Geodynamics Project. U.S. Progress Report—1977

U. S. Geodynamics Committee

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

NATIONAL ACADEMY OF SCIENCES
Washington, D.C.
1977

DISCLAIMER

NOTICE

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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.

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PREFACE

Geodynamics Project: U.S. Progress Report--1977 is the third progress report prepared by the U.S. Geodynamics Committee (USGC) under a recommendation of the Geophysics Research Board (GRB) that progress reports on the U.S. program for the Geodynamics Project be issued annually. The report for 1977 has been prepared in time to be available at the meeting of the Inter-Union Commission on Geodynamics during the General Assembly of IASPEI and IAVCEI (for abbreviations, see Appendix E), Durham, England, August 1977.

Activities in the United States pertinent to the Geodynamics Project fall in two categories: (1) ongoing programs; (2) activities specially stimulated by the USGC. In the report *U.S. Program for the Geodynamics Project: Scope and Objectives*, published in 1973, the USGC identified a series of initial priorities. In order to develop recommendations regarding implementation of these initial priorities, the committee appointed ten reporters. Seven additional reporters have been added, corresponding to subsequently identified priorities; one reporter's task was completed. The reports of these reporters constitute the major part of the progress reports prepared in 1975, 1976, and 1977.

According to the definition adopted by the International Council of Scientific Unions in 1973, the Geodynamics Project terminates at the end of 1979. Although we expect to have important results from some of the activities initiated specifically in connection with the U.S. program for the Geodynamics Project, it has become evident that many of the activities described by the USGC reporters will necessarily extend far beyond the stated lifetime of the Geodynamics Project.

The responsibilities of the USGC include long-range planning in solid-earth studies, taking special account of the revolution in earth sciences in the 1960's, which opened the way to study of the solid earth as a system. It is now evident that the 1970's is a transition period in which we are learning how to develop new insights and techniques for the study of the solid earth. In one form or another, geodynamics is likely to be the focal point of research on the solid earth for decades to come. The USGC has been giving thought to long-range projections for some time, and in May 1976, the GRB formally requested the Committee to take initiative in developing a rationale for an approach to solid-earth studies in the 1980's. To this end, an *ad hoc* meeting was convened in June 1976. The results of this meeting were incorporated into a document entitled "Crustal Dynamics: A Framework for Resource Systems," which was widely circulated in the United States and abroad. This report reflects the belief that there will be increased attention to the basic scientific problems underlying a variety of societal needs, especially resources and hazards. Thus, there must be a greater focus on crustal dynamics, with emphasis on the origin and evolution of the continents.

"Crustal Dynamics" was reviewed by many individuals and at several national and international meetings. In May 1977, the U.S. Geodynamics Committee organized a two-day conference of 40 participants devoted to review and revision of "Crustal Dynamics" taking account of suggestions from those diverse sources. It has become apparent that there was generally favorable reaction to the concept of an ongoing program--probably on an international basis under the International Council of Scientific Unions--along the lines of "Crustal Dynamics" as a natural evolution from the Geodynamics Project. The Geophysics Research Board and the U.S. National Committees for the International Union of Geodesy and Geophysics and the International Union of Geological Sciences have adopted resolutions to the effect that the momentum gained in the Geodynamics Project--most notably, the vastly improved communications among geophysicists, geodesists, geochemists, and geologists--should be maintained in an appropriate international framework.

The U.S. Geodynamics Committee continues to benefit from assistance and advice from a wide range of scientists throughout the academic community and in many government and industrial organizations. A great many of these people and organizations are listed in appendixes to the current and previous progress reports, including the Geodynamics Project correspondents in 175 geoscience departments, those geoscience societies that have taken an active interest in the Geodynamics Project, and some 200 individuals who are known to have contributed to the work of the reporters. We express appreciation to all of these people and organizations, as well as to others who have assisted subsequently with or without our knowledge.

The USGC is pleased to acknowledge the assistance of the National Science Foundation, whose continuing support of the GRB has made this report possible.

Charles L. Drake, *Chairman*
U.S. Geodynamics Committee

July 1977

[In August 1977, IUGG and IUGS agreed to develop an international program for the 1980's that will take advantage of developments in the Geodynamics Project--ed.]

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1. INTRODUCTION

The U.S. Geodynamics Project has previously prepared three principal reports: *U.S. Program for the Geodynamics Project: Scope and Objectives*, issued in September 1973, and progress reports in 1975 and 1976.* The first report includes discussion of some important problems in geodynamics as well as the international background of the Geodynamics Project and the history of planning by the U.S. Geodynamics Committee (USGC). The progress reports primarily document the activities of the reporters in connection with the priorities identified by the Committee.

The 1975 progress report includes discussion of the Committee on the International Geodynamics Project of the Federal Council on Science and Technology (FCST-IGP), which was established in May 1974 "to identify areas of studies considered appropriate, to review annually the federal geodynamics programs and budget and to serve as the focal point for liaison with the U.S. Geodynamics Committee." In 1976, the title of the Council was changed (by statute) to Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). The IGP Committee was given broader responsibilities, and its title was changed to Committee on Solid Earth Sciences (CSES). Under its new and old titles, FCCSET-CSES has met approximately eight times per year. It established a subcommittee to investigate the feasibility of implementing the proposed continental drilling program. The report of that subcommittee was approved by FCCSET-CSES in May 1977. The preface and introduction are reproduced in Part 3, Section 6 of this progress report. In the first annual report of the FCCSET-CSES, the following budgetary levels of activities of federal agencies related to the Geodynamics Project were indicated for fiscal years 1974, 1975, and 1976: $55 million, $65 million, and $68 million, respectively. These figures indicate significant increases in research activities related to geodynamics.

There was considerable discussion in *Geodynamics Project: U.S. Progress Report--1975* of the activities of geoscience societies in connection with the Geodynamics Project (see Appendix B). Eight major societies have shown continuing interest in the project: American Association of

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**U.S. Program for the Geodynamics Project: Scope and Objectives* is available from the Printing and Publishing Office, National Academy of Sciences, Washington, D.C. 20418, for $4.50; *Geodynamics Project: U.S. Progress Report--1975* and the present *Progress Report--1977* are available from the U.S. Geodynamics Committee without charge. *Progress Report--1976* is out of print.

Petroleum Geologists, American Geological Institute, American Geophysical Union, Geochemical Society, Geological Society of America, Mineralogical Society of America, Seismological Society of America, and Society of Exploration Geophysicists. The most visible form of assistance of the societies relates to publications and meetings. In addition, the societies have been helpful in identifying scientists to assist in advising the USGC, and most of the meetings of the USGC have been held in conjunction with major national meetings of the various societies. The societies have also been particularly helpful to the reporters.

The three publications of the USGC were widely distributed in the United States and internationally, to members of the Inter-Union Commission on Geodynamics and its working groups and to other national committees for the Geodynamics Project. Readers of the 1977 progress report should, therefore, have reasonably convenient access to the earlier reports.

The "Report on Priorities" issued by the USGC in March 1977 is reproduced as Part 2 of this progress report.

2. REPORT ON PRIORITIES *

U.S. Program for the Geodynamics Project: Scope and Objectives was issued by the U.S. Geodynamics Committee (USGC) in September 1973. This report contains many recommendations regarding U.S. activities related to the Geodynamics Project; it includes one chapter specifically devoted to "Initial Priorities." In evolving these recommendations, the U.S. Geodynamics Committee was assisted by 14 reporters who consulted widely throughout the scientific community. Following publication of *Scope and Objectives*, the USGC appointed 10 reporters to deal with the initial priorities. These reporters were instructed to consult those members of the scientific community known to be interested in the topic of a particular priority and to evolve recommendations to the USGC regarding implementation of the topic. In addition to the initiative taken by the reporters themselves, the USGC made widely known the names and addresses of the reporters and their topics. Any interested scientist was urged to communicate with the relevant reporter. These notices were sent to Geodynamics Project correspondents in 175 geoscience departments and were published in *EOS* and *Geotimes*.

Subsequently, seven reporters have been added and one of the original reporters completed his task (see Part 3). Draft recommendations have been widely circulated by the reporters and by the USGC prior to actions that have been taken by the USGC. This included publication in *Geodynamics Project: U.S. Progress Report--1975* and *--1976*. There has been a steady series of mailings to the 175 Geodynamics Project correspondents and to the several scientific societies interested in the Geodynamics Project. Several notices about the activities of the reporters have appeared in *EOS*, *Geology*, and *Geotimes*.

In the fall of 1976, the Committee on the International Geodynamics Project of the Federal Council for Science, Engineering, and Technology (FCCSET-CSES) issued its first report.** The FCCSET-CSES first report was primarily a description of the activities related to the Geodynamics Project that are under way in the federal agencies. (It also included an excellent summary of the organizational and scientific background of the

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* Issued 10 March 1977.

**FCCSET-CSES--Federal Coordinating Council for Science, Engineering, and Technology--Committee on the Solid Earth Sciences. This is basically the former Committee on the International Geodynamics Project of the Federal Council on Science and Technology, which was transferred to the FCCSET with a broader responsibility and corresponding change in title.

Geodynamics Project.) The FCCSET-CSES plans to devote attention to recommendations and priorities in its second report.

The responsibilities of the FCCSET-CSES include serving "as the focal point for liaison with the U.S. Geodynamics Committee of the National Academy of Sciences...." To provide input to the FCCSET-CSES, the U.S. Geodynamics Committee devoted considerable discussion at its meeting in November 1976 to preparation of an up-to-date statement of the USGC actions developed by the USGC reporters. That discussion and subsequent communications by mail led to the following statements and recommendations that have been approved by the USGC.

The sequential listing of the topics in this report follows a pattern set in *Scope and Objectives*, with minor modifications as a result of the designation of new reporters. The sequence itself has no implication regarding priorities.

1. Fine Structure of the Crust and Upper Mantle

The USGC notes that the third experiment in deep reflection profiling--the Wind River Experiment in Wyoming--was initiated in 1976. The USGC raised questions about technology, for example, trade-offs in using existing equipment versus designing new apparatus, with longitudinal- versus shear-wave generators as an example. These questions were addressed in a statement prepared by the reporter (see below). The USGC considers that the deep reflection profiling is an extremely valuable activity and should be continued. The Committee is looking at the relation of this fine-structure program to other elements of the U.S. program for the Geodynamics Project, e.g., the plate interiors studies and continental drilling.

> Questions of trade-offs between use of existing equipment versus development of new apparatus are considered regularly by the COCORP program. The question of longitudinal- versus shear-wave generators has been under consideration for the duration of the program. The following points are relevant:
>
> 1. Information on shear properties of the basement and their spatial variation would be most valuable.
> 2. Whether the addition of shear-wave information to longitudinal-wave information at a particular site would be more valuable for solution of geological problems than additional longitudinal-wave data at that site or another site is debatable and may depend on the particular case.
> 3. The COCORP program to date has been dependent on the petroleum industry for development of its basic instrumentation and techniques.
> 4. The petroleum industry spends about $1 billion per year on geophysical prospecting, COCORP less than $1 million; therefore a modest investment of nonindustry funds is likely to produce something that will surpass the industry product only if the goal is not common.

5. Industry has developed, and is developing, shear-wave generators, but they are not in widespread use at present. Progress may be anticipated independently of COCORP, the Geodynamics Project, or other nonindustry action. COCORP is currently monitoring these developments and tests quite closely.
6. In view of the above points, and the urgency of getting on with the exploration of a major frontier of geology--the continental basement--COCORP during the next year plans to emphasize deep profiling based on longitudinal waves alone but will continue to monitor all developments on the shear-wave front and will conduct feasibility tests if appropriate.
7. COCORP plans similar monitoring of other industry or non-industry developments such as data telemetry, 3-D techniques, more powerful vibrators, and new analytical methods.

2. Evolution of Oceanic Lithosphere

This topic is a successor to and a broadening of the concept of the original priority "Mid-Atlantic Ridge." The USGC notes the success of the Cayman Trough study and looks forward to the results of the Galapagos study. The USGC calls attention to continued uncertainty with regard to the support of *Alvin* (the only submersible totally available to the academic community). This tool has proved valuable for geological investigations. Attention needs to be given to this basic problem.

The USGC addressed attention to the multiple-narrow-beam mapping system that has recently become available to the scientific community. The USGC endorsed the following summary and recommendation regarding this system.

Sonarray Mapping System

There presently exists within the U.S. Navy an advanced topographic mapping system that is potentially of great benefit to marine studies related to geodynamics. The system consists of a hull-mounted sonar array having two transducers perpendicular to one another. One transducer emits a beam 90 degrees in arc and 1 degree in width. The reflected signals are received by the second transducer and divided into 90 one-degree by one-degree squares. This results in the display of a bottom profile consisting of 90 point sources the width of which varies as a function of water depth, but in general ranges between 2-4 km.

Coupled with the Sonarray is an inertial navigation system supplemented by satellite and loran data. The navigation system generates a highly accurate shiptrack. The precise speed of the ship over the bottom is tied to the Sonarray profile, resulting in a real-time printout on a Cal-comp plotter of bathymetric data in the form of a contoured topographic map. A wide range of contour intervals and scale factors can be selected for printout, with 1:130,000 and 1:30,000 being the most common scales. The contour interval for these maps is 50 and 5 fathoms, respectively.

The real-time plot makes it possible to monitor the progress of the survey, leading to the construction of a shiptrack grid that ultimately results in total acoustic coverage of the region under study. The system can operate at 15-20 knots, during which gravity and magnetic data are also collected.

During the last few years, the U.S. Navy has permitted this system to be used in unclassified science programs. Thus far, surveys have been made in the Mid-Atlantic Ridge at 36° N, the mid-Cayman Rise, and more recently in the Galapagos Rift. These data are presently being released in the open literature. As the capability of the Sonarray system becomes known, more and more investigators are requesting surveys through the Office of Naval Research Committee on Sonarray Surveys. This rapidly growing increase in requests has quickly exhausted the Naval Oceanographic Office's capacity. As a result, a growing desire is developing within the earth-sciences community to acquire its own Sonarray system. Discussions have taken place between the Chairman of the ONR Committee and the Ocean Survey Division of NAVOCEANO in regard to conducting a workshop consisting of key personnel from NAVOCEANO who are presently responsible for the Navy system and earth scientists to investigate the capabilities of the various Sonarray systems and how the scientific community might ultimately acquire its own system.

Recommendation

It is recommended that the USGC sponsor such a workshop and develop a line of communication between the National Research Council and the U.S. Naval Oceanographic Office. Such a line of communication probably would best be established through the Under Secretary of the Navy for Research and Development.

3a. Internal Processes and Properties

The USGC took note of the reporter's updating of progress reports under the four categories of his topic:

(a) Rheological studies
(b) Phase studies at elevated pressures and temperatures
(c) Ultrasonic experimentation at elevated pressures
(d) Shock-wave experimentation

The USGC then addressed the question of high-pressure research in large volumes. There are certain types of experimentation that require large-volume apparatus (on the order of several hundred cubic centimeters). One is synthesis of large polycrystalline aggregates of geophysically interesting materials. These would be useful in ultrasonic research at elevated pressures and temperatures and also for shock-wave research, which to date has been hampered in its study of minerals by unavailability of appropriate starting materials. A second type of experimentation that requires large volumes may be called "real earth" experiments, that is, the measurement of several properties on rocks at the same time under identical pressure and temperature conditions. Example: To study simultaneously the effect of pressure and temperature on electrical conductivity, elastic-wave velocities, and state of strain. This can be called a "real earth" type of experiment because it is precisely the type of simultaneous measurement that geophysicists make on the earth itself.

