erosion extending back, in places, more than 3.7 billion years. Through this long period it is likely that the earth's lithological and thermal structure have not remained constant; therefore, it is hardly to be expected that all features of continents will be readily explainable in terms of current plate tectonics models.

Within the continents many of the relatively undeformed sedimentary basins are reasonably well explored. However, large areas of older and generally highly metamorphosed and complexly deformed rocks, both exposed and beneath sedimentary rocks, are known only very sketchily. As a consequence, much less is known about the composition, age, and deep structure of the continents than of many parts of the ocean basins. Furthermore, most of the natural resources on which we depend and the earthquakes and other natural hazards that endanger the largest numbers of people are on or close to the continents. Thus, *emphasis on the exploration of continents is a major priority for the next decade* – to provide syntheses leading to the development of models for the origin of various segments of continental crust. A program of drilling for scientific information is a major new initiative, emphasizing utilization for scientific observations of holes being drilled for other purposes by government agencies and by industry.

The plate tectonics model suggests that a major global process involves the accretion and destruction of oceanic crust at subduction zones beneath island arcs or continental margins. The mechanism of destruction of crust is under debate, but one possibility involves at least partial incorporation of oceanic rocks into the deep crust or upper mantle of the overlying continent or island arc. It is further postulated that island arcs – and even fragments of continents – may migrate and become integral parts of an accreting continental mass. An understanding of the development of continental crust therefore requires a knowledge of the composition, thickness, and structure of accreted sedimentary, oceanic, and island arc rocks, and also possible accretions of continental fragments.

The tectonic and chemical evolution of oceanic crust and lithosphere is simpler than that of the continents. However, despite the apparent large-scale simplicity, the few detailed surveys yet carried out in active oceanic rifts and associated fracture zones indicate that, on a smaller scale, the oceanic crust is structurally and lithologically complex. There is evidence that oceanic crust changes in composition as it ages and migrates away from the ridges at which it is generated, and that concentrations of metals are formed within sedimentary and volcanic rocks at ocean ridges and above subduction zones. It therefore seems important to continue active geophysical and geological exploration and deep drilling to determine the composition and structure of the oceanic crust and the nature and origin of related mineral deposits. The most urgent areas for exploration are the ocean ridges, where new crust is generated, and the continental margins, where older oceanic crust merges with continental crust in an unknown way. Thick organic-rich sediments may accumulate in this marginal zone, providing conditions favorable for the generation and accumulation of oil and gas, though these conditions are as yet poorly known.

Importance of Mantle Dynamics

Crustal and mantle dynamics are not separable. New crust generated by rifting is derived from the mantle, and magmas related to subduction zones apparently derive from mantle rocks at depths as great as 250 km or more. Intraplate volcanism must also depend on mantle processes. Furthermore, it is widely believed that the plate motions are related to mantle convection. Hence, the physical and chemical dynamics of the crust are closely related to the dynamics of the mantle beneath; we need to understand the whole system. Fundamental to this understanding is a knowledge of thermal regimes within the deep crust and mantle. The localization of magma generation, rheological properties of crustal and mantle rocks, and lateral and vertical transfer of mantle material are governed largely by the thermal regime, including local perturbations.

III. International Planning

The U.S. Geodynamics Committee was established by the Geophysics Research Board for long-range planning of research on dynamics of the earth's interior and the effects on surface layers. In the 1970's, the USGC served as the U.S. national counterpart of the Inter-Union Commission on Geodynamics (ICG). The ICG, sponsored by the International Council of Scientific Unions (ICSU), was itself created at the joint request of the International Union of Geodesy and Geophysics (IUGG) and the International Union of Geological Sciences (IUGS). Activities of the ICG have been carried forward by ten working groups and a committee on World Data Centres and Data Exchange. Geodynamic investigations have thus progressed on both national and international levels.

Reports of national committees and reports published through ICG and ICSU reflect the feeling of excitement engendered in the earth sciences community by the accomplishments of programs carried forward during the 1970's. Continuity through the 1980's is essential to preserve momentum in unfinished programs and to open new initiatives suggested by advances in earth sciences and changing needs of society. In 1976, the Geophysics Research Board (GRB) requested the USGC to develop a rationale for a program of solid-earth studies to go forward in the 1980's. Such a plan was developed in a draft document under the title "Crustal Dynamics: A Framework for Resource Systems." In 1978, the GRB formally requested the U.S. Geodynamics Committee to carry forward the program in the 1980's noting that it saw no reason to change the name of the Committee. This is consistent with the belief of the USGC that the word "geodynamics" encompasses all activities envisioned in the draft document "Crustal Dynamics."

In 1977, IUGG and IUGS agreed to establish Task Groups on post-Geodynamics Project planning. The meeting in 1978 of these Task Groups led to a joint report "The Lithosphere: Frontier for the 1980s," which calls for a program whose central theme is the current state, dynamics, origin, and evolution of the lithosphere – the earth's crust and upper mantle – with special attention to the continental lithosphere. The report emphasizes the importance of strengthening interaction between basic research and applications, in particular in relation to natural resources, geological hazards, and environmental maintenance. The USGC considers that its proposed program of Geodynamics in the 1980's is completely consistent with the international planning and looks forward to collaboration in the new international program.

Many of the commissions and committees of the unions (especially IUGG, IUGS, IAU) and IUGG associations (especially IASPEI, IAVCEI, IAGA and IAG) are involved with activities closely related to geodynamics. These include the IUGG Committee on Mathematical Geophysics, IAG Commission on Recent Crustal Movements and Commission on International Coordination of Space Techniques for Geodesy and Geodynamics, IASPEI Commission on Controlled Source Seismology, Heat Flow Commission and Commission on Earthquake Prediction, IAG-IASPEI Commission on Earth Model, IAVCEI Working Groups on Volcanism and on Radiogenic Isotopes and Their Applications, IAGA Working Groups on Earth Magnetism; and IUGS commissions, committees and associations – Experimental Petrology at High Pressures and Temperatures, Marine Geology, Tectonics, COGEODATA, Geological Map of the World, and Planetology.*

Several international programs are partially or entirely related to geodynamics. For example, the IAGA-IASPEI program of Electrical Properties of the Asthenosphere (ELAS) should provide important constraints on models of the upper mantle and lower crust. Several projects of the IUGS-UNESCO International Geological Correlations Program (IGCP) are directly relevant to understanding the dynamics of the solid earth. The IAU-IUGG project of Monitoring of Earth Rotation and Intercomparison of Techniques (MERIT) has potential implications for geodynamics.

International cooperation is particularly important in geodynamics. Accordingly, the U.S. program of Geodynamics in the 1980's will include emphasis on active collaboration with scientists in many other countries – particularly in those regions in which critical problems of geodynamics can most effectively be addressed.

*and the Commission on Quantitative Geodynamics and Commission on Physical Properties of the Earth's Interior established by IASPEI, December 1979.

IV. Relation to Various Domestic Activities

During the preparation of the report *U.S. Program for the Geodynamics Project: Scope and Objectives* (issued 1973), the U.S. Geodynamics Committee reviewed the then current activities in federal agencies. The results showed that at least a dozen federal agencies had a significant level of activities pertinent to the Geodynamics Project. The activities of the National Science Foundation and the U.S. Geological Survey were found to "impinge on virtually every major category of the program as outlined by the U.S. Geodynamics Committee." During the intervening years, there have been important increases in geodynamic activities in those two agencies.

NSF programs continue to include a diversity of research activities involving the disciplines most closely associated with geodynamics – geophysics, geology, geochemistry, geodesy – and the three major geographical elements – continental dynamics (including offshore continental margins), oceanic dynamics, and the continent-ocean transition. The USGS held a workshop and prepared the report, *Dynamics of the Continental Crust,* to help coordinate existing activities within the USGS in continental tectonics and geodynamics to assist in providing assessments of the nation's mineral and energy resources and natural hazards. Moreover, major problems pertinent to geodynamics have developed in the National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration. NASA is developing a program on the application of space technology to crustal dynamics and earthquake research, and took the lead in organizing an Interagency Committee to coordinate the interests of NASA, NOAA, NSF, USGS and DMA in this program. The Department of Energy sponsors a large portion of the drilling on land whose potential contribution to geodynamics is discussed in other sections of this report, including a specific program to capitalize on those drilling activities. Strong components of geodynamic activities continue in AFGL, AFOSR, DARPA, NAVOCEANO, NRC, and ONR.

Most of the agencies concerned with problems related to geodynamics have programs dealing with both continental and oceanic areas. Recommendations in this report make clear that the USGC recognizes the importance of both continental and oceanic geodynamic problems – and the relation between them. The USGC also considers the exploration of the continents to be a major priority for the 1980's. In most of the agencies, a trend toward increased emphasis on continents (including continental margins) is already apparent. The need for such emphasis is the central theme of the report of the Geophysics Study Committee, *Continental Tectonics.* Several other boards and committees of the NAS-NRC are concerned with aspects of geodynamics; a selection of relevant reports of the Committee on Geodesy, Committee on Seismology, Ocean Sciences Board (Panel on Continental Margins), U.S. National Committee for Rock Mechanics and U.S. National Committee for Geochemistry appears in Appendix A.

During the Geodynamics Project, the U.S. Geodynamics Committee maintained working relations with nine national geoscience societies: American Association of Petroleum Geologists, American Geological Institute, American Geophysical Union, Geochemical Society, Geological Society of America, Mineralogical Society of America, Seismological Society of America, Society of Exploration Geophysicists, and Society of Economic Geologists; and the Association of American State Geologists. It is expected that the proposed continental scientific drilling program and the increased emphasis on continents will lead to a closer working relation with these and other national societies in connection with the program of Geodynamics in the 1980's.

At the outset of planning for the U.S. program for the Geodynamics Project, chairmen of geoscience departments in colleges and universities throughout the country were invited to nominate Geodynamics Project Correspondents to serve as a communications link between the department and the U.S. Geodynamics Committee. Some 175 departments have done so. It is believed by the USGC that this arrangement has provided a most useful broader base of input to the thinking of the Committee and has been helpful to the departments. The USGC therefore expects to maintain this network of Geodynamics Correspondents as a communications mechanism for Geodynamics in the 1980's.

V. Major Themes for the 1980's

Major themes as now foreseen for Geodynamics in the 1980's are encompassed in the following headings:

- Continents
- Continent-ocean boundary
- Generation of continental and oceanic crust
- Earth's interior: magma generation; thermal regimes; physical, geochemical and petrological characteristics
- Theoretical and laboratory studies
- Trends in instrumentation
- Data and information services

Continents*

Continents, continental evolution and tectonics will be a principal focus for Geodynamics in the 1980's. An increased emphasis on an understanding of the origin and development of continents is justified for basic scientific reasons and because of the relevance to societal problems of a better understanding of the platforms that provide the essentials of life to virtually all the world's population.

The plate tectonics model has had considerable success in explaining and predicting the development and tectonic behavior of the oceanic crust; it has been less successful in explaining continental tectonics. The oldest known crust in the oceans is of the order of 200 million years, the oldest continental crust in excess of 3700 million years. Thus, the record of about 95% of the earth's history can be found only on the continents. In view of the number of people affected, most important societal problems related to resources and natural hazards are continent-centered, although dependent on the dynamics of the earth as a whole. A better understanding of continental tectonics and

*As used in this document, continents include offshore shelves, to the zone where continental and oceanic crusts adjoin. The ocean basins are those areas beyond the continental shelves and underlain by oceanic crust.

crustal evolution would greatly assist scientists and engineers in coping with these problems. One of the principal priorities for the 1980's will be development of a strategy for intensive study of continental dynamics. A major effort to understand the continents has been strongly recommended in the report of the Geophysics Study Committee, *Continental Tectonics*. One important new element in the study of the continents is the proposed continental scientific drilling program. The preparation of topical and regional syntheses of basic geologic and geophysical data will also continue to be of major importance, suggesting greater reliance on well planned team research and exploration.