The USGC appointed a new reporter (Robert Riecker) to develop recommendations regarding large-volume experimentation. Following the pattern set by other reporters, this reporter is seeking suggestions from the scientific community. To this end, an initial meeting of a working group was convened by the reporter in December 1976. A second meeting is planned for late March 1977. The reporter expects to submit initial recommendations for consideration by the USGC in advance of its meeting in April 1977.*

It was reported to the USGC that there is now a good possibility to develop high-pressure systems using excellent quality sintered diamond aggregates. It was stated that these have been tested and are superior to other sintered diamonds when used as tool bits. The USGC endorsed these efforts to make large polycrystalline diamond compacts and to develop practical methods of machining polycrystalline diamonds.

3b. Crystal Growing

The USGC expressed gratification with the following report of the working group convened by the reporter:

> At its meeting on 14 April 1976, the Working Group on Crystal Growing reviewed replies to its request for information from potential users of single crystals and determined that a substantial need existed. As outlined in *Geodynamics Project: U.S. Progress Report--1976*, the group believed that efforts to produce single crystals should get under way. Such efforts are one of the original goals of experimentation within the Geodynamics Project. At least two proposals along this line are being submitted, one for synthetic orthoenstatite and one for olivines intermediate between forsterite and fayalite.
>
> It was another suggestion of the working group that efforts to make small (about 0.1 mm or less) crystals of very-high-pressure phases be encouraged. Although these specimens are somewhat outside the purview of the working group, their use in diamond cell measurements permits much valuable information to be obtained at mantle pressures.
>
> A further proposal is to grow large crystals of the various phases of $MgSiO_3$, $CaMgSi_2O_6$ (diopside), and the substitution of ferrous iron for MgO in these phases. In the latter, a serious attempt will be made to control the

*See Part 3, Section 3c.

oxidation state in the iron-bearing synthetic materials, which is important in obtaining crystals of relevant compositions for geodynamic applications.

The USGC supports the activity of this working group in determining the needs of the community, identifying scientific objectives, and taking action to encourage syntheses of desired crystals.

4. Application of Isotope Geochemistry to Geodynamics

The USGC reiterated its desire to encourage efforts to determine the potential contributions of geochemistry to the Geodynamics Project. Potential contributions in isotope goechemistry were identified. Two suggestions were proposed: compiling geochronology files including evaluation and inclusion in the annual USGC Progress Report of a section regarding advances in isotope and trace-element research pertinent to dynamic processes and crustal structure. Specific topics might include the following:

(a) The existence of a continental lithospheric keel
(b) The metamorphic and compositional state of the lower crust
(c) The evolution of the crust
(d) The existence of blocks of rock of unsuspected age in that crust
(e) The levels at which magmas of various kinds develop their essential character
(f) The evolution of orogenic belts
(g) Progress in metallogenesis using the plate-tectonics concept

The USGC was concerned about the time scale of compiling geochronology files. It may be most useful to encourage compiling data for places where there are other Geodynamics Project activities, for example, areas involved in the deep-reflection profiling, plate interiors studies, and plate margins studies. The USGC appointed a new reporter (Bruce Doe) to assist in evolving specific recommendations on this topic.

5. Geodynamic Modeling

The USGC discussed the question of fundamental research in the earthquake prediction program. The USGC expressed concern that fundamental studies might be neglected. (This is not intended to imply that the USGC objects to other aspects of the program.) The USGC endorsed the following statement of the reporter.

Recommendation for Integration of Modeling Studies into a Program of Research on the San Andreas Fault

Plate tectonics provides a basic framework for understanding geological phenomena on the earth. In terms of plate tectonics, the San Andreas fault represents lateral sliding between the Pacific and North American plates. Since this is a major plate boundary, regular great earthquakes can be expected. The historical seismicity confirms this conclusion. Because of the large population density and indications that a great earthquake in southern California may be imminent, a major research effort on the San Andreas fault should receive high priority.

Studies of the San Andreas fault must in large part be observational. Data on microearthquake activity, seismic velocities, strain, stress, gravity, magnetics, etc. are essential to understanding the fault itself and identifying possible precursors to major earthquakes. However, a balanced program of research must include theoretical modeling studies, both analytical and numerical.

It is only within the last ten years that plate tectonics has provided a basis for modeling the behavior of the San Andreas fault. It is now possible to model the basic processes of strain accumulation and release on the fault. Studies of this type can provide interpretations of data and can suggest critical observations that should be carried out. Many other aspects of the fault can now be subjected to study and analysis with a good probability of new insights.

Since theoretical studies of this type are new, very few scientists are involved at present. A strong background in physics, mechanics, mathematics, and computers must be combined with a strong background in geology. Since few degree programs provide and few thesis advisors encourage this combination, the number of scientists trained with the necessary background is small. Also, there is not a significant focus for this type of effort within the federal agencies.

High priority should be given to modeling studies of the San Andreas fault. A specific focus should be given to this research either as a separate program or as a subprogram of research on the San Andreas fault.

6. Drilling for Scientific Purposes

The USGC reaffirms its resolutions regarding continental drilling adopted in April 1975 and published in *Geodynamics Project: U.S. Progress Report--1975*, pages 10-11, in particular resolution No. 3:

> The USGC endorses the statements of scientific objectives in the report *Continental Drilling* and urges that steps be taken in consultation with the FCST-IGP Committee to determine the best means of implementation of a program to achieve these objectives.

The USGC notes that a subcommittee of the FCCSET-CSES has been actively investigating the question of implementation of the proposed program of

Continental Drilling. The USGC urges prompt establishment of an office for Continental Drilling in an appropriate government agency to be staffed by a full-time coordinator. Such an office would provide both visibility for a national program of drilling and a much needed focal point and clearinghouse within the federal government for information on drilling for scientific purposes.

7. Magnetic Problems

The reporter indicated that the Geological Society of America has approved the proposal for a Penrose conference on magnetization of sediments (12-16 December 1977). The purpose of the conference is stated below. The USGC had earlier indicated the importance of organizing such a conference and expressed gratification that the conference is now definitely scheduled.

Conference on Magnetization of Sediments and Magnetostratigraphy

In the past few years, considerable interest has been focused on the application of paleomagnetic results from sedimentary rocks to problems of (1) understanding the behavior of the magnetic field, (2) regional stratigraphic correlation, and (3) establishment of polar wander curves to be used in tectonic reconstructions on both local and global scales. At the same time, a controversy has developed as to when and by what processes these sediments have acquired their remanent magnetization. With the advent of new, more sensitive and sophisticated equipment (including widespread use of cryogenic magnetometers) during the past few years, the time is right for a significant advance in our understanding of the magnetization of sediments. A Penrose conference is thought to be the proper forum to use to encourage the development and understanding of this topic, for it provides an opportunity to bring into close contact a select group of sedimentologists, sedimentary petrographers, sedimentary geochemists, and stratigraphers and a group of individuals generally classed as geophysicists, namely, rock magnetists, paleomagnetists, and solid-state physicists. The interaction of these groups of individuals representing many subdisciplines is certain to increase our understanding of the origin of the magnetization of sediments and should also foster additional applications of this relatively new branch of science to the more classical problems of stratigraphic correlation, sediment diagenesis, and regional and global tectonics.

8. Plate Boundaries

The USGC received with great interest the following statement from the reporter:

> Seventeen of the eighteen cross sections proposed by the participants in the Plate Boundaries Group were displayed at a poster

session during the Annual Meeting of the Geological Society of America in Denver, 8-11 November 1976. The sections inspired much favorable comment. We were especially encouraged by the offer of four potential participants to construct similar cross sections in southeast Alaska, eastern Oregon-Montana, and Utah-Wyoming, thus extending coverage into other tectonically important areas. Dr. Raymond A. Price (Chairman of the Canadian Geodynamics Committee) has also suggested that a similar program may be started for the Canadian Cordillera. It is thus possible that coverage will eventually be available from Kodiak Island to the Mexican border.

The primary concern of the group at this moment is the early publication of the cross sections and supporting data. The Geological Society of America has expressed interest in publishing this material as part of the map series. A uniform scale of 1:250,000 is currently under consideration. The sections and supporting material would be available separately or could be purchased as a complete portfolio. The participants feel very strongly that publication in color would greatly increase the usefulness of the cross sections, and our immediate problem is to assess the feasibility of color publication. If this turns out to be too costly, we will then proceed with publication in black and white. We are hoping to see publication of most of the sections by December 1977, though at the moment it appears likely the series will be open-ended to accommodate additional sections.

The USGC congratulated the Plate Boundaries Group on its successful preparation and exhibition of the cross sections and strongly supports efforts to publish these cross sections in the most useful form.

9. Plate Interiors

The USGC reviewed the following assessment prepared by the reporter:

(1) Deep Structure of the Lithosphere below Cratonic Basins and Arches

There are currently as many models of cratonic sedimentary basins as there are individuals or teams of interested investigators. No single model or combination of models (thermal contraction, sediment loading, rift-related, extensional, compressional, mantle diapir, crustal thickening or attenuation, for example) is subject to unequivocal acceptance or dismissal without knowledge of the gross and fine structure of the crust and upper mantle below sedimentary basins. No deep seismic reflection profiling has yet been carried out in a cratonic sedimentary basin, and no refraction lines capable of resolving subbasin crust-mantle geometry are known to exist.

(a) A first step toward filling these gaps in knowledge would be a COCORP deep profile within a basin. The Michigan Basin is the archetypical cratonic basin; its Phanerozoic succession has been thoroughly elucidated by drilling and by exploration seismic profiling; and its basement rocks have been penetrated, cored, and investigated to a depth of 1500 m near the basin center. A proposal for a long-record reflection profile has been submitted to the COCORP Site Committee for consideration of a line passing the single deep exploratory borehole, crossing the axis and flank of the Michigan Positive Anomaly, and including a segment of a broad region of apparent mass deficiency.

(b) Attainment of a deep reflection section in the Michigan Basin would be greatly increased in importance if equivalent data for comparison were obtained on the adjoining Wisconsin Arch, an element whose evolution is closely related to that of the Michigan Basin and to much of the continental interior. Not incidentally, a COCORP profile on the Wisconsin Arch would have great significance in terms of current consideration of possible ultra-deep sites for disposal of high-level atomic wastes.

(c) Clearly, suitably designed refraction lines across the Michigan Basin and Wisconsin Arch will be required before acceptable basin/arch models are achieved.

(d) Resolution of controversy over one basin/arch couple will inevitably raise questions about similar basins and arches, e.g., Williston Basin/Sweetgrass Arch; aulacogenic basins, e.g., Anadarko Basin; fault-bounded (yoked) basins, e.g., Denver Basin; and the basins of passive margins.

(2) Phanerozoic Geochronology

Meaningful synthesis of the vast array of data available on the Phanerozoic evolution of the continental interior is dependent on development of an absolute-time chronology permitting analysis of the timing and rates of subsidence and emergence within a single area and from area to area. Currently, individual laboratories and investigators, applying different isotopic ratios and different decay rates, produce widely differing "dates," commonly without reference to supporting field and laboratory data that would permit evaluation of confidence levels. Coordination of data reduction and publication, combined with identification and concentration of effort on the gaps in existing knowledge, would constitute a major advance.

(3) Release of Proprietary Information

Completion of the Michigan-Hatteras Continental Cross Section and certain other projects of the Plate Interiors Group has not proceeded at useful rates, in part because of the lack of ready availability of industrial data--particularly stratigraphically interpreted seismic record sections plotted as depths. The problem has been discussed with the AAPG Research Committee, and cooperation has been agreed upon, in principle; the lack of progress is more an indictment of this reporter than of industry representatives.

The USGC urges COCORP to consider carefully the recommendations prepared by the reporter on plate interiors that are pertinent to the COCORP program. The USGC notes that the question of Phanerozoic geochronology is related to the question of application of isotope geochemistry to geodynamics. This problem might be a suitable topic for a Penrose-type conference including experts in structure of continental interiors and isotope age dating.

10. Geodynamic Syntheses

The USGC reviewed with interest the following status report prepared by the reporter and endorsed the recommendations contained in that report.

Status Report on Data Repositories for
the International Geodynamics Project

Background

The need for compilations and data exchange was discussed in the report *U.S. Program for the Geodynamics Project: Scope and Objectives* issued by the U.S. Geodynamics Committee in 1973 (Chapter 10, pp. 187-188). At the time, we were thinking largely in terms of broad compilations or syntheses of data, both regional and topical, that were pertinent to geodynamic objectives. It rapidly became apparent that a large number of data repositories existed from which the data could be drawn to form the basis of geodynamic syntheses.

In 1975, all the Geodynamics Project correspondents and many others were circularized with a questionnaire, but there was much resulting confusion regarding what constituted a "data bank" or "repository." Consequently, another questionnaire was sent out in July 1976, which yielded many responses. As a result, an impressive listing of data banks has been compiled.*

Scope of Data Repositories

In this report we have tried to err on the side of treating too many activities as being relevant to the geodynamics program. Many activities have been listed without specific permission,** and it is likely that many important

* "First Revision of Draft Report on U.S. Data Repositories for International Geodynamics Project," A.H. Shapley, 10 November 1976.
**Information was provided by another source.

repositories are still unlisted.

We consider that there are three general types of data and repositories:

1. Basic observational data, which are useful to many other scientists as well as to the original observers
2. Individual data syntheses (e.g., geochemistry of various rock types, relationships between rock types and acoustic velocity) which are often too lengthy for detailed publication in the usual scientific literature
3. Data syntheses (e.g., maps, cross sections) whose availability would forestall needless duplication of effort

Recommendations

1. It is obvious that the present list is not exhaustive. Consequently, we recommend that the list be circulated among the Committee and the reporters for possible additions and corrections and that it then be circulated to a wider group (Geodynamics Project correspondents and others) with a similar request for additions and corrections.

2. We believe that certain of these existing data banks and repositories are uniquely relevant to the objectives of geodynamics and that there is no existing repository for some categories of data pertinent to geodynamics. Consequently, we recommend that the Committee make specific recommendations regarding the expansion of certain existing data banks and the creation of new repositories for data not now being collected systematically.

3. We believe that data banks and repositories exist overseas that are pertinent to geodynamic objectives. Consequently, we recommend that this list be forwarded to the Inter-Union Commission on Geodynamics with a similar request for additions and corrections, as well as for the general interest of the international scientific community.

4. When that list of repositories is in hand, the Committee should make specific recommendations regarding syntheses or compilations that appear to be particularly desirable (examples include the AAPG heat-flow map series, the Circum-Pacific Map Project, SEG's North American Gravity Map, and our own compilations regarding plate boundaries and plate interiors).

11. Geodynamic Activities in the Caribbean Area

The USGC noted the detailed report prepared by the reporter and published in the USGC *Progress Report--1976* and the subsequent report of a meeting of a working group on geodynamics of the Caribbean area held in July 1976. In addition, the USGC received the following statement on Caribbean priorities from the reporter in November 1976.

Caribbean Priorities

As stated in my previous reports, the Caribbean Study Group has recommended a series of projects in most of which the first phase is compilation of existing data.

The compilation of a series of cross sections is being started. This can be continued up to a point without funding, but travel funds will be needed to enable cooperating workers to coordinate their results.

It is felt by many members of the Study Group that a meeting of those working or proposing to work in Hispaniola is of utmost urgency. The meeting should be held in Hispaniola and should include all resident geologists and geophysicists.

Hispaniola is certainly critical to a wide variety of the topical problems recommended for study, and if a good coordinated program can be formulated great progress will be made. There are approximately 20 workers from outside Hispaniola who would be involved. It is therefore urgent that funds be made available for such a meeting.

The problem of the "hinge areas" starting with the southeast--Barbados, Venezuela, Grenada, and the Grenadines--is also of high priority but is probably not quite so urgent as Hispaniola, where a number of projects are being talked about without others being aware of exactly what is being proposed.

The USGC strongly supports the proposal to prepare a series of cross sections. This is an excellent way to define the problems and to arouse the interest of the various countries in those problems. The USGC notes that agreement was reached on the preparation of three cross sections (including a section across Hispaniola) by a working group meeting in January 1977. The USGC strongly encourages this activity and expresses hope that the working group can prepare these cross sections in time for presentation at the Caribbean Geological Congress to be held in Curacao, July 1977 (see Part 3, Section 11).

12. Lithospheric Properties

The USGC reiterated its support for the following recommendations. These recommendations were published in the USGC *Progress Report--1976*, pages 61-62:

1. The USGC supports the efforts of the Committee on Seismology in seeking long-term federal funding of global seismic networks.
2. The USGC recognizes the importance of ocean-bottom seismographic techniques in the delineation of oceanic upper-mantle structure and encourages national and international cooperation in projects involving ocean-bottom seismometers.
3. The USGC encourages efforts to explore the feasibility of conducting high-density long-line refraction profiles on the North American continent, perhaps in cooperation with Canadian institutions.
4. Recognizing that seismic reflection profiling has probed the lithosphere to upper-mantle depths in continental as well as oceanic areas, the USGC recommends that further development of reflection methods be supported, because this method may have the potential to probe the entire lithosphere.

13. Aeromagnetic Survey

After reviewing the recommendations in the report *National Magnetic Anomaly Map*, the USGC approved the following resolutions:

1. A major effort should be made to produce a regional national magnetic anomaly map and consistent data set by utilizing available data to the extent possible and by flying additional aeromagnetic surveys for that purpose as needed.
2. In view of the time required to complete the national magnetic anomaly survey, an interim national map and quasi-consistent data set should be prepared from existing available data and magnetic data currently being collected by the Energy Research and Development Administration as part of the National Uranium Resource Evaluation Program.*
3. Since neither 1 nor 2 will be accomplished in the near future, a colored photomosaic of available magnetic data should be prepared as a preliminary magnetic anomaly map.

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*This resolution was approved by the USGC and forwarded to ERDA in September 1976.

3. REPORTERS' REPORTS

Designation of reporters to assist the U.S. Geodynamics Committee (USGC) in implementing the initial and subsequently identified priorities of the U.S. program for the Geodynamics Project is discussed in some detail in *Geodynamics Project: U.S. Progress Report--1975*. These reporters have endeavored to consult as widely as possible throughout the scientific community with persons nominated by the geoscience societies, the Geodynamics Project correspondents in 175 geoscience departments (and their colleagues), and others known to be interested in the specific topic. The activities of the reporters were publicized in the scientific journals, especially *EOS* and *Geotimes*. The USGC believes that this method of assembling advice and recommendations ensures a broad representative input.

Ten reporters were designated in 1973, corresponding to the initial priorities set forth in *U.S. Program for the Geodynamics Project: Scope and Objectives*. One has completed his task; seven others have subsequently been added. The topics and reporters are as follows:

	Topic	Reporter
1.	Fine Structure of the Crust and Upper Mantle	Jack E. Oliver
2.	Evolution of Oceanic Lithosphere*	James R. Heirtzler
3a.	Internal Processes and Properties	John C. Jamieson
3b.	Crystal Growing	Thomas M. Usselman
3c.	Large Volume Experimentation	Robert E. Riecker
4.	Application of Isotope Geochemistry to Geodynamics**	Bruce R. Doe
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 Syntheses	Creighton A. Burk
10b.	Data Centers and Repositories	Alan H. Shapley
11.	Geodynamic Activities in the Caribbean Area	John D. Weaver
12.	Lithospheric Properties	Thomas H. Jordan
13.	Aeromagnetic Survey	William J. Hinze

* Formerly Mid-Atlantic Ridge.

**Topic No. 4 was previously entitled "Chemical Differentiation of Magmas." A final report on that topic was published in *Geodynamics Project: U.S. Progress Report--1975*.

1

FINE STRUCTURE OF THE CRUST AND UPPER MANTLE

JACK E. OLIVER AND SIDNEY KAUFMAN

The COCORP (Consortium for Continental Reflection Profiling) program has the long-term goal of widespread application of the powerful and elegant seismic reflection profiling technique (commonly used by the petroleum industry for exploration of sedimentary basins) to studies of the basement rocks of the crust and upper mantle. The COCORP experiment, which is part of the U.S. program for the Geodynamics Project, began in 1974 with support of the National Science Foundation. COCORP is testing the application of the reflection technique to study crustal structure at depths 5 to 10 times greater than those to which the method is normally applied by industry. There are two principal reasons for undertaking this program. First, the deep basement of the continents is a major frontier of geology. The rocks there are poorly known, but must be closely related to near-surface geology. A knowledge of them is critical to a solution of such fundamental questions as genesis of the continents, formation of certain mineral deposits, and evolution of sedimentary basins. Second, the seismic reflection technique, which far surpasses all other geophysical techniques in spatial resolution of geological features, has exceptional potential for studies of the basement.

The first full-scale test was carried out in Hardeman County, Texas, in early 1975. Preliminary results of that study were summarized in *Geodynamics Project: U.S. Progress Report--1975*; a more complete discussion appeared in the *Bulletin of the Geological Society of America* (Oliver *et al.*, 1976). The test was very productive; information on reflectors and diffractors extending throughout the basement section to depths of approximately 50 km was obtained. Resolution of deep features of the order of a few kilometers in scale was achieved. The Hardeman County site was chosen partly because industry experience indicated that reflection quality within the shallow basement rocks was likely to be good. Thus, it was not clear that equally favorable results would necessarily be obtained elsewhere.

For the second field test, a site spanning the eastern margin of the Albuquerque-Belen Basin of the Rio Grande Rift in Central New Mexico was selected. This site was chosen primarily because of scientific interest in this important geological feature. The field work was conducted late in 1975. Success in obtaining reflections to depths at least as great as about 40 km at the New Mexico site plus related experience elsewhere indicates that the Hardeman results were not unique and implies that the

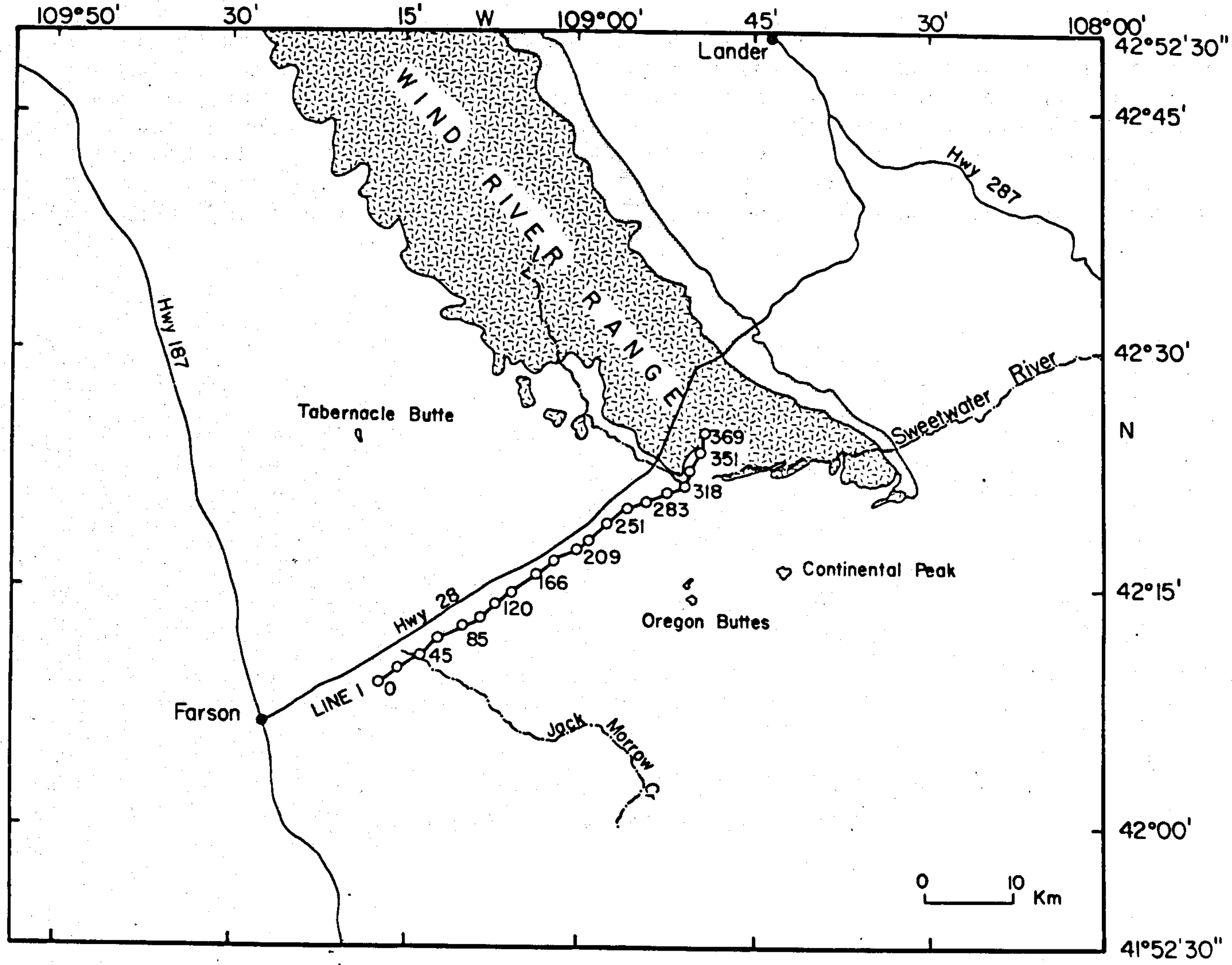

FIGURE 1.1 Location of completed portion of COCORP deep seismic reflection profile in the Wind River Uplift area, southwest Wyoming. Total length is about 52 km. Numbers refer to source points of the seismic survey. Profile is to be extended to the northeast in late 1977.

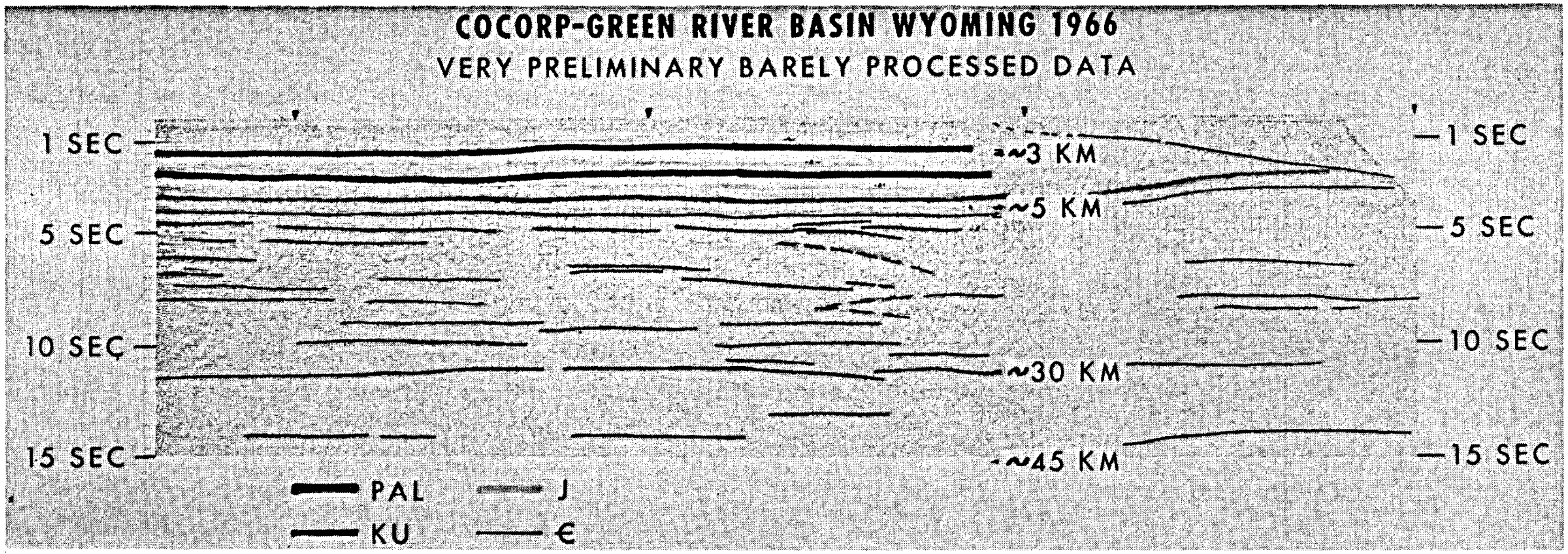

FIGURE 1.2 Preliminary version of the deep seismic section obtained across the Wind River Thrust. First 15 sec of record are shown. Depths are approximate. Flat-lying reflectors on left of shallow portion of the section represent the Green River Basin. The Wind River Thrust is seen as a north (right) dipping event on the right side of the section. Numerous reflectors are apparent within the basement (at times between 5 and 10 sec). A prominent reflector occurs at about 11 sec, possibly representing the Moho. Several sub-Moho events can also be seen. The section was obtained using a 24-fold Common Depth Point technique with a 440-ft source-point spacing.

method will be productive at many, although perhaps not all, sites. The results of this test were reported in *Geodynamics Project: U.S. Progress Report--1976* and in *Geotimes*, July 1976.

The third experiment was conducted in the Wind River uplift area of Wyoming in November 1976 (Figures 1.1, 1.2). The experiment was interrupted by the advent of low temperatures (-28°F) and snow (6-8 ft drifts over the trails). It is expected that the experiment will be resumed in August-September 1977.

Some 52.5 km (32.6 miles) of seismic line were run in addition to a 36-fold two-way expanding velocity spread covering 11.7 km (7.3 miles) and a series of noise studies. The production line started 10 km (6.25 miles) northeast of Farson and extended to the outskirts of South Pass City. A rough examination of the monitor records indicates a reasonably continuous north-dipping event in the 12-13-second region with steeper mixed dips and greater complexity appearing at the northern end of the profile. Noise studies showed a great range of apparent velocities of the source-generated surface and near-surface signals--from that of sound in air to over 2.1 km/sec (7000 ft/sec). The geophone station spacing was 134 m (440 ft) with 32 phones in a variable-spaced array over a linear distance of 186 m (610 ft); the source array of five vibrators spaced at 27-m (88 ft) intervals moved 16 times for each record, covering a linear distance of 241 m (792 ft). The pilot signal was a 20-second linear upsweep from 8 to 32 Hz, and the listening time was 50 seconds.

Data are in a preliminary state of processing. They indicate a fairly strong and continuous reflector at time 11+ seconds (approximately 30-35 km depth). This is tentatively correlated with Moho, although the depth is somewhat shallower than the depth determined for Moho in a refraction survey some distance from the reflection line.