Continent-Ocean Boundary

The continental margins are now the least explored and least understood areas of the earth's crust. A second major priority of the U.S. Geodynamics Committee is, therefore, to develop plans for research operations bridging the gap between the conduct of geological and geophysical exploration on land, and corresponding exploration on the continental margins beneath the oceans. A similar hiatus exists for drilling. Deep-drilling practices are well developed on land and on shallow continental shelves, but these methods have not been extended to drilling in the deep water and thick sediments of the continental slope and rise. Additional difficulties arise because different communities of scientists – involving different institutions and different sources of support – work on land and on the oceans. Because the techniques and instruments used also are different, the resulting data differ in format and quality, thus creating an artificial barrier between the dry land and marine parts of modern margins.

Plate tectonics models predict that the join between continental and oceanic crust will be one of three kinds: convergent (or "active"), divergent (or "passive"), or transform (strike-slip). Convergent ocean-continent margins are related to generation of new continental crust. Processes such as island arc volcanism, accretion of oceanic or continental material as a consequence of subduction, and obduction of exotic rocks on to continental crust are responsible for much of the increase in continental volume. So-called passive, or divergent, continental margins are thought to hold the record of the series of tectonic, volcanic and sedimentologic events accompanying the rifting apart of an earlier continental mass. Volcanic extrusions, coarse clastic sediments, evaporites, and ore deposits may form during rifting. As the crust moves away from the rift, it cools, subsides, and becomes the locus of deposition for thick continent-derived and oceanic sediments, which are in part rich in organic matter. The complex interrelationship of faulted continental basement, evaporites, clastic and carbonate reservoir rocks, and organic-rich source beds control the generation and localization of oil and gas, and possibly also certain types of zinc, lead, and copper ore deposits. Transform margins, of which the San Andreas fault system is an example, commonly occur in conjunction with either convergent or divergent margins. This type of margin characteristically coincides with belts of destructive earthquakes. With a knowledge of the details of origin and development of the three types of margins, earth scientists will be better able to predict the distribution of mineral resources and of earthquake hazards in continental margin environments.

Techniques for geophysical exploration and deep drilling required for operations on the continental slope and rise probably fall within the range of existing technologies, although larger drilling ships will be needed as deeper water and thicker sediments are encountered. Extensive planning will be required to mount a joint attack by marine and continental geophysical, geological, and drilling programs to determine how continental and oceanic crust are joined across both active (converging) and passive (old rift) margins.

Generation of Continental and Oceanic Crust

The processes involved in generation of the earth's crust, i.e., the rocks above the Mohorovicic discontinuity, as well as the genesis and age of the Moho itself, are only partially understood, and therefore are an important area of investigation for an ongoing program in geodynamics. Gross differences in the chemical and physical nature of continental and oceanic crust have long been recognized. The hypsometric diagram for the earth shows two maxima, one slightly above sea level, representing the continents, and one averaging about 4 km below sea level, representing the deep ocean basins. The concept of isostasy suggests that, on the average, rocks of the ocean crust are denser than those making up the continents. Petrological data bear out this generalization.

Oceanic Crust

The ocean basins seem, for the most part, to have been formed by a one-cycle process, beginning with the addition of new mafic igneous rock at spreading ridges. Dredging, drilling, and observations from submersibles reveal the presence of diabase, gabbro, and, very locally, serpentinite, below the ubiquitous basalt layer. "Average" oceanic crust is believed to resemble the thick ophiolite sheets, having a crudely layered structure in the order (top to bottom): basalt-diabase-gabbro-peridotite/serpentinite. If ophiolites are indeed typical of oceanic crust, the mafic components and layered ultramafics commonly beneath gabbro in ophiolite sheets are related to mafic magmas differentiating in chambers near the base of the crust. Periodites beneath the layered ultramafics of ophiolite bodies are strongly tectonized; some evidence indicates that the mafic magmas which presumably originated by partial melting of mantle rocks were not derived from the tectonized peridotite on which they now rest.

Three-dimensional and temporal investigations along ocean ridges will refine knowledge of how crustal rock forms, how elements migrate in the crust, how heat is brought from the earth's interior and dispersed at higher levels, how hydrothermal systems are driven, and how initial structure is imprinted on vast areas of the ocean lithosphere. Studies of the ridge flanks should test models for cooling, aging, and hydrothermal effects in oceanic crustal rocks.

Continental Crust

Unlike oceanic crust, continental crust for the most part represents multicycle processes, perhaps beginning with addition of oceanic igneous and sedimentary rocks to continental margins in subduction zones, as observed in young orogenic belts. Older segments of continental crust commonly show two or more orogenic-magmatic events, resulting in extremely complex structures. Large-scale transposition and rotation of crustal blocks are also indicated. In some cases adjacent blocks of continental crust may have been generated far apart. Criteria for recognizing such inferred complex histories are currently being established.

Following initial formation of continental crust in an orogenic belt, and subsequent uplift, erosion begins to cut deeply, and eventually the crust should be reduced to near sea level. However, in many continents, including segments of North America, large areas of ancient continental crust have been uplifted a thousand meters or more in Neogene time as broad plateaus. Some plateau areas are characterized by outpourings of igneous rock, most commonly basalt. It appears that relatively light material may be added to continental crust at the base, top, and probably internally by mechanisms unrelated to orogeny. Broad areas of subsided continental crust also occur, as for example in the Michigan, Illinois, and Williston basins. Subsidence apparently occurred intermittently and at varying rates over hundreds of millions of years. Such long continuing vertical movements may reflect changes in the thermal regime beneath a continent, but again the processes involved are obscure.

Earth's Interior

The discovery that some 70 percent of the earth's surface is underlain by basaltic and gabbroic rocks less than 200 million years old implies that enormous volumes of mafic magma have been and are being derived from sources within the earth's mantle. If, as now seems probable, tectonic conditions similar to those of the last 200 million years have persisted for at least 2.5 billion years, then very significant changes in the composition of the mantle must have occurred. The plate tectonics model further requires that mafic oceanic crust disappear at approximately the same rate that new crust is formed at ocean ridges. The disappearance seems to be accomplished by subduction of the mafic crust into the upper mantle. The fate of the subducted slabs is a matter of controversy, but in some manner they must be largely reincorporated into the mantle.

Mantle Origin of Basaltic Magmas—Isotopic Studies

In the past, the basaltic nature of volcanic rocks exposed on many oceanic islands and dredged from the sea floor was taken as evidence for a common magma source within a mantle of essentially constant composition. However, with increasing numbers of analyses, it became apparent that significant chemical differences exist between basalts in mid-ocean islands such as the Hawaiian chain, islands such as Iceland along oceanic ridges, and most basalts dredged along the ridges. It has been suggested that igneous rocks making up the mid-ocean islands were related to deep mantle plumes and that those composing most of the mid-ocean ridges have a shallower source, presumably within the asthenosphere. With this concept, differences could still be interpreted in terms of essentially worldwide homogeneity within the mantle.

In the past few years, however, investigations of isotopic variations within chemically similar igneous rocks suggest a much more complex history. The study of various isotope systems, initially $^{87}Sr/^{86}Sr$, Rb/Sr, and the lead isotopes, and more recently, Sm/Nd, indicate significant local differences in the composition of mantle host rocks giving rise to oceanic basalts. For example, $^{87}Sr/^{86}Sr$ ratios of basalts from the mid-Atlantic ridge between 66°N and 29°N show a considerable variation. "Hot spots" such as Iceland and the Azores have unusually high ratios, but equally high ratios were found at 45°N and 35°N along the ridge, and an area of low ratio at 50°N.

The isotopic ratios are compatible with Precambrian source rocks; one school of investigators proposes that there was a discrete episode of mantle differentiation about 1.6 billion years ago, accounting for much of the deduced mantle variation. Alternatively, these data are consistent with essentially continuous, or episodic differentiation. If indeed vast quantities of oceanic crust are absorbed into the upper mantle, as the plate tectonics hypothesis would suggest, then the time-integrated model is perhaps more attractive. In any case the continued exploitation of isotopic data should be vigorously pursued. It would appear that these kinds of data may produce evidence bearing on the circulation of mantle materials through time, and hence of possible mechanisms related to driving the plates. In this context the stable isotopes of helium and the rare earth isotopes samarium and neodymium are extremely promising as tracers for attacking fundamental geodynamic problems such as the origin of igneous rocks and the evolution of mantle and lower crust. The usefulness of the samarium-neodymium system in dating ancient rocks has also been demonstrated. Because of geochemical similarity of these two elements, the system should be unusually resistant to alteration by metamorphism or weathering.

Thermal Regimes and Physical Characteristics

Investigations of physical characteristics, thermal structure, and thermal evolution of the earth's interior together will be an important focus for Geodynamics in the 1980's. The earth is a dynamic planet; internal forces deform and transport material in its crust, mantle and core, generating phenomena of significant concern to its surface inhabitants – earthquakes, volcanism, and the magnetic field. Yet little is known about the state of stress within the earth's interior. Clearly temperature is a critical physical variable, the description of which is essential to our understanding of all these processes. Despite recent advances in various aspects of geodynamics, relatively little is known about the thermal field deep within the earth, and even less about its evolution with time.

Large differences in heat flow are commonly observed in orogenically active, as contrasted to stable, portions of the crust. High heat flow in orogenic areas is commonly associated with the emplacement of magmas into the crust. Apparently much of the heat at the surface is transported upward by molten rock, but fundamental processes resulting in generation of magma are poorly understood. The injection of magma into the crust, and, in some cases the extrusion of large volumes of igneous material are important processes in the generation of continental crust. In addition, the movement of hydrothermal solutions is a major factor in the transport of heat and in the generation of several kinds of mineral deposits. An understanding of the thermal regimes involved is therefore of first order importance.

The earth can be described as a heat engine. Temperature differentials of large but poorly determined magnitude and gradient exist within the earth's deep interior and lower crust. Density differences resulting from these temperature gradients and from compositional differences result in mass movements of hot material upward, both as magmas at relatively shallow depths (down to about 200 km) and probably also as convecting mantle and core material.

Clearly important parameters controlling such movements, and hence the fundamental parameters for the construction of viable models, are the temperature distribution and the state and amounts of water in deep-seated rocks. If these can be determined, and if rheological characteristics can also be estimated, flow and stress fields can be calculated.

Research in process on many fronts promises to expand very rapidly our knowledge of temperature distribution within the earth. For the crust and upper mantle, measurement of heat flow remains an important source of temperature extrapolation to depth, but other powerful tools are developing, such as: quantitative geothermometry and geobarometry determined on minerals of xenoliths and lavas of deep seated origin; physical and chemical laboratory experiments with melting relationships and magma formation; temperature-related effects of electrical conductivity in rocks at depth; and aircraft and satellite magnetic surveys to determine depth to Curie temperatures.