At the north end of the line, the Wind River thrust was clearly evident in a region where Precambrian crystalline rocks overlie sedimentary rocks. Presumably, at depth, the fault is bounded by Precambrian rocks on both sides, but the field work was interrupted before this region was encountered. There are numerous other reflectors within the crust and scattered reflectors within the mantle.

The fourth field test was conducted in the Socorro area of the Rio Grande Rift Region of New Mexico just south and west of the Abo Pass test area (the second field experiment). This experiment was run during the winter of 1976-77. Some 127.1 km (79 miles) of seismic line were run in the neighborhood of Socorro, just south and west of the Abo Pass test area so that a total of 165 km (102.6 miles) of line profile has been obtained in this region of the rift. The field monitor records indicate that the 7-8-second strong reflector, outlining a possible magma chamber, does persist over the area.

Professor Ronald W. Ward (University of Texas at Dallas) and his students have been "piggy-backing" during the work in the Socorro area. They set up an L-shaped array some miles off COCORP's long east-west line (from the eastern edge of the rift at Abo Pass, westward across the valley, to the Colorado Plateau on the west edge of the rift) at a point about 12 miles from the western edge of the line, and recorded all signals as the vibrator array proceeded along the line. Thus, they should have unique refraction and off-line reflection data to augment the COCORP line profile.

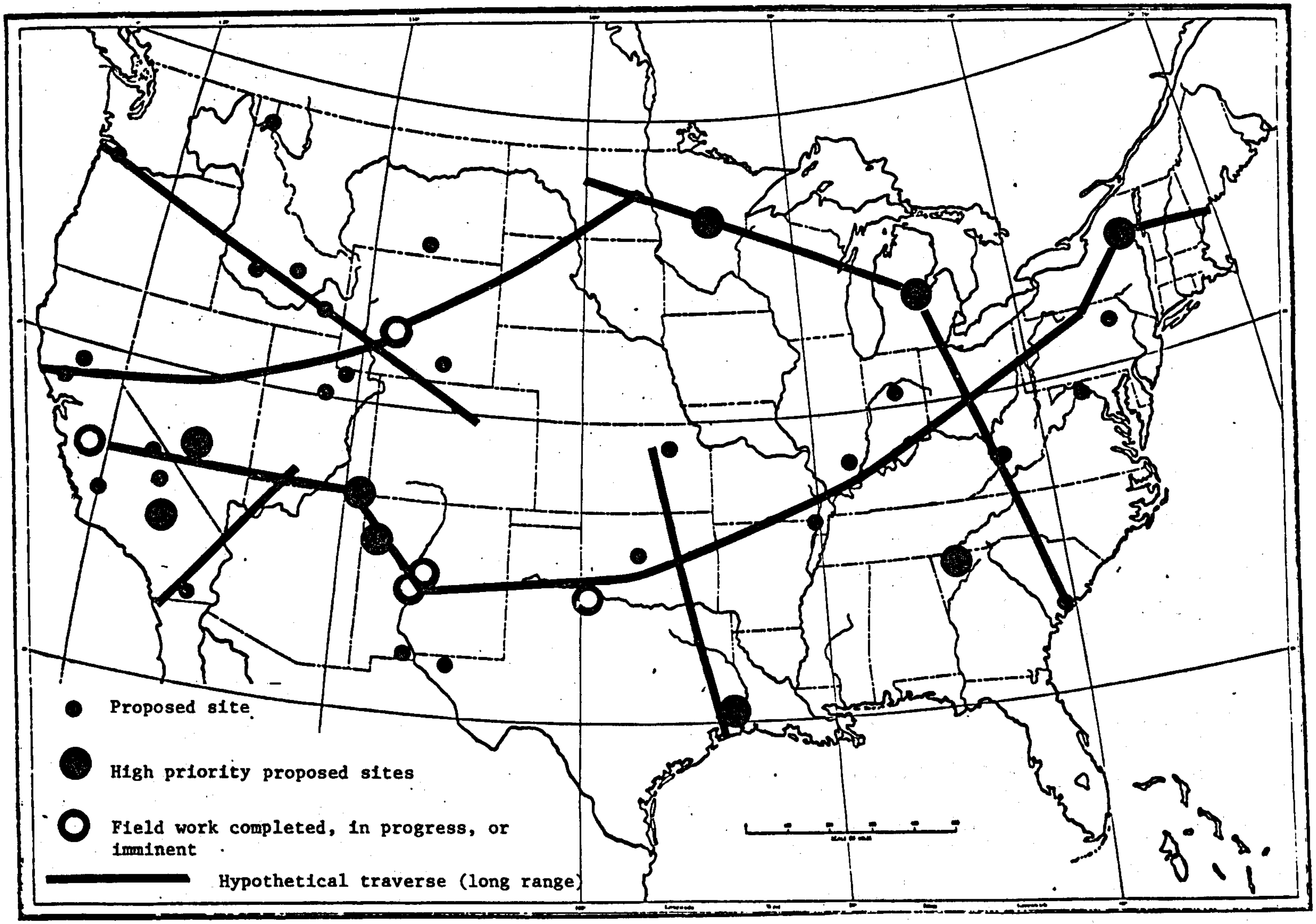

FIGURE 1.3 Status of sites which have been proposed to COCORP for seismic reflection profiling.

The fifth experiment was conducted in the Great Valley of California, May-June 1977.

The sixth experiment is planned for August-September 1977--a return to complete the work in the Wind River Experiment.

Locations of sites of proposed and completed experiments are shown in Figure 1.3.

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Oliver, J.E., M. Dobrin, S. Kaufman, R. Meyer, and R. Phinney (1976). Continuous Seismic Reflection Profiling of the Deep Basement: Hardeman County, Texas. *Bull. Geol. Soc. Am.*, 87, 1537-1546.

__________ and S. Kaufman (1976). Profiling the Rio Grande Rift. *Geotimes*, 21, 20-23.

June 1977

2

EVOLUTION OF OCEANIC LITHOSPHERE

JAMES R. HEIRTZLER

Much of the marine scientific community has been involved in detailed studies of mid-ocean ridge spreading centers. Project FAMOUS was the first of this type of intensive study but work has also begun in the Cayman Trough and in the Galapagos Rift. Narrow-beam echo-sounding surveys, submersible dives, and shipboard studies have been undertaken in both of these quite different localities. In the Cayman Trough, there was recovery of gabbros and other rocks that are thought to be derived from deep in the crust. In the Galapagos Rift, studies were focused on hot geothermal vents in the rift axis and in a region of more diffuse heat flux 10 miles south of the axis. Markers were left to guide the *Glomar Challenger* in finding drill sites at a later date.

The active hydrothermal vents are the first directly observed on a mid-ocean ridge. Water temperatures up to 17°C were measured over them. These vents are the foci of intense biological activity on the sea floor (Figures 2.1-2.4). Tight clusters of clams, mussels, crabs and other organisms near hydrothermal vents on the Galapagos Rift contrast with sparse life found elsewhere in the area. These areas of abundant life were found to be about 50 m across. Some of the inhabitants appear to be related to known species though the rift fauna are in many cases much larger. Analysis of samples is still in the preliminary stages and some of the rift fauna are so far unidentified. Five vent communities were found on the Galapagos Rift and investigated during the dives by the submersible *Alvin*. Four were active; one vent no longer spouted warm water as evidenced by dead clams and mussels. Marine biologists are familiar with two worms similar to those photographed in the rift zone (Figure 2.4) but usually in much smaller forms than those encountered in the rift zone.

A large number of American publications of the Project FAMOUS work appeared in the April and May 1977 issues of the *Bulletin of the Geological Society of America*. Other publications will be forthcoming in the next few months.

Plans are being made to return to the FAMOUS area in the summer of 1978. There are additional plans to do submersible work in the Tamayo Fracture Zone at 21° N in the East Pacific and in the Siqueros Fracture Zone at 9° N also in the East Pacific. Both French and American submersible dives are planned for the Tamayo, pending permission, as required, from Mexico.

The value of multi-narrow-beam echo-sounding surveys has been proven to the scientific community. These surveys are helpful especially when made in conjunction with submersible dives or with deep-sea drilling. A group is meeting to recommend action that the marine research community may wish to take to have this capability on a regular basis.

Many multichannel seismic data are being accumulated, especially for the eastern margin of the United States and for a few similar areas throughout the world. The accurate reconstructions now being made for the North Atlantic Ocean from magnetic and bathymetric data are being matched by the deep multichannel sections being obtained at the present ocean margins.

While seismographs and magnetometers have occasionally recorded on the sea floor, these and other instruments (temperature recorders, strain meters, etc.) are being prepared to be left on the sea floor or in the deep-sea drill holes for extended periods of time.

June 1977

FIGURE CAPTIONS*

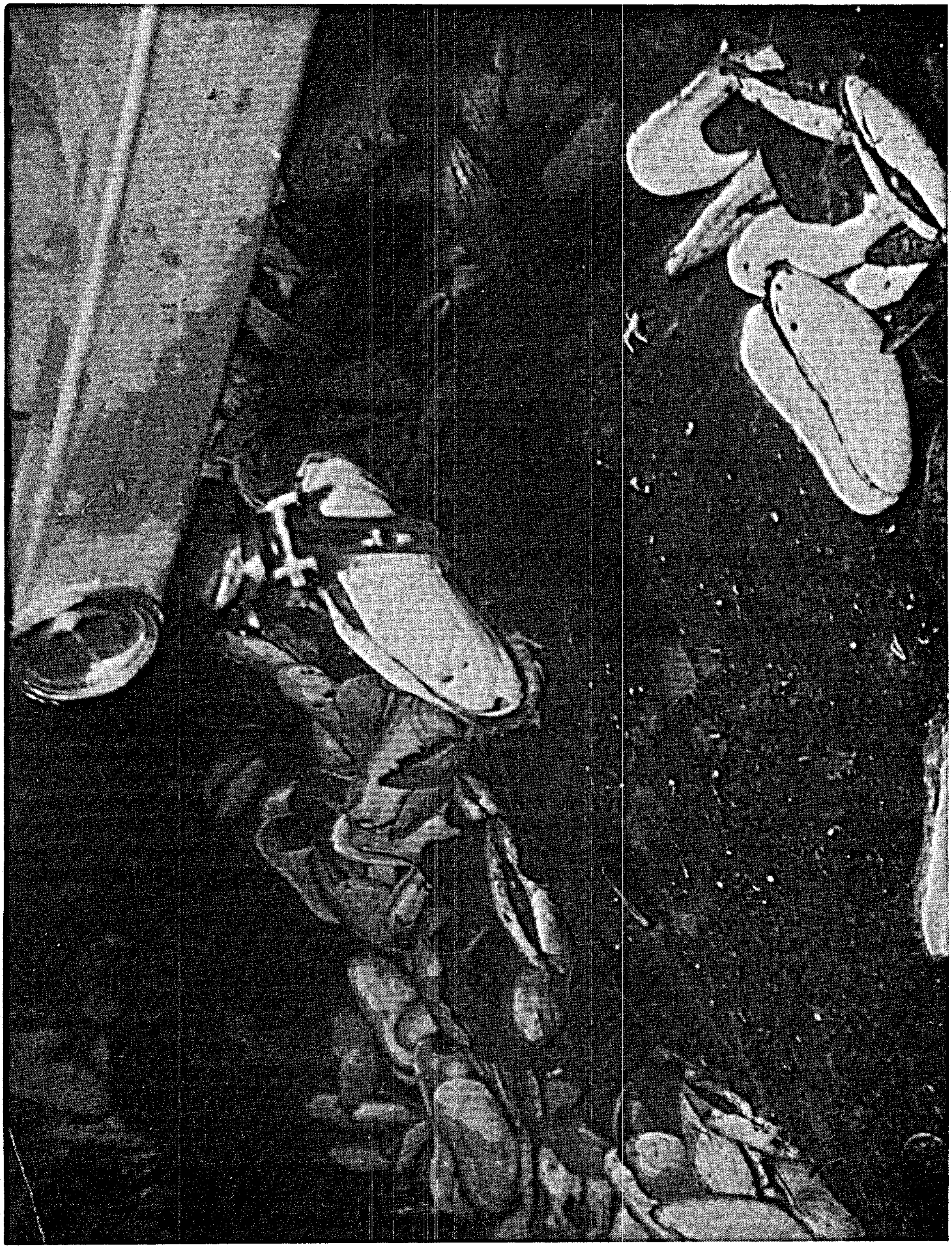
FIGURE 2.1 Crab (about 6 in., 15 cm), seaworms, and dead clams in a hydrothermal region of the Galapagos Rift. (Photographed from the submersible *Alvin* by Robert Ballard, Woods Hole Oceanographic Institution)

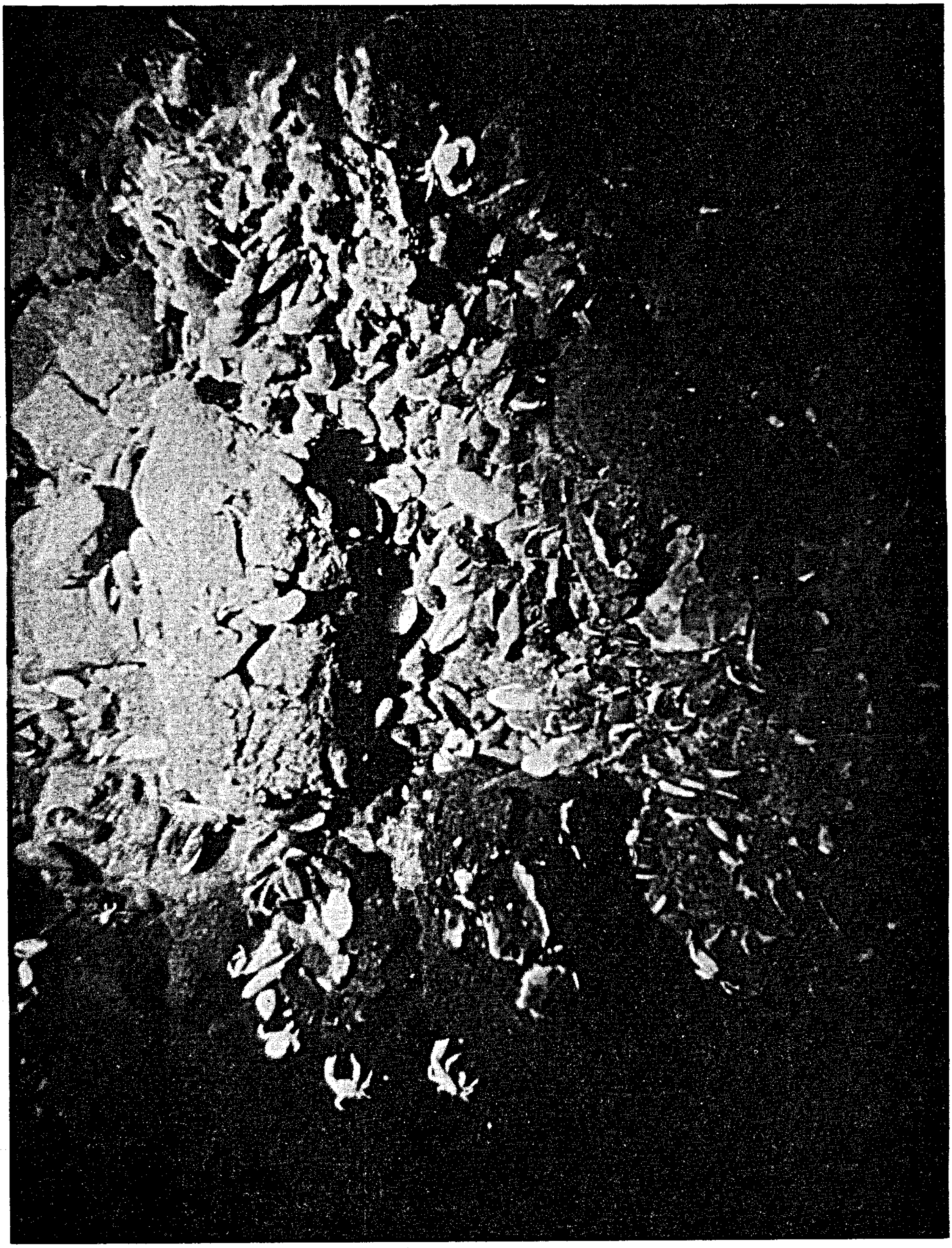
FIGURE 2.2 Large clam (about 12 in., 30 cm) in the mechanical arm of the submersible *Alvin* in a hydrothermal region of the Galapagos Rift. (Photo by Robert Ballard, Woods Hole Oceanographic Institution)

FIGURE 2.3 Clusters of clams, mussels, crabs, and other organisms near hydrothermal vents on the Galapagos Rift at a depth of about 9000 ft (2800 m). (Photographed from the submersible *Alvin*, Woods Hole Oceanographic Institution)

FIGURE 2.4 Tubeworms about 14-18 in. (36-46 cm) long at the depth of about 9000 ft (2800 m) in the Galapagos Rift Zone. Limpets, crabs, seaworms, and an unknown variety of fish are also seen in the photograph. (Photographed from the submersible *Alvin* by John Edmond, Massachusetts Institute of Technology)

* Figures 2.1-2.4 appear on pages 26-29





3A
INTERNAL PROCESSES AND PROPERTIES

JOHN C. JAMIESON

The area of laboratory studies of internal processes has reached the stage that is typical of experimental work in general. Namely, over the last four or five years new techniques and apparatus have been evolved and the experimentalists are in the process of exploiting these using them on geophysical materials. This will be seen quite readily in what follows.