Research on possible physical mechanisms for the attenuation of seismic energy, both at shallow and great depths in the mantle, is expanding; several competing models are being explored, as well as investigations on the role of stresses and temperatures in the earth's interior in influencing attenuation. Recent improvements in the capability to derive theoretical seismograms for spherical earth models with complex variation of elastic properties offer the hope that the influences of small changes such as radial velocity or density gradients can be discerned on actual seismograms; the diagnostic capability of seismograms has heretofore been largely limited to the identification of large scale discontinuities in earth structure. These new studies hold out the promise that information can be derived regarding temperatures and changes and physical properties that are required for modeling convective motions within the mantle, and perhaps also within the earth's core. The 1980's should also see a continuing bold attack on the problems of seismic wave propagation through three-dimensional distributions of inhomogeneities within the earth by both analytic and synthetic methods.

Rheological properties, incipient melting, seismic attenuation, and electrical conductivity are all thermally activated processes that are also sensitive to water content, but the activation energies are usually different for each process. Electromagnetic sounding methods can penetrate seismic low-velocity layers from which seismic energy tends to be excluded. For these reasons, the extension of electrical methods as a supplement to seismic measurements in the upper mantle promises to increase the constraints on possible earth models.

From the diversity of techniques and objectives of the various experimenters, it is clear that future progress in thermal and rheological studies requires interdisciplinary cooperation and, furthermore, that continued vigorous investigations promise to yield large dividends for nearly all branches of geology, geochemistry, and geophysics. We therefore regard the investigation of thermal and physical regimes within the earth as high priority for Geodynamics in the 1980's.

Theoretical and Laboratory Studies

Inferences drawn from incomplete and imperfect data play an essential role in the methodology of the geological sciences. The primary "experiments" from which knowledge of the earth is derived are provided by nature, with many important parameters likely to be varying simultaneously in uncontrolled and unknown ways. Interpretation of field data in earth science is heavily dependent on conclusions drawn from applications of the basic sciences of chemistry, physics, and biology to the study of the component elements of the earth system. The program for the 1980's will require new and imaginative theoretical and laboratory programs to provide an improved foundation for the formulation of new hypotheses.

Experimental and theoretical studies of the behavior of rocks and minerals at elevated temperatures and pressures and the relationship of these properties to large-scale dynamic processes in the earth's interior have led to significant advances during the last decade. Examples are increased understanding of the mechanism of earthquakes, of the genesis of volcanic magmas, of polymorphic phase transformations and melting phenomena in solids, and of rheological behavior of minerals. Studies in the mineral physics of mantle materials should be encouraged as part of this new program, because crustal and mantle dynamics are not separable problems. Indeed, the unravelling of the history and dynamics of the continental and oceanic crusts will depend critically on an improved understanding of deeper processes.

The dependence of the physical properties of rocks on temperature, volatile content, and stress (both hydrostatic pressure and deviatoric stress) is a critical factor in the interpretation of surface observations related to structures, composition and processes in the earth. If adequate accuracy of calibration can be established, techniques now available will make possible the extension of laboratory observations of rock properties to pressures corresponding to great depths in the earth and important new data on the equation of state of mantle-like materials will be forthcoming.

Deformation of rocks by flow and fracture plays an essential role in the evolution of the lithosphere. Some factors that influence the rheology and strength of rocks have been studied in laboratory experiments. Extension of these studies to higher temperatures and pressures, with added emphasis on the relation of the rheological properties to other physical properties, will aid the interpretation of field observations of deformed rocks.

The relative motion of lithospheric plates must be accompanied by flow of mantle material. The exact nature and extent of this flow remains one of the principal unsolved problems of geophysics. There is now substantial evidence that mantle-wide convective circulation occurs; thus the underlying flow regimes driving the plate motions are not necessarily shallow. Material properties and processes at pressures up to 130 GPa (mantle-core boundary) may therefore be relevant to surface processes. As yet we do not have the capability to obtain appropriate rheological information on mantle materials at core-mantle boundary conditions because of the requirement for the development of large volume apparatus to conduct experiments at these high pressures and temperatures.

Analysis of the dynamics of the crust or mantle involves consideration of rate-dependent processes. The few experimental results taken on olivine constitute most of our meager knowledge of rate-dependent processes in minerals and rocks. This is an inadequate base for analysis. Numerous variables – such as temperature, grain size, volatile content, tensorial stress and its gradients, crystal class and dislocation density – control rate-dependent processes; these variables are not well understood. With the information presently available we are not able to distinguish among the various kinds of rate-dependent processes that may be at work in crustal motion; extrapolation with confidence to a geological time scale is not yet possible.

Experimental petrology and geochemistry have provided basic knowledge of the physics and chemistry of mineral and rock formation. Special emphasis should now be placed on the study of the kinetics of chemical reactions pertinent to processes occurring in the lithosphere. Metastable high temperature and high-pressure phases of minerals will then be useful in deciphering the history of the rocks.

To understand the dynamics of the crust, a knowledge of the thermodynamics of the subducting slab is required. At present, however, the amount of melting, if any, the effect of volatiles, and the chemical reactions in the neighborhood of the slab are still unknown. Models of the interaction of the crust and the mantle must be consistent with studies of crustal metamorphic rocks. Studies on glaucophane schists, eclogites, and pyrope peridotites will continue to be important elements in attempts to construct geotherms and to correlate volcanic events of the past with horizontal and vertical plate motions.

Better mathematical models of other processes within continuous media, including nonlinear deformation, fracture, and fluid migration, and the analysis of the models by finite-difference or finite-element techniques will contribute to the achievement of the objectives of the program. Problems ranging from the causes of concentration of minerals in ore deposits to the mechanics of geothermal reservoirs to rupture during an earthquake require such analyses. If the modeling is to be realistic, close coordination between the theorists and those engaged in interpreting field data will be required.

Theoretical solid-state physics and physical chemistry have much to contribute to the solution of the problems to be addressed under this program. Theoretical equations of state applicable from crust to core would be of enormous value in extrapolating laboratory and surface geological data to the deep interior. Improvements in theory relating variability of rock properties with temperature, water content, and stress are also needed. The increased participation of theoretical physicists and chemists in geologically related research will be most helpful.

A theory relating temperature to measurable parameters of the earth, i.e., the equation of state for high temperatures and high pressure, is urgently required. Both theoretical and experimental approaches are needed to obtain reliable functional equations.

Although physically isolated from surface processes, the nature of the core and heat transport within and from it are inextricably tied to theories of the magnetic field and the chemical and thermal evolution of the earth. Many other regions and properties also influence the dynamic processes in the mantle and overlying crust – including the lithospheric boundary layer, the zone of major phase transformations, and viscosity variations with depth. Hence, the physical and chemical dynamics of the crust are intimately connected to the earth's deep interior.

Flow at the crust-mantle boundary is flow at high pressure; there are critical questions to be answered in the related theoretical mechanics. The pressure dependence of parameters related to rheology, thermal expansion, and thermal and electrical conductivity is not well understood.

Trends in Instrumentation

Advances in the study of the earth are critically dependent on instrumentation. This relation is stressed in virtually all the reports of the various committees and groups concerned with aspects of research relating to geodynamics and was the principal subject of one report, *The Impact of Technology on Geophysics.* That study addressed all the various major areas of geophysics – upper atmosphere, atmosphere, oceans, fresh water and solid earth. Its conclusions are demonstrably applicable to geodynamics. Technology affects geodynamic research in four main ways: instrumentation; transportation (the ability to make observations at diverse places on, above, and below the surface of the earth and ocean); communication; and computation. In all four aspects, geodynamics makes use of technology and instrumental development, much of which was motivated by research not related to geodynamics. For example, the development of microscopy and x-ray fluorescence spectroscopy together allowed the development of the electron microprobe, which made possible rapid, nondestructive analyses of minute volumes of rocks and minerals. This instrument assisted petrologists and geochemists to trace much more accurately the evolutionary history of igneous and metamorphic rocks and to deduce therefrom practical information on phenomena such as the life history of active volcanoes, the maximum depth and temperature experienced by exhumed rock bodies, and the origins of mineral deposits. Another example is the development of methods of determining precise position and differences of position on the surface of the earth: laser ranging to retroreflectors on the moon and on artificial satellites, very-long-baseline interferometry, and geodetic positioning satellites. These techniques hold promise of making it possible to determine positions on the earth with an accuracy of a few centimeters, thus bringing within reach the direct measurement of relative motion across plate boundaries. Ultimately, perhaps, as the state of the art improves, it may be possible to develop an essentially complete picture of strain within the earth's crust on which rigorous dynamic analysis could be based.

Instruments Considered in Three Categories

Instruments or techniques under development, or being planned, that will make possible better determination of geodynamic phenomena. The next generation of instruments beyond the electron microprobe, now under development and testing, includes instruments such as the ion microprobe and laser microprobe in which a finely focused beam ionizes the surface of a specimen, the ions then being analyzed by mass spectrometric techniques. In volcanology, geochemistry, and petrology, the development of synchrotron radiation techniques holds promise of revolutionizing these areas as x rays revolutionized the study of minerals 60 years ago. With synchrotron radiation, the potential exists to observe the breaking of molecular bonds during a chemical reaction, possibly even during structural rearrangement at high pressures. The development of the diamond-cell, high pressure apparatus is now making possible the observation of mineral properties at pressures and temperatures characteristic of the lower mantle, though the accuracy of pressure calibration is still in question.

In another broad area, a group of new and developing artificial satellites promises rapid improvement in our capability to carry out remote sensing. These techniques have the ability to provide a regional view of continental structures; they have been particularly useful in permitting recognition of certain lineaments that are difficult to identify from ground-based observation. New multispectral sensors have the potential for providing lithological and structural information in broad areas of the earth that are poorly known at present. Specific observations which may lead to substantial improvements in our knowledge of continental structure and evolution include measurement of the earth's magnetic and gravity fields and precise determination of locations and rates of change of locations, both vertical and horizontal, on the earth's surface. Data from the latter may ultimately permit direct measurement of relative plate motions and of slow vertical movements within the plates.

Portable gravimeters are now being developed that are capable of measuring the absolute value of gravity at a single point; this is a great improvement over present instruments that measure the change in gravity from one point to another. This capability will be useful for both tectonophysics and geodesy. For example, small changes in gravity, measured with a portable absolute gravimeter, may provide important precursory information for the prediction of earthquakes and volcanic eruptions. In a related area, sea surface topography obtained from GEOS III and SEASAT altimeters has provided a much more accurate geoid reference surfaçe over the oceans.

The development of superconducting magnetometers capable of detecting individual quantum jumps in magnetic fields will find important application in the study of paleomagnetism and paleomagnetic stratigraphy.

Instruments that have been developed but are not generally available to the scientific community. The narrow beam multibeam sonar for detecting detailed submarine topography, together with multichannel seismic techniques, will increase knowledge of the structure of critical oceanic areas. The continued development of "intelligent" instruments – those capable of recognizing and recording only the information desired – will bring about a greatly increased capability to explore the nature of the ocean crust and mantle and details of behavior in earthquake-prone areas. Such instruments include ocean bottom seismographs, which can be dropped and left in place for some months and which will automatically recognize and record earthquake data. On signal they float to the surface for recovery. More sophisticated ocean bottom observatories are being designed.

Drilling for scientific purposes permits direct measurement and sampling at otherwise inaccessible depths. It also involves a diversity of downhole instrumentation. Potential applications of drilling on land and at sea are calling for drilling technology and instrumental capability exceeding the current state of the art.

Because of the expense, drilling on land for scientific purposes has been largely restricted to relatively shallow holes. Several thousand wells are drilled annually in exploration for petroleum and natural gas; an increasing amount of drilling on land is also being conducted by federal agencies for specific mission purposes. The report *Continental Scientific Drilling Program* proposes a national effort to obtain greater scientific return from this large amount of drilling. The plan calls for add-on experiments, including maintenance and instrumentation of certain holes as scientific observatories. The plan also calls for drilling (both shallow and deep holes) to solve specific scientific problems.

The solutions to some important problems require drilling to great depths or into geothermal and magmatic regions. High temperatures cause problems for both drilling and associated instrumental measurements. Development of miniaturized instruments reliable to temperatures on the order of 500°C will be needed for these studies.

In the oceans, including the offshore continental margins, the solution of technical problems related to drilling deep into the earth in great water depths will allow exploration of large areas in both active and passive continental margins. It will be necessary to engineer and install blowout preventers, and also risers to permit circulation of heavy mud for drilling in thick sediments beneath deep water. A ship would have to be constructed or modified to meet the weight and stability requirements for this kind of operation.

Space technology has opened the way to study the geology and geophysical characteristics of the moon, planets, and their satellites. The ability to send space probes and even men to make measurements and to return samples to earth for laboratory analysis has expanded geoscience from the investigation of only one body – the earth – to a comparative science encompassing the study of all the planets in the solar system, their satellites, the asteroids, and comets. From such studies a much better view of the origin of the solar system and of the earth itself is emerging.

Finally, problems relating to archiving and retrieval of many kinds of geodynamic data indicate the importance of the development of micro-volume long-life methods for archiving experimental and analytical data.

Instruments that are obsolescent or worn out and need to be replaced, modernized or upgraded. Many of the scientific facilities at universities and some governmental laboratories are in need of being replaced or modernized. The state of art in instrumentation, as it exists in industry and some foreign universities, is often far ahead of that in U.S. academic and government laboratories. For example, the improved resolution of analysis made possible by the new generation of digital instruments (laser Raman spectroscopy, high-performance liquid chromatography, differential polarography), and by microprocessers for older instruments is yet to become widely available to the earth sciences.

Both teaching and research are increasingly hampered by outmoded and often decrepit facilities and instruments. Ultimately, the cumulative effects of poor tools and poor working environment will be evident in the quality of science accomplished and of scientists being trained. Modernization of scientific instrumentation and facilities should be given high priority in planning for Geodynamics in the 1980's.

Data and Information Problems and Services

Even as new instrumentation is bringing unique data sets to bear on research problems, new data processing technology and concepts are revolutionizing the operation of data exchanging and services.

The rapid conversion to digital recording in many fields and the technology to handle the resulting vast data files create important opportunities for research and needs for new types of data service. Because the processing of these data bases require sophisticated hardware and software as well as expertise, there is a growing need for facilities that can combine these into "data utilization centers."

Recent experimental workshops have pioneered in the team approach to using multidisciplinary, digital data bases for special problems with specific objectives. Technology permits the on-line, remote accessing and transfer of data and the ability to examine – interactively and graphically – massive data bases in ways that were not previously feasible.

The growing sophistication of data requirements emphasizes the need for comprehensive data management planning prior to undertaking large data-gathering projects. Good planning assures that data are collected in a form useful to secondary as well as primary users, that the data will be compatible with those already collected, and that the distribution system meets the needs of the users.

In areas of fast program development, communications of planned experiments, workshops, symposia, quick-look results, and data availability are being announced through monthly and quarterly newsletters. Exchange of inventories among data centers and referral services is often a practical alternative to developing central all-inclusive facilities.

A different kind of problem is the collection and organization of vast quantities of numerical data which exist in the scientific literature, including chemical analyses of rocks and minerals, data on the characteristics of sedimentary rocks, faunal lists, and radiometric age determinations. A start is being made in collecting this type of data, an example being the Radiometric Age Data Bank, recently organized by the U.S. Geological Survey in Denver, which now has completely encoded known published data for Wyoming, Minnesota, Wisconsin, Michigan, Nevada, and the six New England states, and partially for other states. It is hoped that these data will soon be available through the National Geophysical and Solar Terrestrial Data Center. Relatively ready accessibility of data has already resulted in important regional studies, for example, the extent of Proterozoic metamorphism of Archean rocks of Wyoming.

Despite the rapid growth in digital data there remain classes of data that are available primarily in traditional hard copy forms such as maps, photographs and graphs. Data centers will continue to serve needs for data in these forms and should help in the integration of these forms with digital data and the education of users of analog data in modern digital technology.

Data centers provide a natural link between researchers concerned with basic scientific problems and the applied research community. Many of the studies of crustal structure, origins, and movements are directly applicable to mineral resources exploration and natural hazards mitigation; data service centers are convenient sources for these data for both uses.

Data center activities are becoming increasingly important to scientific enterprises, as reflected in numerous national and international committees and working groups. These include CODATA, COGEODATA, ICSU Panel on World Data Centres, and several committees in the National Research Council.

VI. Implementation

Using as a guide the overall objectives for the coming decade, the USGC assessed current activities and programs and recommended ongoing or modified objectives. This section follows the approach adopted by the USGC in the chapter "Initial Priorities" in the report *U.S. Program for the Geodynamics Project: Scope and Objectives* (1973). [See Appendix B.] The sequence has no significance with respect to relative priorities.

Plate Boundaries—Continent-Ocean Transition

As an outgrowth of discussions by an *ad hoc* working group, this topic evolved into a synthesis of existing knowledge bearing on ancient and modern plate boundaries in North America. Because the Appalachian area was being studied by Working Group 9 of the Inter-Union Commission on Geodynamics, the Alaskan and Western margins of North America and the Ouachita-Marathon orogenic system were selected for special consideration. A series of 23 cross sections of these ancient and modern orogenic systems is now in preparation for publication by the Geological Society of America.

A major activity now getting under way is a series of transects across continental-ocean transitions, designed to explore the phenomena associated with the contact zone between oceanic and continental crust. Planning groups are being organized to select corridors along which three-dimensional transects—maps and profiles of geophysical and geological information—will be prepared. The objective of this group of transects is twofold: (1) an assessment of the state of understanding of the structure and history of the transitional regions of North America between typical cratonal and oceanic lithosphere; (2) identification of the major problems and corresponding recommendations regarding the most promising research to solve those problems. These transects will make use of all available geological and geophysical information—both surface and subsurface—in the selected corridors. Special attention will be focused on melding data taken on land and data obtained offshore. The results of these transects are expected to provide guidance for future geological and geophysical investigations, including site selection for drill holes to resolve particularly significant problems. It is currently foreseen that some 15-20 such continent-ocean transects will be undertaken on the east and west coasts of North America including transects undertaken by Canadian and Mexican groups. The Canadian, Mexican and U.S. transect groups have agreed that there should be coordination of the work of the groups; in effect, this is a program of North American continent-ocean geodynamic transects.

Plate Interiors

Because the exploration of the oceans has been pursued vigorously by the marine geology and geophysics community, "plate interiors" activities within the USGC focused essentially on "continental interiors." Studies of continental interiors are complicated by the diversity of the scientific community involved and by the complexity of the subject–a thicker crust and less well defined lithosphere, a greater variety of structures and rock types, and a much greater age span of the rocks.

Preliminary deep-reflection seismic work was carried out in the Michigan basin by COCORP, and a deep drill hole in the center of the basin was instrumental in an attempt to understand the mechanism of basin formation, characterized by slow, localized, crustal subsidence over very long periods of geological time. Similar cryptic vertical motions affect continental areas worldwide. Crustal strain measurements and earthquakes indicate that continental interiors are also subjected to significant horizontal differential stresses of unknown magnitude and origin. Studies of both vertical and horizontal strains should be actively pursued.

Accretion of oceanic crust and sediments to continental margins and extensive volcanic and plutonic phenomena along youthful orogenic belts are mechanisms active in the evolution of modern continents. However, the most ancient crystalline rocks of the crust seem to differ significantly from these younger accreted masses, and it is uncertain whether the pattern of rigid plate interaction we now envision was active during the first half of earth history. Furthermore, the drifting apart of continental fragments and subsequent reassembly in different patterns, as is now strongly indicated, implies another mechanism for crustal accretion. In an intensive study of continental interiors, therefore, it will be necessary to identify and quantify forces currently acting and, also, to dissect the various component blocks and fragments to analyze the evolution of the North American continent through time. For this purpose, synoptic geological and geophysical mapping will be required to define the composition, age, tectonic history, and latitudinal movement (defined by paleomagnetic, paleontological and isotopic studies) of units within the crust, and also the nature of recent and ongoing deformation. Although areas affected by older orogenic, plutonic, and metamorphic events pose difficult problems, the determination of evolutionary history now seems feasible.

Early in the ongoing program, interdisciplinary studies should be initiated of corridors containing both currently active continental margins and possible ancient analogues. Appalachian profiles may contain as many as three collisions as well as the inferred Grenville suture (New York-Alabama lineament). Ouachita-Gulf Coast profiles cross several tectonic elements of collision, transform, and rifted margins. Cordilleran profiles contain complex assemblages of tectonic elements that have yet to be stabilized into a cratonic element.

Within the craton, major collision borders of different ages, rift and possible aulacogen elements, and mixed rift, collision, transform elements have been recognized and should be the focus of studies to identify their characteristic elements and history.

Fine Structure of Continental Crust and Upper Mantle

Deep-reflection studies of the crust and upper mantle, using seismic techniques developed for petroleum exploration, have been carried out by the COCORP (Consortium for Continental Reflection Profiling) for four years. This activity has opened the way to a new understanding of the extension to depth of complex geological structures observed near the surface. A program of deep-reflection studies should be continued in the 1980's. These studies are expected to play an important role in connection with the proposed continental scientific drilling and continental margins programs. The value of the combination of deep reflection and drilling investigations in the same region has already been demonstrated in the Michigan basin. The recommendations in *Continental Scientific Drilling Program* specifically stipulate that deep-reflection (and other geophysical and geological) studies should precede selection of sites for dedicated deep drill holes. These studies should be broadened to include interval velocity determinations within the lower crust and upper mantle. Refraction, wide angle reflection, and ray tracing studies in Europe and the Soviet Union indicate the presence of extensive low-velocity layers in the deep continental crust and upper mantle. If confirmed, the existence of such layers would have wide implications concerning the origin and tectonic behavior of continental crust.

Crustal Strain and Crustal Movements

Earthquakes and related adjustments along faults attest to the presence and heterogeneity of strain, and therefore of stress, within the crust. *In situ* strain measurements and interpretation of stress pattern by focal plane analysis of earthquake data are standard procedure now in many earthquake-prone regions. Such measurements provide a basis for localizing areas where strain is increasing and where earthquakes may be anticipated.

Regional reconnaissance maps showing strain – and inferred stress – in crustal rocks have been prepared also for some areas such as the central and eastern United States, where large earthquakes are rare or unknown. However, these maps clearly indicate that the "stable" continental crust is nearly everywhere elastically strained. The orientations of inferred stress fields differ among the various regions.

Interplate boundaries marked by rapid changes in stress, such as the San Andreas fault system, are being intensively studied as a part of the program on earthquake prediction. The study of crustal strain in intraplate areas is still in a primitive state, however. Such studies should be strongly encouraged to provide a comprehensive view of existing crustal strain throughout the North American continent.

One of the exciting possibilities for Geodynamics in the 1980's is the development of techniques – laser ranging, long-baseline-interferometry, and satellite positioning systems – that will permit precise determination of positions from which rates and directions of relative plate motions can be calculated. Results of such direct measurements would provide key data to test many aspects of the plate-tectonics hypothesis which to date have been based mostly on indirect evidence. From these measurements, it should also be possible to identify areas of build-up of local strain (that may be a prelude to earthquakes).