Starting in 1972 with the advent of truly hydrostatic media for studies to 100 kb in diamond cells, the development of this technique has been very great. I am not referring here to the extreme pressures being reported from Carnegie, which is a feat all in itself, but to the development of a relatively cheap technique which can be utilized in many mineralogical laboratories which are already doing single crystal x-ray diffraction. This is evidenced by the several publications of Hazen, currently at Carnegie Institution, appearing mostly in the *American Mineralogist*. This should be a very active area in the foreseeable future. There is now starting to appear an interaction between diamond cell work and ultrasonics as evidenced by a paper presented at the spring meeting of AGU by D. J. Weidner (SUNY Stony Brook) *et al.* In this case a single crystal of orthoenstatite was studied ultrasonically to determine some elastic constants and all elastic constants were determined using Brillouin scattering. A recent paper by Weidner and Carlston demonstrated that such elastic constants can also be determined on very fine-grain high-pressure phases (they did so on coesite). The Bassett group at Rochester has shown the feasibility of the diamond cell combined with Brillouin scattering. This is certain to be picked up by other laboratories. Although this particular use still seems inferior in accuracy to precision ultrasonic measurements on large single crystals as a function of pressure, such crystals are not always readily available; hence, the Brillouin-scattering technique should thrive. In addition, recently the team of William Bassett, John Liu and John Sharry has been successful in quenching a new phase of silica from glasses at 300 kb heated by a laser. In quenched samples, they identified the recovered samples as a rutile-type phase, namely stishovite, plus additional lines. Indexing x-ray diffraction lines of this new material indicates a density slightly less than stishovite, so the relative stabilities are unknown.

The development of elastic-wave measurements (both longitudinal and shear) in isotropic aggregates to pressures of 100 kb at Los Alamos and Watervliet now leads to a tripartite overlap between the ultrasonic measurements, the explosive-type shock-wave measurements at Los Alamos and the high-velocity gun measurements of Ahrens at Caltech. The ultrasonic measurements are basically a precision determination of Poisson's ratio as a function of pressure. In order to obtain the longitudinal and shear-wave velocities as a function of pressure, it is necessary to use known shock-wave data on the materials of interest and reduce the measured Hugoniots to isothermal giving compressions and bulk sound speeds. Then the bulk sound speeds are split mathematically using the measured Poisson's ratio; hence, the longitudinal and shear-wave velocities may be determined along an isotherm. Using standard shock-wave type thermodynamics, these velocities may be converted back to the Hugoniot and hence the longitudinal and shear velocities observed behind a shock wave. In the pressure range (90 kb) of this experimentation, on alkali halides, the variation of the parameter γ/V used to convert from Hugoniot to isotherm and reverse is small and assumed constant. In addition, the high velocity gun technique is now evolving to a point where shear velocities may be measured. These will then be compared to the ultrasonically derived shear-wave and longitudinal velocities since, from the combined shear-wave velocities in shock and bulk sound speed from shock data, one may derive the longitudinal wave velocity. The ultrasonic determinations require approximately one day per sample if the samples have previously been prepared. Thus, a large quantity of data should be produced in the next few years.

With the progress in the previously suggested areas as described above, it was decided that initiatives should be taken now in a different direction, namely the areas of high pressure research in large volumes. There are certain types of experimentation which at best can be done only in large-volume apparatus (a pressure cell on the order of several hundred cubic centimeters). One example of such research is the synthesis of large polycrystalline aggregates of geophysically interesting materials. These would be useful in ultrasonic research at elevated pressures and temperatures and also for shock-wave research: to date study of minerals has been hampered by unavailability of appropriate starting materials. A second type of experimentation which needs large volumes can be termed "real earth" experiments, namely the measurement of several properties on rocks at the same time under the identical pressure and temperature conditions. A simultaneous study might be the effect of pressure and temperature on electrical conductivity, elastic wave velocities and state of strain. I call this a "real earth" type experiment because this is directly analogous to the types of simultaneous measurements made on the earth itself by geophysicists. This is included in the Report on Priorities (Part 2, Section 3a). The USGC appointed a new Reporter on large volume experimentation (Robert Riecker). His report follows (Section 3c).

There is a good possibility now to develop high-pressure systems using some excellent quality sintered diamond aggregates. It was stated that these have been tested and are superior to other sintered diamonds when used as tool bits. All the experimentation discussed above that is actually under way can be termed the mineralogy of the mantle. This is an obvious necessity as a precursor to studying what I would like to term the petrology of the mantle, i.e., the study of the physical (and chemical) properties of real rocks such as the suggested large volume experimentation. This does not mean that study of mantle mineralogy should be curtailed in any manner. It is a necessity and should be encouraged. Each ongoing technique discussed above is really appropriate only on individual minerals.

The reference to petrology means the study of the physical properties of real rocks. In our earlier divisions, experimental petrology meant the study of synthetic rock systems. This area is well covered and thriving, and should continue to be encouraged.

May 1977

3B
CRYSTAL GROWING

THOMAS M. USSELMAN

The working group on single-crystal growth previously prepared a list of the desirable single crystals for geodynamic experimentation (*Geodynamics Project: U.S. Progress Report--1975*) with a large input from the scientific community. It has been the opinion of the working group that more knowledge would be gained from studying synthetic silicates rather than natural crystals. In this respect, the properties of the pure end members of solid solutions may yield data in order to calculate the physical properties of the more complex solid solutions. This approach has yielded much geodynamically important data in the case of pure forsterite.

Progress

Jun Ito of the University of Chicago has increased the size of orthoenstatite single crystals and has obtained dimensions up to 17 mm x 6 mm x 5 mm (although these show significant strain due to the growth technique) and up to 12 mm x 5 mm x 3 mm (showing no apparent imperfections). Dr. Ito has freely dispensed many of his smaller crystals (several millimeters in size) to more than 30 interested laboratories currently investigating crystal structure, elastic constants, compressibility, calorimetry, diffusion properties, phase equilibrium, electrical conductivity, and other physical properties of this important pyroxene. It appears likely that crystals of orthoenstatite large enough for creep and deformation experiments and other geodynamically important studies requiring large crystals will be grown in the near future.

Ito has also proposed and is proceeding with investigations in (1) the growth of diopside crystals (of which several small crystals have been distributed to various laboratories) and (2) potential techniques of incorporating ferrous iron into these pyroxenes.

Cabell Finch of Oak Ridge National Laboratory expressed an interest in the working group's needs and has become involved with the crystal growth of iron-bearing silicates. Encouraged by the working group, Dr. Finch has succeeded in producing a boule of fayalite (1-cm diameter) and is currently improving the growth techniques and preparing a publication on these crystals. He has expressed a willingness to share these boules on a collaborative basis, and has distributed several fayalite crystals to laboratories carrying out geodynamic measurements.

Dr. Graham and Dr. Spear of Pennsylvania State University have initiated their investigations with attempts to grow single crystals of olivine with a range of Mg:Fe ratios. This activity reflects interest expressed by the working group.

Initial contacts have been made with Dr. Sunagawa of Tohoku University, Sendai, Japan, in an attempt to coordinate the goals of the working group with those of the International Mineralogical Association's Commission of Crystal Growth of Minerals (of which Dr. Sunagawa is chairman). Such coordination was discussed during a Penrose Conference on the Application of Crystal Growth Theory and Experimentation to Rock Forming Processes (December 1976). The Commission is aware of interest in experimentation on single crystals in connection with geodynamics; Dr. Sunagawa has offered to keep us informed of any new developments regarding the growth of single crystals. He informed about a group at Tohoku University actively working in growth of geodynamically relevant single crystals.

Availability

It currently appears that the crystal growers are willing to distribute their products to laboratories on an individual basis. At the present time, the working group is not planning to act as a curatorial group. Our function will continue to make the potential crystal users aware of where they might obtain the crystals (Table 3b.1) needed for their investigations, and, if necessary, assist their efforts. To implement this function, a semiannual newsletter will be circulated to the known physical property laboratories. The working group will also attempt to interest additional crystal growth laboratories in the needs related to the Geodynamics Project.

Recommended Research

The working group will continue to encourage research in crystal growth for geodynamic research, placing an additional emphasis on the growth of wustite-periclase solid solutions and garnets.

Ferro-periclase, (Mg,Fe)O, has recently been found as an inclusion in diamonds and may warrant consideration as both an upper and lower mantle phase. Syntheses of the appropriate crystals are feasible at low pressure and research should be encouraged as soon as possible.

High pressure synthesis and growth will be required for the geodynamically interesting garnet. Natural garnets are complex solid solutions and it is felt that studying the properties of the important pure end members will yield a better understanding of the physical properties of garnets. The high-pressure crystal-growth processes necessary for garnet are currently underdeveloped and should receive greater technological attention. In this regard, we will be working closely with Working Group 3c (Large Volume Experimentation) in encouraging high pressure crystal synthesis and growth. With recent advances in miniaturizing measurements of physical properties (e.g., elastic constants using the Brillouin technique), crystals of 0.1-0.2 mm can be utilized. Crystals of this size range may currently be grown in existing high pressure laboratories, and the attempted growth of pure end member garnets should be encouraged immediately. However, some physical property measurements, such as creep and deformation studies, will be impossible until high-pressure technology develops capabilities for the growth of large single crystals.

Recommended Action

1. A newsletter will be prepared and widely distributed to make crystal users aware of where synthetic crystals may be obtained.
2. An effort will be made to interest crystal growth laboratories in investigating geodynamically relevant materials, especially (Mg,Fe)O and iron-bearing silicates.
3. The working group will attempt to interest existing high-pressure facilities in the synthesis and growth of garnet and other high-pressure silicates.

Table 3b.1 Availability of Synthetic Single Crystals

Olivine:	Forsterite (Mg_2SiO_4)	- commercially available
	Fayalite (Fe_2SiO_4)	- Dr. Finch, Oak Ridge; Drs. Graham and Spear--research in progress
	Olivine $(Mg,Fe)_2SiO_4$	- Drs. Graham and Spear--research in progress
Orthopyroxene:	Enstatite ($MgSiO_3$)	- Dr. Ito, Chicago
	Hypersthene $(Mg,Fe)SiO_3$	- Dr. Ito--research planned
Clinopyroxene:	Diopside ($CaMgSi_2O_6$)	- Dr. Ito--research in progress
	Hedenbergite ($CaFeSi_2O_6$)	- not available
	Augite $Ca(Mg,Fe)Si_2O_6$	- not available
Spinel:	Spinel ($MgAl_2O_4$)	- commercially available; Dr. Dugger, AFGL
	Hercynite ($FeAl_2O_4$)	- Dr. Slack, General Electric

June 1977

3c

LARGE VOLUME EXPERIMENTATION

ROBERT E. RIECKER

The reporter has convened three meetings of the Working Group on Large Volume Experimentation (December 1976, March and June 1977). The following report was submitted to the USGC after the second meeting.

The working group feels strongly and unanimously that there is a critical need for medium- to high-pressure large-volume experimentation to address important geophysical problems. Equipment is either feasible to build or to modify now. There are two principal types of experiment that need to be performed: *mineral synthesis* applies mainly to the mantle, and *large-volume measurements* apply mainly to problems within the crust. Pressures and volumes differ for each set of experiments.

Large-volume measurement experimentation involves low to medium pressure, but very large volumes (1-10 kb and volumes to a large fraction of a cubic meter), with emphasis on the simultaneous measurement of a variety of properties of the rock under investigation. Such experiments would contribute to research in the physics and chemistry of fracture, acoustic velocities and emission, electrical and thermal properties, attenuation and dispersion of elastic waves, and brittle/ductile transitions in rocks and minerals.

Recommendations

1. Whole-sample strain measurements to determine relationships between development of failure zones and whole-sample size, as in dilatancy and hydrofracture experiments
2. Simultaneous measurements of several physical, mechanical, and chemical properties on samples that are large with respect to flaws and fabric
3. Measurements on a larger selection of rock and mineral types because of their range in flaw and fabric domain
4. Measurements that require extensive instrumentation *internal* to the pressure vessel, such as optical and ultrasonic interferometry and controlled thermal gradients

These recommended experiments can and should be performed in apparatus with the following characteristics:

either:

- confining pressure - nominally 10 kb
- working dimension - 30-cm diameter externally heated to 300°C
- pore pressure access
- biaxial external stress capacity (hydrostatic plus one additional external load direction)
- loading rates - 10^{-9} to 10^{-4}/second

or

- confining pressure - nominally to 5 kb
- working dimension - 30-cm diameter, externally heated to 300°C
- pore pressure access
- triaxial external stress capacity (hydrostatic plus two external load directions)
- loading rates - 10^{-9} to 10^{-4}/second

Low- to medium-pressure, large-volume simultaneous measurements would contribute to national needs in:

- crustal and upper mantle dynamics
- earthquake prediction and control
- volatile transport and mineral deposits
- geothermal energy extraction
- waste management and storage
- reservoir stimulation

Mineral synthesis experimentation involves very high pressure, but more modest volumes (several hundred kb and volumes on the order of a cubic centimeter). An improved understanding of dynamic processes in the mantle requires accurate characterization of the state of the mantle (e.g., composition, mineralogy, temperature, state of strain). The fundamental limitation to this characterization at the present time is the difficulty of synthesizing and accurately measuring physical properties of high-pressure phases either within their stability fields or on recovery at atmospheric conditions.