It is expected that several years will be required before results applicable to geodynamics can be obtained. If these results are successful, direct determination of current relative plate motions will certainly constitute a major contribution to Geodynamics in the 1980's.

Evolution of Oceanic Lithosphere

Plans and priorities for ocean exploration have been considered in great detail in reports by JOI and JOIDES panels and working groups; therefore this topic is not extensively reviewed here. Nevertheless, gaining an understanding of the origin and evolution of the oceanic lithosphere is a major objective of the program of Geodynamics in the 1980's. Studies of the evolution of oceanic lithosphere are related to the new priority studies on continent-ocean crustal transition and origin of continental and oceanic crust, as discussed earlier. Attention should be directed primarily toward the oceanic ridges and continental margins. It is along the ridges that ocean crust and lithosphere are generated and along the active margins that continental crust is currently being formed; both are probable sites of ore formation.

With respect to the sedimentary component of the oceanic lithosphere, the age and rate of deposition can now be determined by analysis of the intermediate daughter isotopes of the uranium decay series. A related method similar in principle utilizes the decay of unsupported uranium-234 to date coral and other marine carbonates. These methods are still under development, but are already providing important data about Pleistocene climatic history. Notable among the accomplishments are the dating of high sea-level stands, correlation of drastic changes of the rate of deep-ocean sedimentation with the growth and decline of continental ice sheets, and estimates of the puzzlingly slow rate of accretion of manganese nodules, a potential economic resource.

In regions of thin sediment cover, it is now possible to use controlled source electrical methods to provide information on the depth of water penetration and alteration of rocks throughout the crust. Natural source electromagnetic methods are now able to provide profiles of electrical conductivity completely through the lower lithosphere, thereby providing data to evaluate the evolution of the lithosphere as an aging thermal boundary layer.

Drilling for Scientific Purposes

Continental

Exploration of the continents, a high-priority goal for the 1980's, will require knowledge of the character, and changes in character, of geological, geochemical and geophysical properties with depth. In those parts of the country that have been extensively explored for oil and gas, depth control has been provided by many thousands of deep holes. However, there are many parts of the country, especially those areas underlain by ancient crystalline rocks, in which there are few deep holes. Indeed, the nature of crystalline basement underlying even the well explored sedimentary basins is poorly known. Geophysical methods, especially reflection and refraction seismology, gravity, and magnetics, provide clues to the third dimension, but positive identification of rock types and determination of critical relationships can be made only by drilling. Such drilling not only provides a knowledge of the geology immediately adjacent to the hole but also allows extension of that geology by geophysical means.

In 1974, a workshop on continental drilling for scientific purposes led to a report, *Continental Drilling,* addressing the important scientific problems that could be attacked by drilling. Three are judged to be of special importance: the mechanism of faulting and earthquakes; hydrothermal systems and active magma chambers; and the state and structure of the continental crust, including heat flow and thermal structure, ambient stress, and origin of the crystalline continental crust. The report recommended a systematic program of scientific drilling on land, including both shallow and deep holes. The U.S. Geodynamics Committee strongly endorsed the scientific objectives set forth in that report.

In 1978 it was recognized that a substantial amount of drilling was being done by various federal agencies for mission objectives. This recognition led to a second workshop. Between the two workshops the focus changed from one of initiating scientific drilling to one of maximizing the scientific value of current and planned drilling efforts of federal agencies and industry and supplementing these efforts with holes drilled solely for scientific purposes. The results of the second workshop were published in the report, *Continental Scientific Drilling Program*, issued by the U.S. Geodynamics Committee in 1979. The principal recommendation of that report was:

> *"The convergence of current basic scientific interests with the rapidly growing efforts of federal agencies to acquire, by drilling, the data needed for the missions that our society has given them; the need for an involved and well-informed scientific community to supply advice and interpretations; the need to maximize the effectiveness of research efforts based on an expensive tool; and the need for technological innovations to achieve program objectives – all these call for a mechanism to provide a central focus for continental scientific drilling and for communication and cooperation.*
>
> "The U.S. Geodynamics Committee makes the following principal recommendation, that *a Continental Scientific Drilling Program be initiated to achieve expanded knowledge and understanding of the uppermost part of the crust of the earth in the United States for the objectives outlined in this report. This program would provide a central focus for the scientific aspects of federal drilling activities and a mechanism for communication and cooperation with academic, industrial, and state scientific constituencies."*

The objectives of the continental drilling program for scientific purposes were described in the reports of four panels: basement structures and deep continental basins; thermal regimes of the crust; mineral deposits; and earthquakes. The need for development of new instrumentation to achieve some objectives was also stressed.

The proposed program, especially the communication aspect, would open the possibility of wider use of data from the holes and also for add-on experiments at comparatively small supplementary cost. In addition to the proposal for add-on experiments in connection with a drilling hole being undertaken by federal agencies, the report proposes selective drilling of holes dedicated to broader scientific objectives.

In December 1979, in response to recommendations of several federal agencies, the Geophysics Research Board established the Continental Scientific Drilling Committee whose purpose, broadly stated, is to encourage the development of the proposed Continental Scientific Drilling Program.

Ocean Margins

Between the ocean basins and land area (including the shallow continental shelves) lies an area of deep water and thick sediments, the outer continental shelf, slope, and rise, which as yet is not accessible to drilling. Within this area occurs the little-understood change from oceanic to continental crustal structure. Two very different types of continental margins exist – the passive (or rifted) margins and the active (or accreting) margins. Rifted margins, such as those bordering eastern North America and Western Europe and Africa, form by the splitting of old continents accompanied by generation of new oceanic crust. These margins undergo a complex history of faulting, cooling, crustal aging, subsidence, and sedimentation and are the loci of important concentrations of organic matter, giving rise to oil and gas deposits, and to potentially economic concentrations of metals, especially copper, lead, and zinc. Converging margins involve underthrusting and destruction of oceanic crust and are commonly associated with young mountain systems, earthquakes, and volcanism. In this environment deep basins with major oil and gas fields also developed, as well as important ore deposits related to accompanying igneous and hydrothermal activity. There are, therefore, basic scientific and practical reasons for exploring these marginal areas, by both geophysical methods and drilling.

A number of committes have addressed the science and technology of an ocean-margin drilling program. We have therefore devoted less space to this subject than its importance justifies. We strongly endorse a well conceived program of ocean margin drilling for scientific purposes. Such a program should be coordinated with the continental drilling program, and with the present international program of ocean drilling, so that for the first time, transects with rock samples would be available across wide areas of differing crustal character.

Oceanic

The Deep-Sea Drilling Program has produced data of great scientific value for geodynamics. A continuation of drilling in the deep oceans can be expected to yield additional important results. In particular, continental margin drilling and drilling deep into the oceanic crust promise to yield a wealth of geodynamically significant data. These topics were discussed briefly earlier in this document and are considered at length in several recent reports and therefore are not further elaborated here. Specific plans and timetables for deep sea and continental margin drilling are currently under review by various groups.

Magnetic Problems

Studies of marine magnetic signatures, continental aeromagnetic surveys, rock magnetism, paleomagnetism, and magnetostratigraphy continue to provide essential information for the solution of geodynamic problems. The origin of magnetic patterns observed at sea is not well understood; core drilling results to date have not identified a unique source region. Nevertheless the fine structure of magnetic patterns correlates very well between different areas, even at scales of less than one kilometer. This enigma may be resolved by comparing details of rock magnetism with the associated magnetic anomaly field.

Paleomagnetism has made major contributions to the concept of continental drift, yet the pre-Mesozoic magnetic field of the earth and the record of continental drift superimposed on it is still only poorly understood. In view of the discoveries of apparently rotated and migrated microplates within the past few years, increasing use of this technique can be anticipated. The search for such microplates, only just begun, promises new insights into mechanisms of continental margin accretion, and perhaps also the development of criteria for recognition of similar phenomena along ancient sutures within modern continents. Considerable effort will still be required in order to interpret the magnetic record properly, especially with respect to homogeneity on a continental or cratonic scale and the effects of diagenesis and metamorphism on the paleomagnetic record.

Aeromagnetic Survey

The USGC continues its strong support of efforts to prepare a regional magnetic anomaly map and consistent data set of the United States and adjacent marine areas by utilizing available data to the extent possible and by acquiring additional magnetic data as needed. The Committee notes that most industrialized nations have long since completed such maps and that the scientific and economic benefits from these maps rapidly defray the costs of production. In response to immediate needs, the Committee urges the rapid completion of a photo-composite national magnetic anomaly map based on existing magnetic maps.

Magsat, a dedicated magnetic field mapping satellite, was launched in the fall of 1979. During this six-month mission, scalar and vector magnetometers map the earth's magnetic field at an altitude of about 350 kilometers. In addition to information on the main geomagnetic field and its secular changes, crustal magnetic anomalies are expected to be recovered with a wavelength resolution of a few hundred kilometers and a sensitivity of a few gammas.

Isotope Geochemistry

During the past decade, many new developments have occurred in the application of both radioactive and stable isotopes to problems of importance to geodynamics. Applications discussed earlier in this report include the uses of isotopes for attacking problems of the origin of igneous rocks, the evolution of the mantle and lower crust, the recognition and definition of geological provinces, and the age and rate of deposition of oceanic sediments. With the development of increasingly sensitive instruments and the ready availability of data, isotopic studies promise to be of growing importance in the solution of geodynamic problems.

Internal Processes and Properties

Important topics under this heading include the origin of magmas within the lower crust and upper mantle; driving mechanisms and energy sources for plate motion; equation of state parameters, constrained by factors such as seismic velocity and attenuation, moment of inertia, composition, temperature, and pressure; the temperature distribution, both laterally and as a function of depth, and its relation to rheology, viscosity, seismic attenuation, mass transfer within the crust and mantle; effects of the presence of water and other volatiles; and many other physical and chemical phenomena.

A unique interpretation of mode of origin of magmas is still elusive. Many of the above-mentioned topics enter into our further elucidation of this problem. Abnormally high temperatures must occur beneath stable oceanic and continental crust to produce basalt, andesite or granite in volume. Temperature distribution with depth in various tectonic environments, an important but poorly known control, is in turn linked to flow patterns – convection or advection – in the mantle. These flow patterns must be compatible with the production of new material in ocean ridges and its loss beneath subduction zones and with the existence of long persistent "hot spots" beneath oceans and continents. Thermal-mechanical behavior is often connected with chemical differentiation. Chemical differentiation has not been satisfactorily incorporated into convective models.

Although an enormous amount of data is available, complete phase diagrams for major magma types are yet to be obtained. They would provide additional constraints regarding magma generation.

A relatively new field is that of fluid dynamics of magmas, requiring the determination of physical properties such as viscosity and specific gravity at varying temperatures. Problems involved include magma separation and rise; convection in magma chambers; mechanics of mixing of two similar magmas, as in the repeated influx of basalt beneath ocean ridges, or two dissimilar magmas such as the basalt-rhyolite pair; and the physics of eruption, including de-gassing and explosions. Relevant geological information bearing on composition, volume, and emplacement relationships of plutonic and volcanic associations will also be required. In short, we seem to have promising, generalized models relating magma genesis to source and to gross tectonic environment, but data are lacking for the construction of unique models.