Specific Recommendations

1. Phase equilibrium studies in multicomponent systems to P = 250 kb and T = 1500°C with emphasis on accurate characterization of P and T
2. Synthesis of specimens of high-pressure phases of various mantle minerals in volumes sufficient to enable measurement of their physical properties *in situ* or upon recovery
3. Measurement of physical properties (e.g., elastic-wave velocities, thermal expansion, diffusion, and other transport properties) of materials at hydrostatic pressures to 100 kb and temperatures to 2000°C

Table 3c.1: Some Recent Developments in High-Pressure Apparatus

Laboratory & Director	Max. P (kb)	Max. T (°C)	Characteristic Sample Dimension or Volume	Current Work or Status
Cornell (Ruoff) Belt	70	1500	5 cc	Hot pressing metal aggregates
Cornell (Ruoff) Split-sphere	80	25	16 cc	Room temperature presently
UCLA (Kennedy) Piston Cylinder	60	1500	5 cc	Hot pressing
Stony Brook (Liebermann) Girdle	60	1200	3 cc	Mineral synthesis
Lehigh (Sclar)				
Belt A	60	2000	3 cc	Quench recovery
Belt B	160	1500	0.4 cc	Quench recovery
Brigham Young (Hall) Tetrahedral				
Watervliet Arsenal (Davidson) Bridgman Anvil	270	25	0.2 cc	Acoustic velocities
Georgia (Giardini)				
Tetrahedral	70	1500	25 cc	Sintering of cubic BN & diamond
Girdle	70	1500	3 cc	
Ft. Monmouth (Zeto)	50-250	25-1500	5 cc	Operational
LASL (Morris)	175	25	large	Active - hot pressing
LASL (Riecker) Bridgman Anvil	150	1000	1 cm	Torsion, friction

Table 3c.1 (continued)

Laboratory & Director	Max. P (kb)	Max. T (°C)	Characteristic Sample Dimension or Volume	Current Work or Status
Sandia (Modresky) Piston Cylinder	4	1500	8 cm	Under construction
Diamond Cell (Many)	1000	800-2000	0.05 mm	Widely used mineral synthesis
Nagaya, Japan (Akimoto, Kumazawa) Multi-axial	200	1500	5 mm	Active
University of West Ontario (Beck) Multi-anvil	60	300	3 mm	Active
ANU, Canberra, Australia (Ringwood)	120	1400	1 mm	Mineral synthesis
Harvard (O'Connell)	50	25	5 cc	Ultrasonics
Lawrence Livermore Lab. (Heard, Duba)	120	1200	0.5 cc	Electrical conductivity, phase studies
Lawrence Livermore Lab. (Heard, Duba)	300	25	0.2 x 0.05 cc	X-ray, electrical conductivity
Lawrence Livermore Lab. (Heard, Duba)	80	400	1 cc	Torsion, friction
Lawrence Livermore Lab. (Heard, Duba)	80	1400	1 cc	Electrical conductivity, phase studies

Examples of specific features of apparatus to address these recommendations are:

- multiple-anvil, solid-media high-pressure systems (e.g., cube anvil, split sphere, tetrahedral anvil)
- pressure - 150 to 300 kb
- temperature - 1500°C
- working volume of pressure medium - 3 to 5 cc
- associated apparatus:
  - *in situ* x-ray-diffraction apparatus using energy-dispersive detection systems
  - apparatus for measuring elastic and thermal transport properties

These recommended experiments in *mineral synthesis* could contribute to national needs in:

- mantle dynamics
- physical and chemical state of the mantle
- mantle heterogeneity

Many, and possibly most, of these experimental recommendations cannot be executed in geoscience laboratories within the United States as currently equipped. While diamond anvil technology has led to very significant advances in high-pressure mineralogy recently, limitations of small specimen volume and inhomogeneity in pressure and temperature distribution make the diamond cell unsuitable for the experiments we recommend. However, technology for execution of our recommendations already exists and could be adapted to studies of these geophysical problems if sufficient funds were available for capital equipment *and* technical support.

We recommend that research in the areas indicated above be encouraged actively by national agencies and that funding be made available for: (1) extension of existing facilities, and/or (2) establishment of modest new facilities to undertake such work. We emphasize that funds required are comparable to those commonly devoted to analytical facilities in geochemistry (e.g., electron microprobes or automated mass spectrometers). Table 3c.1 presents a list of known existing apparatus which might be suitable for medium- to high-pressure large-volume experimentation.

At its meeting in April 1977, the USGC endorsed the recommendations set forth above and urged the working group to encourage implementation of its recommendations.

May 1977

4

APPLICATION OF ISOTOPE GEOCHEMISTRY TO GEODYNAMICS

BRUCE R. DOE

Inasmuch as this is the first year for a report on isotopic applications to geodynamics, this report will not restrict itself to just the previous year. Instead, it will cover some of the more relevant papers to appear over the last several years. The applications will be divided into three categories: plate tectonics, geochronology, and other applications.

Plate Tectonics

A manuscript is in press by Doe and Zartman presenting a general treatment for the development of lead isotope evolution in a plate tectonics context. The authors divide the active part of the outer earth into three principal end members of oceanic mantle, upper continental crust, and lower continental crust. By mixing these three components together, they can explain the lead isotopic composition of mature orogenes (such as Japan or Indonesia). Primitive orogenes (such as the Mariana arc), in contrast, are found to have an oceanic mantle type of lead (see Meijer, 1976). Although the lower crust--which has been depleted in uranium, thorium, and lead in differing degrees, generally as a result of granulite facies, or higher rank metamorphism--makes only a small contribution, it is nonetheless critical in explaining the different lead isotope trends in mature orogenes from either those of the oceanic mantle or continental upper crust. The paper also gives the first comprehensive treatment for the evolution of $^{208}Pb/^{204}Pb$. They examine various tectonic environments backward into the Phanerozoic and place them in a tectonics context. For example, the Devonian and Triassic sections of the Shasta mining district in the Klamath Mountains of northern California are classified as a primitive orogene. Sun *et al.* (1975) began to unravel the complexity of the mantle and development of the character of oceanic basalts in a study of the Reykjanes Ridge. They explain the observed isotopic parameters and large-ion-lithophile elements geochemistry of the basalts through a mixing process involving interaction of a rising plume of magma with the oceanic lithosphere. The major element chemistry, however, seems to be controlled by crystal fractionation at shallow depths and variable partial melting.

G.L. Cumming (1976) has analyzed basalts from the Mid-Atlantic Ridge (DSDP Leg 37). He finds that the lead in these basalts has an isotopic composition similar to what would be expected in a continental lithosphere with an integrated formation age of about 600 m.y. ago, an age that is

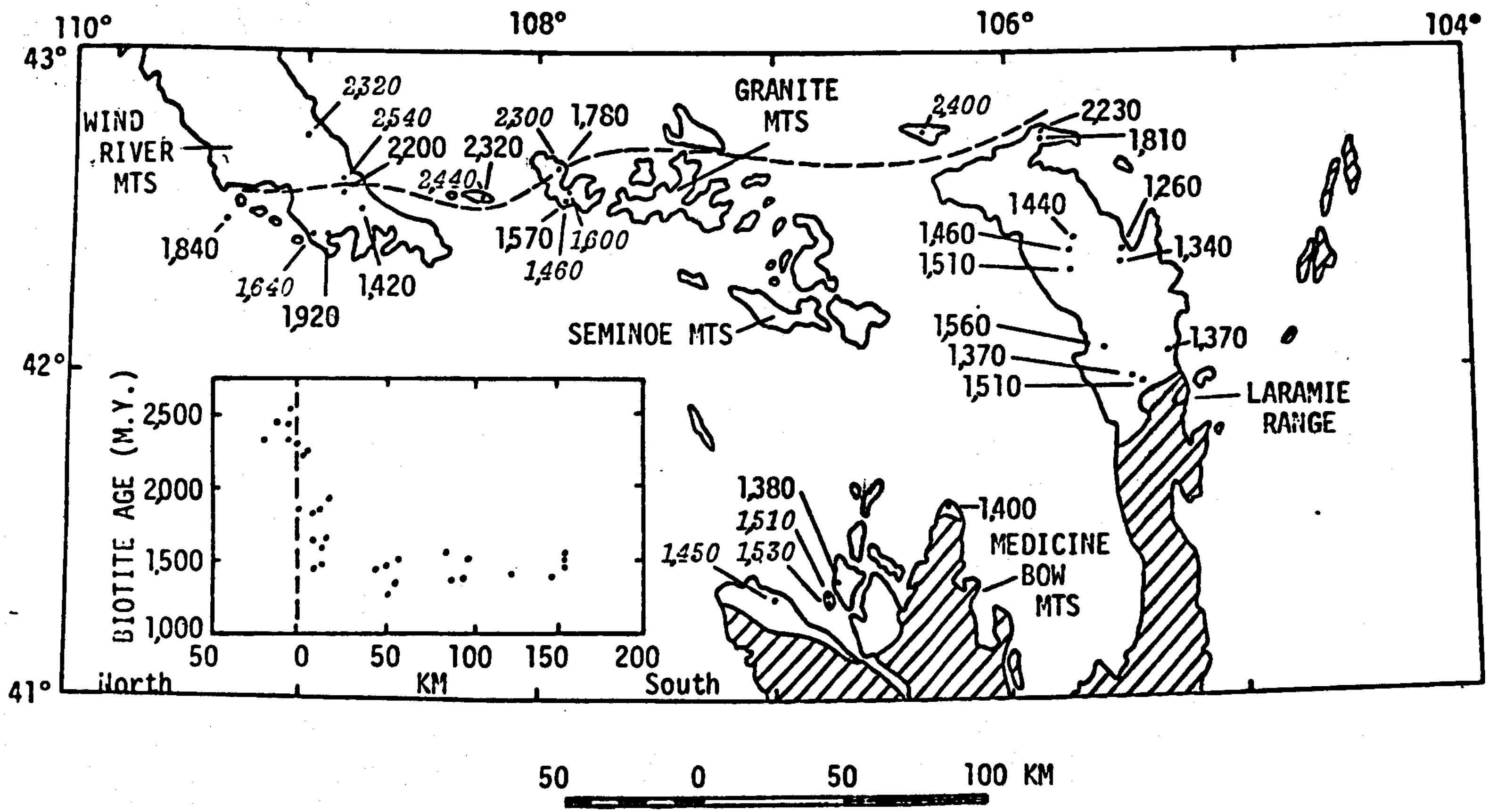


FIGURE 4.1 Major age discontinuity (dashed line) in the Archean rocks of south central Wyoming. Diagonally ruled areas are rocks of Proterozoic age. Inset figure shows ages plotted against distance north (left in inset figure) and south of the dashed line. (Peterman and Hildreth, 1977)

compatible with what is observed in continents laterally from the Ridge--the Appalachians--whereas farther to the north the integrated formation age is older--about 1500-2000 m.y.--which is compatible with ages of continental material laterally from the ridge at that point. He therefore links the formation of the mantle underlying the Atlantic Ocean to continent formation. Although the data are compatible with this hypothesis, it should be considered speculative at this time because alternatives are being considered.

A controversy is developing between proponents of a static continental mantle "keel" formed at the time of the overlying continental crust (Leeman, 1975) and semicontinuous "underplating" of asthenosphere onto the bottom of the continental section (Brooks *et al.*, 1976). Both schools do have some continental mantle formed at the time of the crust, however, and at least some mantle "keel" on the continents formed at or near the time of the overlying crust is becoming increasingly well established.

Church (1976) has beautifully shown by isotopic studies involving strontium and lead that volcanics in the Cascades may have had fundamentally a mantle origin but that variable and significant assimilation of continental crust into the magmas has occurred.

Geochronology

Work continues on development of a radiometric age data bank (RADB) by R.F. Marvin of the U.S. Geological Survey in Denver, Colorado. Wyoming is now complete, a total of 1500 records is currently in the bank, and the Lake Superior Region is being worked on. The accessing program used is the CRIB form of GIPSY.* Funding is being pursued to do similar work for California, Nevada, and Utah next fiscal year. File preparation is being done as far as possible through grants and contracts with institutions (one with the Minnesota Geological Survey) and individuals with particular interest in the geology of the states in question. Pending decisions on the method for formal release of the bank, small requests are currently being handled by Richard Marvin.

The question is always asked whether data banks are good for anything. Two papers have recently appeared demonstrating the valuable potential of this particular data bank. Using a "manual" bank involving 20 students plotting data, Snyder *et al.* (1976) have synthesized about 2000 ages in the southwestern U.S. and determined among other things that compressional tectonics changed to tensional tectonics along a progressive path in the "magmatic arc" of California and Nevada during the Cenozoic.

It turns out that excellent use can be made of "failures" in determining the ages of rocks, i.e., "ages" that have been partially or completely reduced from those ages of rock formation as a result of metamorphism or other processes. In utilizing the RADB, Peterman and Hildreth (1977)

*CRIB--Computerized Resource Information Bank of the U.S. Geological Survey. GIPSY--General Information Processing Systems of the University of Oklahoma.

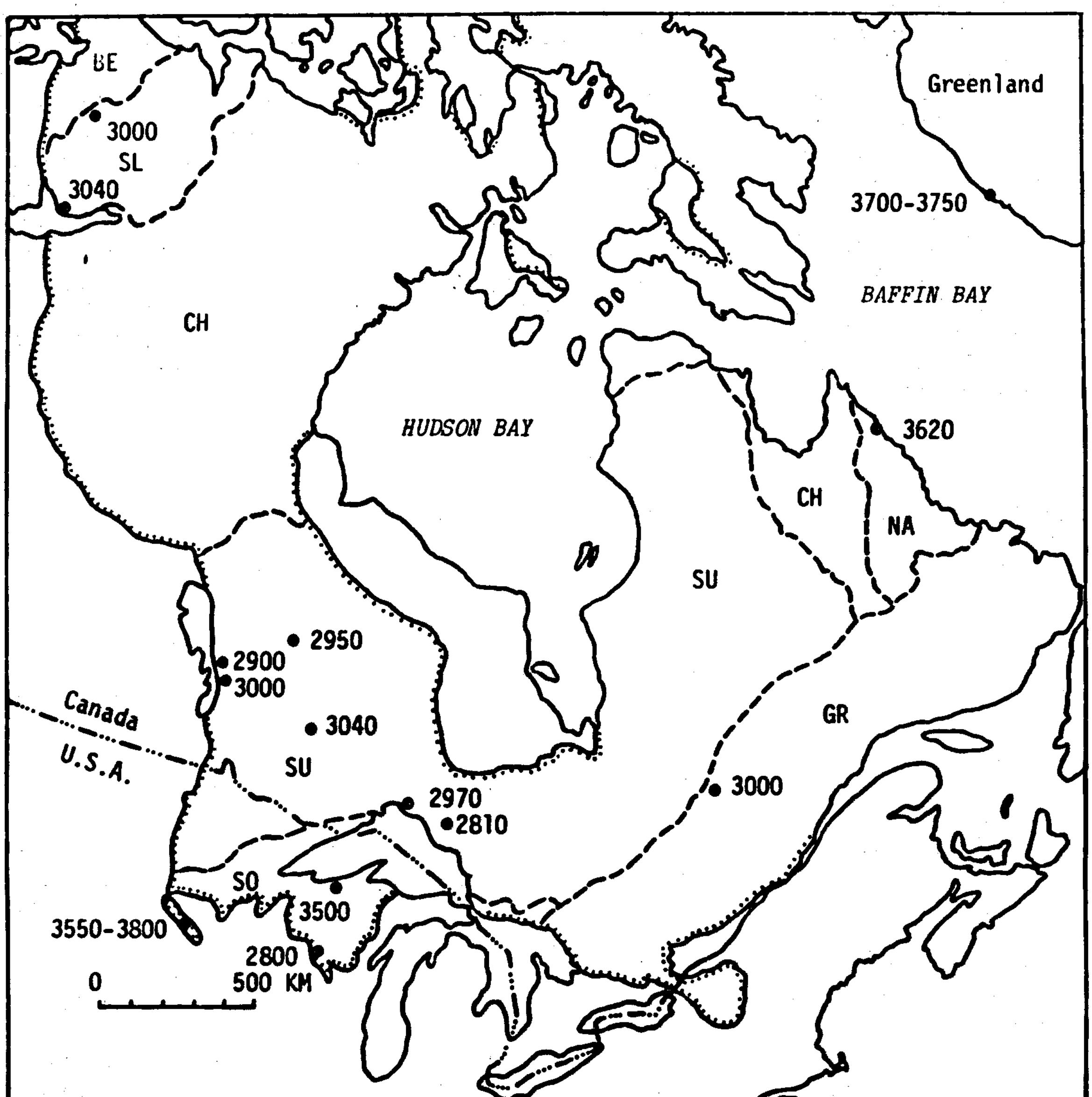


FIGURE 4.2 All localities in North America with rock age determinations 2800 m.y. and older. Province abbreviations: BE-Bear; CH-Churchill; GR-Grenville; NA-Naine; SL-Slave; SO-Southern; SU-Superior. (Peterman, 1977)

discovered a major age discontinuity in south central Wyoming about 100 to 150 km north of the well-known discontinuity between rocks of Precambrian-X age and those of Precambrian-Y age (Figure 4.1). This discontinuity is very sharp and must represent a major fault of great vertical uplift on the south where rocks of Precambrian-W age were being metamorphosed during Precambrian-X time.