The convective circulation of hydrothermal solutions is the dominant process in establishing geothermal systems and in concentrating the components of most hydrothermal ore deposits. It also is important as a heat-transfer mechanism during burial metamorphism of subsiding geosynclines where kerogen matures into petroleum. Nevertheless, we have yet to establish when such circulation is initiated, to what depths it is effective, what quantities of fluids are involved, what chemical components the fluids may transport, how long the process is maintained, and whether osmotic pumping contributes significantly to the flow patterns caused primarily by convection. Clearly, there would be important economic and scientific consequences to understanding this control on temperature and fluid flow in the upper crust.

Comparative Planetology

Of great importance to a comprehensive hypothesis for the origin and development of the earth are the observations made on the moon and other bodies within the solar system. It appears that planets similar in size to the earth, such as Mars and Venus, have had quite different histories and that the most distant planets have widely differing compositions, which in some way reflect the earliest history of the solar system and therefore also of the earth. Within the coming decade, study of available samples and data regarding topography and composition of the moon, Mars, and Venus should be particularly rewarding.

Geodynamic Activities in the Caribbean Area

The USGC reaffirms its earlier statements emphasizing the importance of understanding the geodynamics of the Caribbean area. United States organizations working in the area will endeavor to encourage the participation of local organizations in both planning and execution of research activities to resolve the complex geodynamic problems of the area.

Geodynamic Modeling

This topic is concerned both with large-scale modeling of global processes such as mantle convection and with local processes such as stress accumulation related to faults. Geodynamic modeling rationalizes available data and may motivate new sets of observations required to construct and test successive hypotheses. It is essential that adequate priority be given to the modeling aspects of all geodynamic endeavors.

Geodynamic Syntheses

The Geodynamics Committee emphasized the importance of appropriate geodynamic syntheses. Because many studies, carried out independently, never reach the synthesis stage, the Committee felt that continued emphasis on this area is warranted. The continent-ocean transects described earlier are expected to represent a concrete and valuable example of geodynamic syntheses.

Geodynamic Data

Geodynamic research involves diverse kinds and sources of geological, geophysical, geochemical and geodetic data. There are a large number of data repositories – formal and informal – in which substantial quantities of data pertinent to geodynamics have been accumulated. Accomplishment of many kinds of geodynamic research is dependent on – or can be greatly assisted by – the availability of data from diverse sources within the required time frame.

The USGC recognized that it is difficult for most researchers to be aware of more than a few of the many data repositories. Thus the USGC encouraged the preparation of the *Directory of the U.S. Data Repositories Supporting the International Geodynamics Project* (completed and issued by World Data Center A for Solid-Earth Geophysics, 1978). Expansion and updating of that report is expected in the early part of the program of Geodynamics in the 1980's.

The USGC supported the recommendation of the NAS-NRC Committee on Data Interchange and Data Centers (CDIDC) that there should be developed a national geophysical data policy or guidelines that would treat the issue of planning for data management (especially early planning in connection with experiments and monitoring that produce large quantities of data) and the issue of developing criteria for decisions about long-term retention of various kinds of data.

The USGC specifically endorsed the report of the Panel on Solid-Earth Geophysics (Appendix F in the CDIDC report *Geophysical Data Interchange – Assessment 1978*). The possibility of organizing an inter-committee task group to look at the various aspects of solid-earth data under the cognizance of NAS-NRC committees – especially geochemistry, geodesy, geodynamics, geology, oceanography, rock mechanics and seismology – has been explored. The areas of data policy and planning and of data centers and repositories are of such importance and complexity as to warrant separate consideration.

Appendix A
Related Reports

A selection of reports and workshops related to Geodynamics in the 1980's.

Applications of a Dedicated Gravitational Satellite Mission, Committee on Geodesy, National Academy of Sciences, 55 pp., 1979.

Application of Space Technology to Earthquake Research and Crustal Dynamics, Office of Space and Terrestrial Applications, NASA TP-1464, 340 pp., August 1979.

Caribbean Problems, a report on a workshop held to identify important geological problems related to the evolution of the Caribbean, 20-23 April 1977, State University of N.Y. at Albany, 44 pp., July 1977.

Continental Drilling. E. M. Shoemaker, editor. Report of the Workshop on Continental Drilling, Ghost Ranch, Abiquiu, New Mexico, June 1974, published by the Carnegie Institution of Washington, 56 pp., 1975.

Continental Margins: Geological and Geophysical Research Needs and Problems, Ocean Sciences Board, National Academy of Sciences, 302 pp., 1979.

Continental Scientific Drilling Program, U.S. Geodynamics Committee, Geophysics Research Board, National Research Council, Nat'l Academy of Sciences, Washington, D.C., 192 pp., 1979.

Continental Tectonics, Geophysics Study Committee, Geophysics Research Board, National Academy of Sciences, 197 pp., 1980.

"Crustal Dynamics: A Framework for Resource Systems," U.S. Geodynamics Committee, (draft working document–see Appendix B):

Part I – Background

Part II – Focus of a Crustal Dynamics Program

1. Oceanic Crustal Evolution
2. Continental Crustal Evolution
3. Continental Margins, Island Arcs and Orogenic Belts
4. Mass Transport and Kinetic Processes
5. State and Composition of the Crust
6. Vertical Movement of Continental Interiors

Directory of U.S. Data Repositories Supporting the International Geodynamics Project, Report SE-14, World Data Center A for Solid-Earth Geophysics, NOAA, Boulder, CO, 40 pp., 1978.

Dynamics of the Continental Crust: Proposals for a U.S. Geological Survey Program in the 1980's, U.S. Geological Survey Open File Report, 1979.

Earthquake Research: An Aid to the Safer Siting of Critical Facilities, Committee on Seismology, National Research Council, National Academy of Sciences, Washington, D.C. (in press).

The Earth's Crust: Its Nature and Physical Properties, Heacock, J. G., Editor, Amer. Geophys. Union, Geophys. Monograph 20, 754 pp., 1977.

The Future of Scientific Ocean Drilling, ad hoc Subcommittee of the JOIDES Executive Committee, Seattle, Washington, 92 pp., 1977.

Geodynamics International, Reports of the Interunion Commission on Geodynamics, Nos. 9-15, issued as reports SE-2, SE-5, SE-10, SE-12, SE-15 and SE-19 (1976-1979), by World Data Center A for Solid-Earth Geophysics, NOAA, Boulder, CO.

Geodynamics: Progress and Prospects, Charles L. Drake, Editor, Amer. Geophys. Union, 238 pp., 1976.

Geodynamics Project: U.S. Progress Report–1975, U.S.Geodynamics Committee, National Academy of Sciences, 87 pp., 1976.

Geodynamics Project: U.S. Progress Report–1976, U.S. Geodynamics Committee, National Academy of Sciences, 75 pp., 1976.

Geodynamics Project: U.S. Progress Report–1977, U.S. Geodynamics Committee, National Academy of Sciences, 75 pp., 1977.

Geodesy: Trends and Prospects, Committee on Geodesy, National Academy of Sciences, 88 pp., 1978.

Geology, Geophysics and Resources of the Caribbean, Report of the IDOE Workshop on Geology and Marine Geophysics of the Caribbean Region and Its Resources, Kingston, Jamaica 17-22 February 1975, John D. Weaver, Editor, Intergovernmental Oceanographic Commission, UNESCO, 150 pp., 1977.

Geophysical Data Centers: Impact of Data-Intensive Programs. Geophysical Data Panel, Committee on Data Interchange and Data Centers, Geophysics Research Board, National Academy of Sciences, 32 pp., 1976.

Geophysical Data Interchange–Assessment 1978, Committee on Data Interchange and Data Centers, Geophysics Research Board, National Academy of Sciences, 70 pp., 1979.

Geophysical Predictions, Geophysics Study Committee, Geophysics Research Board, National Research Council, National Academy of Sciences, Washington, D.C., 215 pp., 1978.

Global Earthquake Monitoring: Its Uses, Potentials, and Support Requirements, Panel on Seismograph Networks, Committee on Seismology, National Academy of Sciences, 75 pp., 1977.

The Impact of Technology on Geophysics, Geophysics Study Committee, Geophysics Research Board, National Academy of Sciences, 121 pp., 1979.

Interunion Commission on Geodynamics, (Secretariat) Reports Nos. 1-8, Paris, 1971-1976 (for continuation, Nos. 9 onwards, see *Geodynamics International*).

Limitations of Rock Mechanics in Energy-Resource Recovery and Development, U.S. National Committee for Rock Mechanics, National Academy of Sciences, 67 pp., 1978.

"The Lithosphere: Frontier for the 1980's," A Program of International Research in the Solid-Earth Sciences as proposed jointly by the Task Groups on Planning of the International Union of Geodesy and Geophysics and the International Union of Geological Sciences, 1979.

National Magnetic Anomaly Map, Report of the National Magnetic Anomaly Map Workshop, 17-19 February 1976, Golden, Colorado (available from

National Magnetic Anomaly Map Committee, c/o Dept. of Geosciences, Purdue University, West Lafayette, Indiana 47907), 38 pp., July 1976.

"The Ocean Crustal Dynamics Plan for the 1980's," Joint Oceanographic Institutions Inc., Washington, D.C. (in preparation).

Orientations in Geochemistry, U.S. Geochemistry Committee, National Academy of Sciences, 122 pp., 1973.

Predicting Earthquakes: A Scientific and Technical Evaluation—With Implications for Society. Panel on Earthquake Prediction, Committee on Seismology, National Academy of Sciences, 62 pp., 1976.

"A Program for Ocean Crustal Dynamics" from a workshop held at Lamont-Doherty Geological Observatory, January 1977 (informal draft).

Report of the Workshop "Research Frontiers in Exploration for Non-Renewable Resources," A. W. Rose, H. L. Barnes, C. W. Burnham and H. Ohmoto, Penn. State University, NSF/RA 770031, 164 pp., 1977.

Trends and Opportunities in Seismology: Part I: Opportunities and Benefits. Part II, Background and Progress. Committee on Seismology, National Academy of Sciences, 158 pp., 1977.

U.S. Program for the Geodynamics Project: Scope and Objectives, U.S. Geodynamics Committee, Geophysics Research Board, National Academy of Sciences, 235 pp., 1973.

Appendix B
History of the U.S. Geodynamics Committee

In March 1968, Merle Tuve (then Chairman of the Geophysics Research Board) and Harry Hess convened a meeting to discuss a program in solid-earth studies to capitalize on the remarkable developments then beginning to be recognized as a revolution in earth sciences. The results of this meeting were discussed at the meetings of the Geophysics Research Board (GRB) and also of the American Geophysical Union. This led to a resolution by GRB to establish the Committee on Solid-Earth Problems with the primary purpose of fostering and encouraging continued research on the dynamics of the earth's interior and the effects on the surface layers. That same year, the International Union of Geodesy and Geophysics (IUGG) and the International Union of Geological Sciences (IUGS) began planning for an international program to be dedicated to the investigation of the dynamics of the solid earth. That planning led to approval of the International Geodynamics Project by ICSU and the establishment of the Interunion Commission on Geodynamics to guide the program. In September 1970, the President of ICSU requested member countries to establish national committees for the Geodynamics Project and to evolve programs for participation in the project. Accordingly in March 1971 the President of the National Academy of Sciences formally changed the title of the Committee on Solid-Earth Problems to the U.S. Geodynamics Committee to serve as the U.S. National Committee for the Geodynamics Project, with the following additional charge:

> The responsibilities of the U.S. Geodynamics Committee include cooperation with the Inter-union Commission on Geodynamics and the development of a program for U.S. participation in the Geodynamics Project, surveying as necessary current activities in the relevant areas of science and coordinating with government agencies, private institutions and industry to ensure that a coherent program evolves responsive to needs in basic research and in applications.
>
> I believe that you and your colleagues on the Geodynamics Committee have challenging tasks ahead in developing a rewarding program in

solid-earth studies stimulated by the remarkable developments in earth sciences during the past several years. The initiative already taken by your committee during the past year represents useful steps in this direction.