The findings by Peterman and Hildreth are particularly of interest because most Precambrian features tend to be tensional in nature (for example, greenstone belts) but the Wyoming find involves vertical tectonics. Vertical tectonics in the Precambrian may be much more common than currently thought. Their apparent variety may be a consequence of difficulty in recognition. For another example, Goldich *et al.* (1961) found a similar example in the Minnesota River Valley where rocks at least 2600 m.y. in age that were highly metamorphosed at 1850 m.y. to the west abruptly disappear toward the east. Again, a major vertical tectonic event must have occurred. Such major features may well best be discovered through so-called "failed" age determinations on rocks, and this illustrates the need for a comprehensive age data bank including all determinations where the analytical data are sound.

In Figure 4.2, Zell E. Peterman of the U.S. Geological Survey in Denver has shown all the localities in North America where rocks have been found with ages 2800 m.y. or older. A bibliography of sources for the age information may be obtained from Zell Peterman.

Other Applications

J.R. O'Neil presented a paper at the 1977 spring meeting of the AGU in Washington, D.C. on the use of geochemical indicators in earthquake prediction. He has made studies of hydrogen/deuterium and oxygen isotopes in concert with radon measurements by Chi-yu King on well waters in the Oroville Dam area of California. No distinct variation is found on the oxygen isotopes; however, some deuterium and radon effects were noted contemporaneous with and perhaps 2 to 4 days prior to some magnitude 3 to 5 earthquakes. The earthquake predictive aspects of these geochemical indicators are continuing to be investigated.

April 1977

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3. Mantle-asthenosphere interactions--S.-S. Sun, M. Tatsumoto and J.-G. Schilling (1975) Mantle plume mixing along the Reykjanes Ridge axis: lead isotope evidence, *Science*, 190, pp. 143-147.

4. Continental mantle nature of Atlantic Ocean asthenosphere--G.L. Cumming (1976) Lead isotope ratios in DSDP Leg 37 basalts, *Earth Planet. Sci. Lett.*, 31, pp. 179-183. (lead isotopes)

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Geochronology

8. Data bank--R.F. Marvin (1977) Radiometric Age Data Bank (RADB). Written communication, 22 April.

9. Precambrian vertical tectonics--Z.E. Peterman and B.R. Doe (1977) Precambrian vertical tectonics. Written communication, 22 April.

    a. Example from Minnesota--S.S. Goldich, A.O. Nier, H. Baagsgaard, *et al.* (1961) The Precambrian geology and geochronology of Minnesota, *Minn. Geol. Survey Bull.*, 41, 193 pp.

    b. Example from Wyoming--Z.E. Peterman and R.A. Hildreth (1977) Reconnaissance geology and geochronology of the Precambrian of the Granite Mountains, Wyoming, *U.S. Geol. Survey Open File Report 77-140*, 86 pp.

10. Dating switch from compressional to tensional tectonics--W.S. Snyder, W.R. Dickinson, and M.L. Silberman (1976) Tectonic implications of space-time patterns of Cenozoic magmatism in the Western United States, *Earth Planet. Sci. Lett.*, 32, pp. 91-106.

11. Old rocks--Z.E. Peterman (1977) Ages of rocks 2800 m.y. and greater in the Canadian Shield. Written communication, 22 April.

12. Blocks of rock of unsuspected age--J.H. Chen (1977) U-Pb isotopic ages of the Southern Sierra Nevada batholith and Independence dike swarm, California, *GSA Abstracts* with prog., 8, no. 6, p.810.

Other

13. Earthquake prediction--J.R. O'Neil (1977) Stable isotope variations in earthquake prediction: Abstract in *EOS*, 58, no. 6, p. 437.

5

GEODYNAMIC MODELING

DONALD L. TURCOTTE

A program of research on the San Andreas fault, particularly related to earthquake hazards and predictions, has a high national priority. Seismicity on the San Andreas fault is clearly a problem in geodynamics. The fault represents a major plate boundary and the plate tectonics hypothesis provides a basic understanding of the fault's behavior. The predictions of fault behavior by geodynamic modeling and their verification by observations represent a major opportunity for the Geodynamics Project.

An indication of the systematic behavior of the San Andreas fault is given in Figure 5.1. In this figure the felt intensities of earthquakes which occurred between 1880 and 1972 within 100 km of the fault are given as a function of latitude. The fault is divided into sections. The northern locked section extends from near Redwood City to the northern terminus of the fault at Cape Mendocino. There has been no reported fault creep or seismicity on this section of the fault since 1906. Average surface displacements of 4 m occurred on this section of the fault in the 1906 earthquake although surface displacements of a smaller magnitude extended farther south as shown in the figure. The decrease in seismicity on this section of the fault following the earthquake is evident in the figure. This decrease is strong evidence that the regional stress field was significantly reduced by the earthquake.

The southern locked section was the site of the great earthquake of 1857. Since that time no fault creep or seismicity has been reported on this section. There appears to be some increase in the level of seismicity adjacent to this section which may be associated with a regional increase in stress level; however, it is difficult to separate this increase from the improved data collection due to the large increase in population and the installation of many seismometers.

The central and southern free sections of the fault are sites of continuous seismic activity and fault creep. It is doubtful that these sections are accumulating sufficient stress to result in great earthquakes, although the surface breaks during great earthquakes on the locked sections extend into these free sections.

Models of fault behavior require hypotheses on the yield strength (for plastic behavior) and failure strength (for faulting) as a function of depth and position on the fault. The rheological behavior of the interacting plates must also be specified both in terms of continuum behavior and the role of subsidiary faults. This is particularly important in considering the bends in the fault. The interactions of the lithosphere with

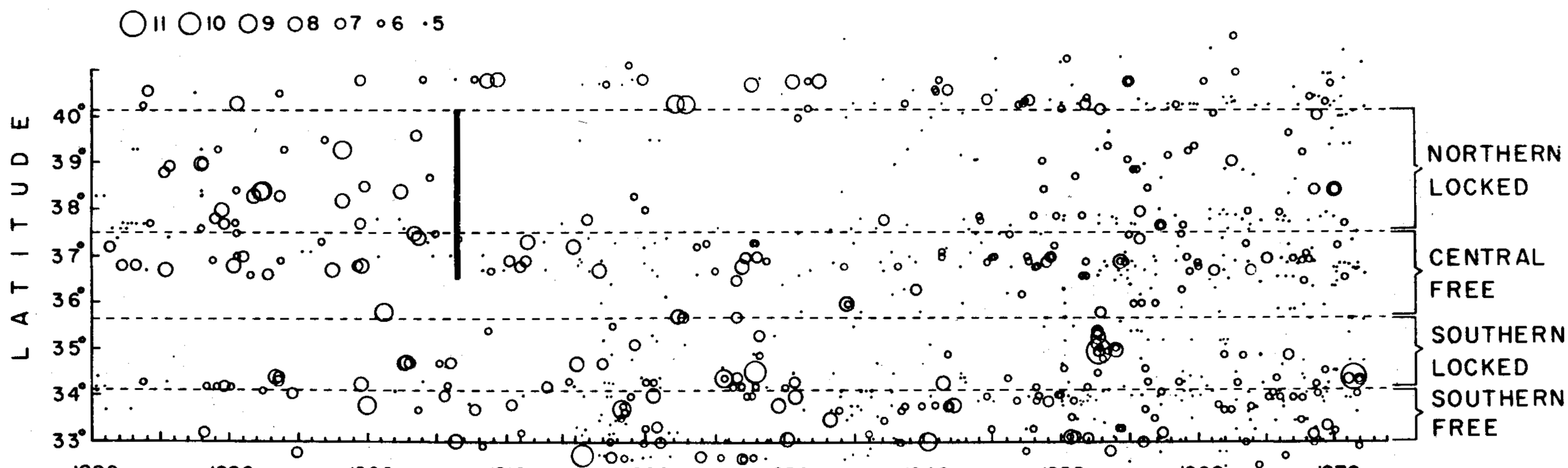

FIGURE 5.1 Felt intensities of earthquakes within 100 km of the San Andreas fault as a function of latitude from 1880 to 1972. From 1880 to 1930 the Rossi-Forel scale of felt intensities is given; from 1931 to 1972 the modified Mercalli intensity scale of 1931 is used. The solid line shows the surface break of the 1906 earthquake. The dashed lines divide the fault into sections depending upon whether there is continuous seismic activity and creep on the fault. (From D.L. Turcotte, Stress accumulation and release on the San Andreas fault, *Pure Appl. Geophys.*, in press, 1977)

the asthenosphere are likely to be important and the driving forces must be considered.

Models predict the spatial distribution of stress and strain during both the accumulation and release phases of the fault's behavior. The results can be compared with available observations and will also be useful in providing priorities for future observations.

It is concluded that geodynamic modeling will play an important role in a balanced program of research on the San Andreas fault. The U.S. Geodynamics Committee supported this view by endorsing the statement that appears in Part 2, Section 5.

June 1977

6
DRILLING FOR SCIENTIFIC PURPOSES

EUGENE M. SHOEMAKER

In lieu of a report by the reporter, the table of contents, summary, and introduction are reproduced from the report:

CONTINENTAL DRILLING

RECOMMENDATIONS OF THE

PANEL ON CONTINENTAL DRILLING

OF THE FCCSET

COMMITTEE ON SOLID EARTH SCIENCES

D. L. Peck, USGS (Chairman)
J. F. Lance, NSF
J. G. Heacock, ONR
D. M. Kerr, ERDA
J. W. Salisbury, ERDA

(April 22, 1977)

CONTENTS

SUMMARY

A program of crustal studies using drill holes in crystalline rocks on land is needed to develop a basic understanding of the physical properties and structure of the earth's crust, active processes in the crust, and, above all, the relationship between these items and the location of natural resources. Solving these problems will contribute fundamentally to progress in areas of critical national need. These include a number of ongoing Federal programs in geothermal and nuclear energy, the search for new mineral resources, and the reduction of earthquake hazards, including their effect on nuclear plant siting. We recommend that a 5-10 year Federal Continental Drilling Program (CDP) be implemented along the lines described in the report of the U.S. Geodynamics Committee Workshop on Continental Drilling (Carnegie Institution of Washington, 1975), the summary of which is attached (1). Such a program should include shallow and intermediate drilling (30-3000 m), followed by deep drilling (3000-9000 m) after substantial and comprehensive investigations have been accomplished. Because of the large anticipated cost of such a program (estimated to be as much as

$20M/year) and the complex scientific, technical, and managerial problems involved, we recommend that the program be started by establishing as soon as possible a CDP Office and related organizational structure to carry out a one- to two-year planning phase initially. Furthermore, we recommend that the organizations most directly concerned with the program should devote the resources required for the initial phases ($3.3M), as indicated on page 17 of the report.

This first phase will establish the Interagency Steering Group and advisory committees, listed below, under whose direction and with whose assistance the CDP Office will develop the detailed program rationale, the scientific goals, the technical feasibility and needs of the planned program, the cost estimates, and the schedule and plan for a scientifically valid series of drill hole sites and objectives. The CDP Office will also establish the feasibility of the program by surveying the recommended drill sites.

The panel recommends that the program be an interagency effort which uses the good offices of ERDA for certain administrative and operational support. Program management should be from a *CDP Office* in ERDA Headquarters with policy direction from an *Interagency Steering Group*, scientific advice from a broadly based *Scientific Advisory Committee*, data handling and coordination assistance from an *Information and Data Management Unit*, and advice on drilling, sampling, and well-logging technology from a *Drilling Technology Advisory Committee*.

The Nevada Operations Office of ERDA will manage field operations and provide drilling, logging, and other common services and support from commercial sources. The *Operations Manager* in ERDA/NV will require the assistance of an *Environmental Impact Group*, a *Drilling Services and Contract Unit*, and a *Facilities Planning Board*.

The collection and analysis of scientific field data will be carried out under the guidance and sponsorship of the agency or agencies having principal programmatic interest.

INTRODUCTION

Because of the major contributions of the Deep Sea Drilling Program to our understanding of the properties of the sea floor and the processes that produced the ocean sediments and underlying rocks, the U.S. Geodynamics Committee reviewed the major contributions that drilling on land could make and recommended that a formal study be initiated to consider the questions involved and to make recommendations on the advisability of proceeding with a continental deep-drilling program (*U.S. Program for the Geodynamics Project: Scope and Objectives*, National Academy of Sciences, 1973, pp. 184-186). As a result, a Workshop on Continental Drilling was convened in 1974 under the sponsorship of the Carnegie Institution of Washington consisting of about 50 people drawn from industry, universities, and government. Its purpose was to "investigate the contribution that could be made by land drilling to resolve major problems of geodynamics and consider the mechanisms by which the responsibility for scientific planning, establishment of priorities, administration, and budgeting for a land-drilling program within the framework of the aims of the Geodynamics Project would be established."

The report of the Workshop (*Continental Drilling**, Carnegie Institution of Washington, 1975), the summary of which forms Attachment 1, concluded that the time has now arrived when a systematic program of studies utilizing relatively deep drill holes on land should be applied to the solution of several basic geodynamic and related problems--solutions from which direct benefits to society can be foreseen. It noted that two kinds of scientific advance can be made with the aid of deep drill holes: (a) discovery and direct observation of geologic processes currently active in the crust, and (b) determination of the physical state and structure of the continental crust.

The Workshop recommended that there be a program of scientific exploration of the continent by means of drilling; that this be a national program of broad participation, including academic, government, industry and professional societies; that a management system be developed to ensure the wise selection of problems and effective participation of the scientific community; and that the period of the program, including planning, should be approximately 10 years, recognizing varying time periods in the different program elements.