In developing a plan that was eventually published in *U.S. Program for the Geodynamics Project: Scope and Objectives*, the USGC addressed chairmen of geoscience departments in some 200 colleges and universities throughout the country, requesting them to designate for each department a Geodynamics Project Correspondent to serve as a communications link between the department and the USGC.

The USGC then prepared an initial outline and called upon 14 *ad hoc* working groups involving some 170 scientists drawn from the academic community, government and industry, to assist in developing recommendations for the program. In developing these recommendations, the USGC held a series of meetings over a three-year period and transmitted draft documents not only to its *ad hoc* working groups but also to the Geodynamics Project Correspondents and to appropriate officials of major scientific societies, seven of which specifically endorsed the directions taken by the committee in its planning: the American Geophysical Union, American Association of Petroleum Geologists, Geochemical Society, Geological Society of America, Mineralogical Society of America, Seismological Society of America, and Society of Exploration Geophysicists.

The main outline of the document *Scope and Objectives* included the following topics:

Americas Plate
Small Plates and Plate Margins
Internal Properties and Processes
Boundaries, Movements and Structures of Lithospheric Plates
Deep Drilling
Data Exchange and Compilations of the Geodynamics Project

The final stage of preparation of *Scope and Objectives* was the development of a section on Initial Priorities. An outline of that chapter is the following:

SIX NEW OPPORTUNITIES
- Fine Structure of the Crust and Upper Mantle
- Mid-Atlantic Ridge
- Internal Processes and Properties
- Chemical Differentiation of Magmas
- Geodynamic Models
- Drilling for Scientific Purposes

SEVEN SPECIAL PROBLEMS
- Extension of the Chronology of Geomagnetic Reversals at Least through the Mesozoic
- Pole Positions in the Paleozoic
- Fine Structure of Magnetic Reversal Chronology
- Motions on a Planetary Scale
- Temperature Distribution

Structure and Dynamics of Downgoing Slab
Shape of the Asthenosphere
REGIONAL MANIFESTATIONS OF GEODYNAMIC PROCESSES
Plate Boundaries
Plate Interiors
Geodynamic Syntheses

The question of total level of funding was also addressed; it is reviewed in Appendix C.

Scope and Objectives was published in September 1973. In November 1973, the Federal Council on Science and Technology formally recognized the importance of the Geodynamics Project and authorized establishment of an *ad hoc* Committee on the International Geodynamics Project of the Federal Council. In order to develop its own planning and to be responsive to the FCST Committee, the USGC promptly appointed 10 reporters, corresponding (with minor variations) one each to ten of the topics in the chapter "Initial Priorities." The duty of the reporters was to consult the scientific community as appropriate by mail and by meetings and to develop recommendations regarding action to be taken by the USGC in order to implement the various priority topics. To this end, the above-referenced scientific societies and the Geodynamics Project Correspondents were informed of the appointment of these reporters and their topics and were urged to communicate directly with the reporters. Establishment of this series of reporters was also announced in several scientific journals.

In the following years, the main activities of the USGC were closely related to the work and the recommendations of the reporters. This is clearly evidenced in the USGC progress reports issued in 1975, 1976, and 1977. Throughout the 1970's, the USGC also considered new topics for which reporters were required.

By December 1979, the list of reporters and topics had been modified appreciably from the original ten for various reasons: completion or rearrangement of tasks; resignations and one death; addition of new topics, including three in 1979. The complete list of topics and reporters as of December 1979 is presented below; this corresponds to the list of reporters at the beginning of this report.

In 1976, at the request of the Geophysics Research Board, the USGC began developing a rationale for a program of solid-earth studies to go forward after the formal termination of the Geodynamics Project in December 1979. The initial draft of a statement of this rationale was prepared by an *ad hoc* committee chaired by Gene Simmons and was circulated in the summer of 1976 under the title: "Crustal Dynamics: A Framework for Resource Systems." The initial document of some 20 pages evolved in the coming two years to a draft of almost 200 pages. In September 1978, the Geophysics Research Board decided to request the USGC to guide the new program being developed for the 1980's. The GRB specifically noted that it saw no reason to change

USGC Reporters (December 1979)

Topic		Reporter	Note
1.	Fine Structure of the Crust and Upper Mantle	Jack E. Oliver	
2.	Evolution of Oceanic Lithosphere	James R. Heirtzler	1
3b.	Crystal Growing	Thomas M. Usselman	2
3c.	Large Volume Experimentation	Robert E. Riecker	
4.	Application of Isotope Geochemistry to Geodynamics	Bruce R. Doe	3
5.	Geodynamic Modeling	Donald L. Turcotte	
6.	Drilling for Scientific Purposes	Eugene M. Shoemaker	
7.	Magnetic Problems	Charles E. Helsley	
8.	Plate Boundaries	John C. Maxwell	
9.	Plate Interiors	Laurence L. Sloss	
10a.	Geodynamic Data	M. Nafi Toksoz	4
10b.	Data Centers and Repositories	Alan H. Shapley	5
11.	Geodynamic Activities in the Caribbean Area	(John D. Weaver)	6
12.	Lithospheric Properties	Thomas H. Jordan	7
13.	Aeromagnetic Survey	William J. Hinze	7
14.	Comparative Planetology	James W. Head	8
15.	Continent-Ocean Geodynamic Transects	Robert C. Speed	8
16.	Ancient Suture Belts	Eldridge M. Moores	8
17.	Electrical Properties of the Asthenosphere	Charles S. Cox	8
–	Final Symposia and Reports for the Geodynamics Project	Charles L. Drake	9

Notes
1. Original title: Mid-Atlantic Ridge. Current title was adopted in 1975.
2. Topic 3a original title: Internal Processes and Properties, John C. Jamieson, reporter; Jamieson resigned in 1978. Topic 3b was added in 1975, Thomas Shankland, reporter. Shankland resigned in 1976; he was succeeded by Thomas Usselman in the same year. Topic 3c was added in 1976.
3. Original title: Chemical Differentiations of Magmas, Klaus Keil, reporter. A final report on that topic was published in *Geodynamics Project: U.S. Program Report–1975*. The current title and reporter were added in 1977.
4. Original title: Geodynamic Syntheses, Creighton Burk, reporter. Burk resigned in 1978. The current title and reporter were added that same year.
5. Added in 1977.
6. Added in 1975. Weaver died 27 November 1979.
7. Added in 1975.
8. Added in 1979.
9. Added in 1978.

the name of the committee. There was already an established pattern of rotation of membership on the USGC.

In the fall of 1978, the USGC recognized that the draft document "Crustal Dynamics" had evolved in a way that led to imbalance among various sections; many of them contained more detail than the committee thought was appropriate. Therefore the decision was made to prepare a condensed, balanced version of that draft and to change its title to *Geodynamics in the 1980's*.

A concomitant decision was made that the draft document "Crustal Dynamics" had served its purpose by making known to the scientific community the lines of thinking of the USGC, attracting comments from a wide range of the community, and finally leading to the more focused report *Geodynamics in the 1980's*. Thus the committee formally decided to make no effort to issue that document in its longer version.

In response to the new directions outlined in *Geodynamics in the 1980's*, the USGC has already added five new reporters—for geodynamic data, continental margin transects, comparative planetology, ancient suture belts, and electric properties of the asthenosphere. It is expected that other revisions will be made in the list of topics and corresponding reporters in the near future and, as in the 1970's, the list of topics will be subject to regular review by the USGC.

Appendix C
Budgetary Implications

In preparing the report *U.S. Program for the Geodynamics Project: Scope and Objectives* issued in 1973, the USGC included a chapter "Initial Priorities" (see Appendix B for further discussion, especially the relation of these priorities to the system of reporters). In developing these priorities, various factors were considered, including two important questions: Is the research area likely to produce significant advances with incremental increase in support? Are data from this research area critical for advances in related areas?

To provide a frame of reference, the committee surveyed activities in 12 federal agencies that were conducting activities related to problems of geodynamics. The purpose of the survey was to determine the level of support of these activities in terms of direct cost (on the assumption that incremental funding would be related primarily to direct costs). The result of that survey showed a total level for the 12 agencies of $48 million in fiscal year 1972. The proposed comparable total level recommended by the U.S. Geodynamics Committee for the following six years averaged $59 million annually.

In preparing *Geodynamics in the 1980's*, the USGC did not repeat the kind of survey that had been undertaken in 1972. In *Scope and Objectives*, the USGC drew attention to the important relations between basic geodynamic understandings and a variety of societal problems. In the years following, this relation has been increasingly recognized by the federal agencies and by many Academy committees concerned with scientific areas that overlap the interests of the Geodynamics Committee (see Appendix A). As a result, programs that relate to geodynamics have been greatly strengthened or are in the process of being strengthened in many federal agencies for basic science and for the mission requirements of the agencies. Incremental funding has been approprirate for some programs. In others, the agencies have recognized the need for major expansion of certain activities and for new initiatives. Programs under way or under active consideration include deep reflection profiling, drilling on offshore continental margins, narrow-beam profiling for oceanographic vessels, systematic updating of the national levelling and gravity network, and space techniques for determination of precise positions on the surface of the earth.

Under these circumstances it is increasingly difficult to distinguish between the needs for increments in the basic research budgets as compared with expenditures and increases related to highly specific mission objectives. This problem is clearly illustrated by the drilling activities of federal agencies on land, currently estimated at approximately $500 million per year. *Geodynamics in the 1980's* and the separate report, *Continental Scientific Drilling Program*, stress the fact that the scientific return from this large investment could be substantially increased with the establishment of a suitable communication and coordination mechanism and appropriate incremental funding of only a few percent of the existing investment. This pattern of evaluation of scientific priorities and their relation to mission objectives is expected to continue, with increasing recognition of the importance of various aspects of the dynamics of the solid earth. The U.S. Geodynamics Committee believes that no purpose is served by endeavoring to make a quantitative overall forecast of what the various support levels and changes will or should be for Geodynamics in the 1980's.

Appendix D
Geodynamics Correspondents

The U.S. Geodynamics Committee invited any interested geoscience department to nominate a correspondent for the Geodynamics Project to serve as a focal point for communications between the department and the U.S. Geodynamics Committee. Correspondents are nominated by the chairman of the department. This system of Geodynamics Correspondents is being continued in conjunction with the program of Geodynamics in the 1980's.

Geodynamics Correspondents

Institute	Department	Correspondent
University of Alabama	Geology and Geography	W. Gary Hooks
University of Alaska	Geophysical Institute	D. B. Stone
	Institute of Marine Science	J. Robert Moore
Amherst College	Geology	Richard M. Foose
Arizona State University	Geology	Donal M. Ragan
	Center for Meteorite Studies	Carleton B. Moore
University of Arizona	Geosciences	John Sumner
	Mining & Geological Engineering	Charles Glass
University of Arkansas	Geology	R. H. Konig
Boston College	Geophysics	James W. Skehan, S.J.
Boston University	Geology	Arthur H. Brownlow
Bowling Green State Univ.	Geology	Edmund F. Pawlowicz
Brigham Young University	Geology	Myron G. Best
Brooklyn College of the City University of New York	Geology	Somdev Bhattacharji
Brown University	Geological Sciences	Terry Tullis
Bryn Mawr College	Geology	Lucian B. Platt
University of California		
Berkeley	Geology and Geophysics	Chi-yuen Wang
	Materials Science & Engineering	W. E. Farrell
Davis	Geology	Kenneth Verosub
Lawrence Livermore		Alfred Duba
Los Angeles	Earth and Space Sciences	John M. Christie
	Inst. of Geophysics & Planetary Physics	Leon Knopoff
Riverside	Earth Sciences	Tien-Chang Lee

Institute	Department	Correspondent
San Diego	Geological Research Division	Joseph R. Curray
	Inst. of Geophysics & Planetary Physics	James N. Brune
	Marine Physical Laboratory	George G. Shor, Jr.
Santa Barbara	Geological Sciences	Arthur G. Sylvester
Santa Cruz	Earth Sciences	Robert S. Coe
California Institute of Technology	Geological & Planetary Sciences	Eugene M. Shoemaker
Carnegie Institution of Washington	Geophysical Laboratory	David Mao
	Terrestrial Magnetism	D. E. James
Case Western Reserve Univ.	Geology	Philip O. Banks
University of Chicago	Geophysical Sciences	Peter J. Wyllie
University of Cincinnati	Geology	I. A. Kilinc
Colorado School of Mines	Geology	L. Trowbridge Grose
	Geophysics	Maurice W. Major
Colorado State University	Earth Resources	M. E. McCallum
University of Colorado	Geological Sciences	Max Wyss
Columbia University	Geology	Ian W. D. Dalziel
	Henry Krumb School of Mines	John T. Kuo
	Lamont-Doherty Geological Observatory	Manik Talwani
University of Connecticut	Geology and Geophysics	Peter Geiser
	Institute of Marine Sciences	Peter Dehlinger
Cornell University	Geological Sciences	Jack E. Oliver
Dartmouth College	Earth Sciences	Charles L. Drake
University of Delaware	Geology	Robert E. Sheridan
Duke University	Geology	Bruce R. Rosendahl
Emory University	Geology	William B. Size
Florida International Univ.	Physical Sciences	Florentin Maurrasse
Florida State University	Geology	William F. Tanner
	Geophysical Fluid Dynamics Institute	David Loper
	Oceanographic Institute	Raymond C. Staley
University of Florida	Geology	Douglas L. Smith
Franklin & Marshall College	Geology	Edward C. Beutner
George Washington Univ.	Geology	John F. Lewis
Georgia Institute of Technology	Geophysical Sciences	Charles E. Weaver
University of Georgia	Geology	Norman Herz
Harvard University	Geological Sciences	Adam M. Dziewonski
University of Hawaii	Geosciences	George H. Sutton
	Oceanography	James E. Andrews
University of Houston	Geology	Milton B. Dobrin
Hunter College of the City University of New York	Geology and Geography	Horst S. Scherp
Idaho State University	Geology	Marshall Corbett
University of Idaho	Geology	George A. Williams
University of Illinois	Geology	V. V. Palciauskas
Indiana State University	Geography and Geology	John H. Cleveland
Indiana University	Geology	Haydn H. Murray
Iowa State University of Science and Technology	Earth Sciences	Kenneth E. Windom
University of Iowa	Geology	Richard A. Hoppin
Johns Hopkins University	Earth and Planetary Sciences	Bruce Marsh
Kansas State University	Geology	Charles P. Walters

Institute	Department	Correspondent
University of Kansas	Geology	M. E. Bickford
Kent State University	Geology	John J. Anderson
University of Kentucky	Geology	Ronald Street
Lehigh University	Geological Sciences	Kenneth Kodama
Louisiana State University	Geology	Rex Pilger
Louisiana Tech University	Geosciences	Leo A. Hermann
University of Maine	Geological Sciences	Philip H. Osberg
	Oceanography	L. Kenneth Fink, Jr.
Massachusetts Institute of Technology	Earth and Planetary Sciences	Sean C. Solomon
	Mathematics	Willem V. R. Malkus
University of Massachusetts	Geology and Geography	George E. McGill
Miami University	Geology	Norman K. Grant
University of Miami	Geology	Frederick Nagle
	Marine Geology & Geophysics	C. G. A. Harrison
Michigan State University	Geology	F. W. Cambray
Michigan Technological University	Geology and Geological Engineering	J. Kalliokoski
University of Michigan	Geology and Mineralogy	Rob Van der Voo
University of Minnesota	Geology and Geophysics	V. Rama Murthy
University of Mississippi	Geology and Geological Engineering	Velon H. Minshew
University of Missouri		
Columbia	Geology	Eric Rhinehart
Rolla	Geology and Geophysics	Gerald B. Rupert
	Mining, Petroleum and Geological Engineering	David J. Barr
Montana State University	Earth Sciences	Robert Chadwick
University of Montana	Geology	Anthony Qamar
Mount Holyoke College	Geology and Geography	Martha M. Godchaux
University of Nebraska	Geology	Samuel B. Treves
University of Nevada	Geology and Geography	Keith Priestley
New Mexico Institute of Mining and Technology	Geosciences	Allan R. Sanford
University of New Mexico	Geology	Jonathan F. Callender
City College of the City University of New York	Earth and Planetary Sciences	Nicholas M. Ratcliffe
State University of New York		
Albany	Geological Sciences	Paul J. Fox
Binghamton	Geology	William D. MacDonald
Buffalo	Geological Sciences	Dennis Hodge
	Geosciences	Carl K. Seyfert
Stony Brook	Earth and Space Sciences	Robert Liebermann
College of Cortland	Geology	John L. Fauth
College at Fredonia	Geology	Richard Gilman
College at New Paltz	Geology	Gilbert J. Brenner
College at Oneonta	Earth Science	John Sales
College at Oswego	Earth Science	Robert E. Maurer
College at Plattsburgh	Earth Sciences	James F. Olmsted
North Carolina State University	Geosciences	C. J. Leith
University of North Carolina	Geology	John J. W. Rogers
Museum of Northern Arizona		William J. Breed
Northern Illinois University	Geology	Lyle D. McGinnis
Northwestern University	Geological Sciences	Robert C. Speed
Ohio State University	Geodetic Science	Urho A. Uotila

Institute	Department	Correspondent
Ohio State University	Geology	Hallan Noltimier
	Institute of Polar Studies	David H. Elliott
Ohio University	Geology	Moid U. Ahmad
University of Oklahoma	Geology and Geophysics	Robert L. DuBois
Oregon State University	Geology	E. Julius Dasch
	Oceanography	George H. Keller
University of Oregon	Geology	Brian H. Baker
Pennsylvania State University	Geosciences	MacKenzie L. Keith
University of Pittsburgh	Earth and Planetary Sciences	Ellis Strick
Princeton University	Geological and Geophysical Sciences	John Suppe
Purdue University	Geosciences	Ted V. Jennings
Queens College of the City University of New York	Earth and Environmental Sciences	Edward Schreiber
Rensselaer Polytechnic Institute	Geology	Samuel Katz
University of Rhode Island	Geology	Reinhard K. Frohlich
	Graduate School of Oceanography	Jean-Guy Schilling
Rice University	Geology	Hans Ave Lallement
University of Rochester	Geological Sciences	Lawrence W. Lundgren
Rutgers University	Geology	Martha Hamil
San Diego State University	Geological Sciences	Monte Marshall
Smith College	Geology	H. Robert Burger
University of South Carolina	Geology	Donald T. Secor
South Dakota School of Mines and Technology	Geology and Geological Engineering	Alvis L. Lisenbee
University of South Florida	Geology	Richard C. Vierbuchen
University of Southern California	Geological Sciences	Ta-liang Teng
Southern Connecticut State College	Earth Sciences	Robert A. Radulski
Southern Illinois University	Geology	Jay Zimmerman, Jr.
Southern Methodist University	Geological Sciences	Eugene Herrin
University of Southern Mississippi	Geology	Richard L. Bowen
University of Southwestern Louisiana	Geology	Gary L. Kinsland
St. Louis University	Earth and Atmospheric Sciences	Stanislaw A. Vincenz
Stanford University	Geology	Norman H. Sleep
	Geophysics	Amos M. Nur
Syracuse University	Geology	John T. Bursnall
University of Tennessee	Geology	Dietrich Roeder
Texas A&M University	Geology	John W. Handin
	Geophysics	Anthony F. Gangi
	Oceanography	Thomas W. C. Hilde
Texas Christian University	Geology	Carlos Aiken
Texas Tech University	Seismological Observatory	D. H. Shurbet
University of Texas		
Austin	Geological Sciences	Ralph O. Kehle
Dallas	Geosciences	Mark Landisman
El Paso	Geological Sciences	G. R. Keller
Galveston	Marine Science Institute	J. Lamar Worzel

Institute	Department	Correspondent
Tulane University	Geology	Hamilton M. Johnson
University of Tulsa	Earth Sciences	Stanley J. Laster
Utah State University	Geology	Clyde T. Hardy
University of Utah	Geological and Geophysical Sciences	Robert B. Smith
Vanderbilt University	Geology	Richard G. Stearns
University of Vermont	Geology	Rolfe S. Stanley
Virginia Polytechnic Institute	Geological Sciences	Lynn Glover, III
Washington State University	Geology	Peter R. Hooper
Washington University	Earth Science	Larry A. Haskin
University of Washington	Geological Sciences	Bernard Evans
	Oceanography	Brian T. R. Lewis
Wesleyan University	Geology	Jelle deBoer
West Virginia University	Geology and Geography	Richard Williams
Western Michigan University	Geology	John D. Grace
Western New Mexico Univ.	Physical Sciences	John E. Cunningham
Western Washington State College	Geology	M. E. Beck, Jr.
Wichita State University	Geology	James N. Gundersen
University of Wisconsin		
Madison	Geology and Geophysics	Robert P. Meyer
Milwaukee	Geological Sciences	David E. Willis
Oshkosh	Geology	James I. Hoffman
Woods Hole Oceanographic Institution	Geology and Geophysics	J. R. Heirtzler
University of Wyoming	Geology	Peter N. Shive
Yale University	Geology and Geophysics	Sydney P. Clark, Jr.

Appendix E
Acronyms and Abbreviations

AFGL	–	Air Force Geophysical Laboratory
AFOSR	–	Air Force Office of Scientific Research
CODATA	–	Committee on Data for Science and Technology
COGEODATA	–	Committee on Storage, Automatic Processing and Retrieval of Geological Data
COCORP	–	Consortium for Reflection Profiling
DARPA	–	Defense Advanced Research Projects Agency
DMA	–	Defense Mapping Agency
DOE	–	Department of Energy
IAG	–	International Association of Geodesy
IAGA	–	International Association of Geomagnetism and Aeronomy
IASPEI	–	International Association of Seismology and Physics of the Earth's Interior
IAU	–	International Astronomical Union
IAVCEI	–	International Association of Volcanology and Chemistry of the Earth's Interior
ICSU	–	International Council of Scientific Union
IUGG	–	International Union of Geodesy and Geophysics
IUGS	–	International Union of Geological Sciences
JOI	–	Joint Oceanographic Institutions Inc.
JOIDES	–	Joint Oceanographic Institutions for Deep Earth Sampling
NASA	–	National Aeronautics and Space Administration
NAVOCEANO	–	Naval Oceanographic Office
NOAA	–	National Oceanic and Atmospheric Administration
NRC	–	Nuclear Regulatory Commission
NSF	–	National Science Foundation
ONR	–	Office of Naval Research
USGC	–	U.S. Geodynamics Committee
USGS	–	U.S. Geological Survey
WDC	–	World Data Center