The U.S. Geodynamics Committees in a related move also recommended (1973, pp. 37-38) that a program of deep seismic reflection be encouraged and supported, and this recommendation was endorsed by the NAS/NRC Geophysics Research Board. As a result, the NSF has sponsored since 1974 a Consortium for Continental Reflection Profiling (COCORP) to evaluate the feasibility of applying high-resolution exploration geophysical techniques to the study of the fine structure of the deep crust and upper mantle in areas of geologic interest. In the two areas (Hardeman County, Texas, and the Abo Pass area, New Mexico) that have been studied to date, reflections have been obtained from depths of several tens of kilometers. Study of a third area (the Wind River uplift, Wyoming) is in progress, and the project plans to investigate three to five new sites each year. Deep seismic reflection under this project can provide essential background information for selecting sites for continental deep drilling.

As a follow-on to the Workshop on Continental Drilling, the Federal Council for Science and Technology *ad hoc* Committee on the International Geodynamics Project** established in September 1975 an interagency panel drawn from the USGS, ERDA, ONR, and NSF to develop a national plan for the funding and implementation of a continental drilling program. The conclusions of the panel are summarized in this report.

[*End of excerpts*]

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* *Continental Drilling*, Report of the Workshop on Continental Drilling held at Ghost Ranch, Abiquiu, New Mexico, 10-13 June 1974, E.M. Shoemaker and G.A. Swann, Conveners. Published by the Carnegie Institution of Washington, June 1975. Copies available upon request from the U.S. Geodynamics Committee.

**Now the Federal Coordinating Council on Science, Engineering, and Technology.

8

PLATE BOUNDARIES

JOHN C. MAXWELL

Three years ago the Plate Boundaries Group decided that the principal contribution it could make to North American geology would lie in a study of ancient continental margins. A similar program in the Appalachians was already under way, coordinated by Professor John Dewey; hence, we restricted our studies to Alaska, the western Cordillera of the United States and the Ouachita-Marathon trend. Eighteen people working in these areas were asked to construct cross sections showing observed geological and geophysical data along the line of section, and extending offshore where pertinent (Figure 8.1). The cross sections will be accompanied by strip maps showing the basic geological data, and by interpretive cross sections if the participant so desires. The completed sections and supporting data and comments will be published in the Geological Society of America map series.

During the Geological Society of American convention in Denver, November 1976, 17 of the 18 cross sections, mostly in preliminary form, were on display. Eight of these sections have subsequently been transmitted to Douglas Kinney of the U.S. Geological Survey (he also serves as GSA Associate Editor for Geologic Maps) for editorial review. We hope that all of the sections will be received for publication within the coming year. It is anticipated that additional sections will be added to the 18 sections listed below.

An important recent development is the decision of the Canadian Geodynamics Committee to prepare similar cross sections, seven across the Canadian Cordillera and one across the orogenic belt in the Arctic Islands. It is planned to publish these in the GSA map series.

Participants and Areas of Cross Section

1. R.E. von Huene, J. Casey Moore, George W. Moore--Alaska Peninsula-Kodiak Island-Aleutian Trench
2. Peter Misch--Northern Cascade Mountains
3. M. Clark Blake--Southwestern Oregon-Medford 2° sheet and extensions
4. Gregory A. Davis, P. Cashman, C. Ando, L. Gouland--Central Klamath Mountains approximately through Cecilville, California
5. W. Porter Irwin--Southern Klamath Mountains and extensions
6. Paul R. Gucwa, Michael A. Jordan, John R. Kleist, David H. Lehman, Jay A. Raney, Deborah M. Fritz, J.C. Maxwell--Northern California Coast Range and Sacramento Valley-Cape Vizcaino Quadrangle, north of Fort Bragg to Elk Creek and northeastward across the Sacramento Valley

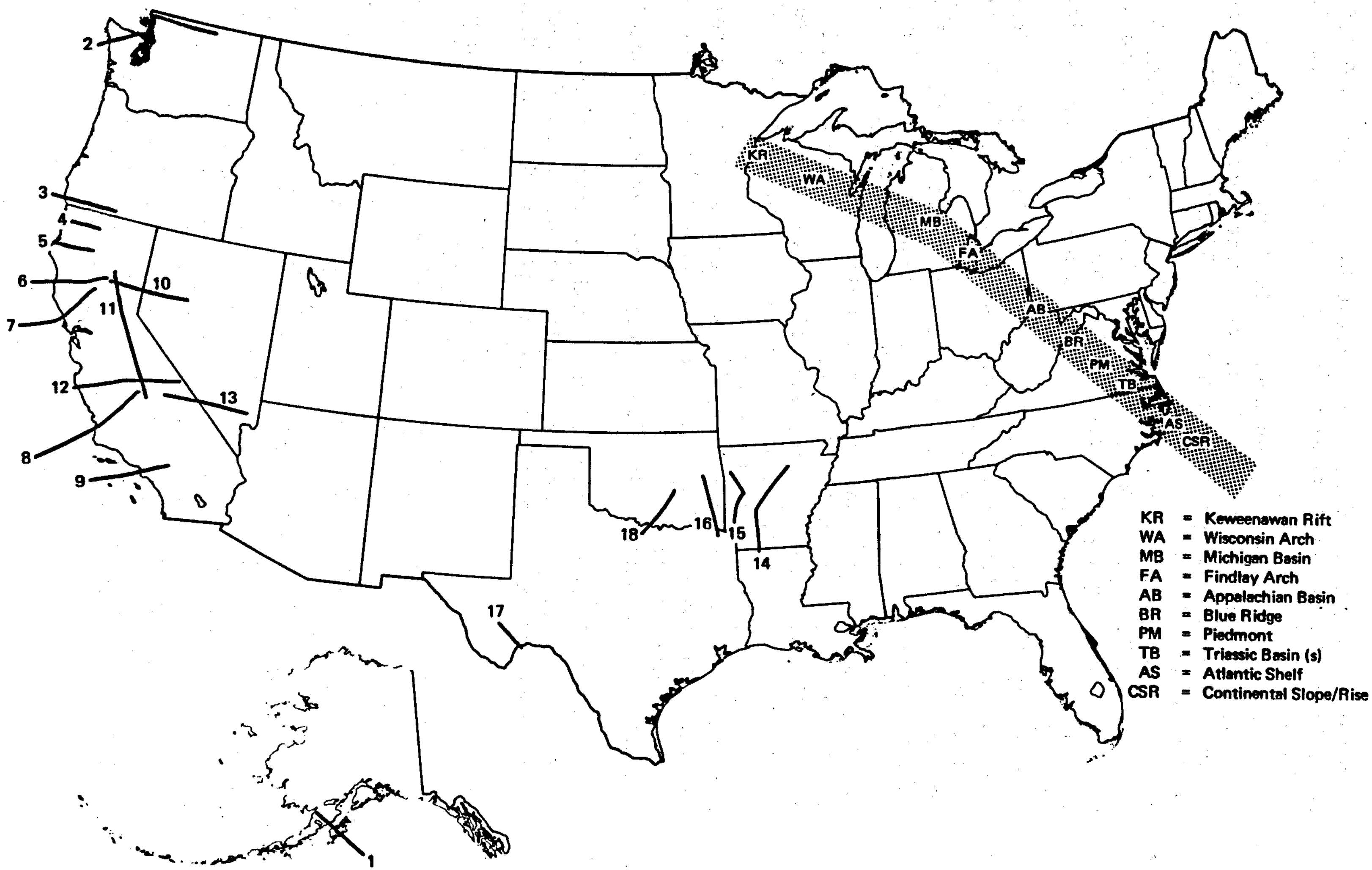

FIGURE 8.1 Map showing locations of cross sections (Numbers 1-18) of the Plate Margins Group and the Michigan Basin-Atlantic Shelf traverse of the Plate Interiors Group.

7. John Suppe, Eli A. Silver, Robert McLaughlin--Northern California Coast Range-Continental Margin-Fort Ross-northeastward to vicinity of Willows
8. Benjamin M. Page, Holly C. Wagner, David McCulloch, John Spotts--From edge of continental shelf northeastward, passing near San Luis Obispo and Avenal to point near mouth of King's River on east side of San Joaquin Valley
9. John C. Crowell, Larry Beyer, Shawn Biehler, Perry Ehlig, George Feister, Ed Hall, Jack Vedder--Tranverse Ranges region and adjacent continental borderland, Southern California
10. Eldridge M. Moores, R.C. Speed--Northern Sierra-Sonoma-Antlers orogenic belts
11. Eldridge M. Moores--Longitudinal section in the western Sierra Nevada
12. Paul C. Bateman, Donald Ross--Point Sur to 37° N, 120° W, then eastward across the Sierra Nevada
13. Bennie W. Troxel, B.C. Burchfiel, Lauren Wright--Southern Sierra Nevada, across Death Valley area and thrust belt of southern Nevada
14. George W. Viele--Eastern Ouachita Mountains-Batesville, Arkansas-Arkadelphia, and southward to Sabine uplift
15. Jay M. Zimmerman, Dietrich Roeder, Robert C. Morris, David P. Evansin--Section through Ouachita Mountains of western Arkansas, from a point north of Fort Smith through the Crystal Mountains to Caddo Gap, and thence south to Cretaceous overlap
16. John Wickham, Paul Lyons, Robert C. Morris--Ouachita Mountains of Oklahoma, Arkansas Basin, Potato Hills, Broken Bow uplift, and south to the Sabine uplift
17. William R. Muehlberger--Section through the Marathon Mountains and hinterland
18. Rodger E. Denison--Section through northern Texas, Muenster Arch near Bonita, northeast across Marietta Basin, Wichita-Criner axis, Ardmore Basin, Arbuckle uplift, to vicinity of Sulphur, Oklahoma

May 1977

9
PLATE INTERIORS

LAURENCE L. SLOSS

Plate interiors are definable as those parts of the globe that are not divergent, convergent, or transcurrent plate margins; it would be a very large order to attempt to report on the geodynamic investigations currently being pursued under this broad-blanket heading. Fortunately, many specific problems and study areas pertinent to plate interiors have been identified and subsumed by individual working groups reporting separately (of the 13 topics listed by USGC, at least nine bear directly on the geodynamics of plate interiors); the present report attempts to cover aspects of plate-interior research not treated elsewhere.

Michigan Deep-test Experiments

Geodynamics Project: U.S. Progress Report--1976 presented some of the preliminary results of measurements, observations, and experiments made possible by the drilling of a deep borehole near the center of the Michigan Basin. Further data have been disseminated at regional and national meetings and several papers will appear in an early issue of the *Journal of Geophysical Research*; items of particular interest to the geodynamics community include the following:

Petrology of Igneous Rocks. Altered igneous rocks penetrated in the interval 4970 - 5324 m (T.D.) were first considered to be a metagabbroic intrusion into red Keweenawan (?) sediments. Detailed petrologic and geochemical analyses (McCallister, Boctor, and Hinze) reveal that the rock is more adequately described as a spilitic basalt flow of greenschist facies. The Purdue group compares the Michigan rocks to strikingly similar examples known from mid-ocean ridge systems where low-grade metamorphism under moderate overburden in the presence of saline waters is thought to have taken place. The metamorphic grade is higher than that represented by Keweenawan tholeiitic flows of the Lake Superior region.

Significantly, paleomagnetic studies of oriented cores (Van der Voo and Watts) indicate that, while pole positions for the overlying red sediments fit a Keweenawan age (~1000 m.y.), the subjacent lavas suggest a younger (500 - 700 m.y.) age. If the petrologic and paleomagnetic determinations hold up, consideration must be given to a postimplacement thermal pulse, perhaps related to the nearby Grenville Front, that affected the magnetic field of the spilite without shifting apparent pole positions of the red sediments. Should this prove to be the case, the geochemical environment

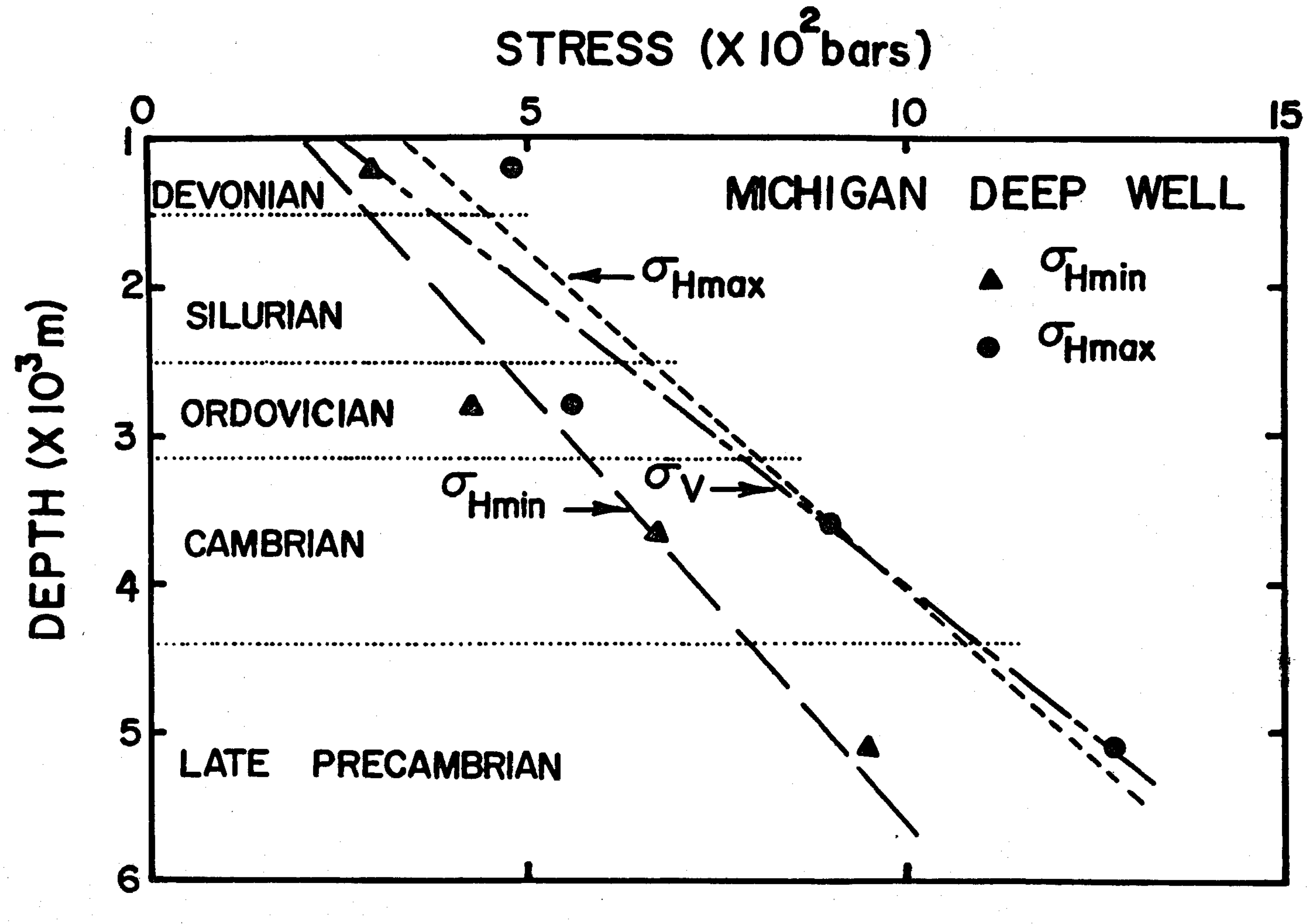

FIGURE 9.1 Stress magnitudes as a function of depth determined by hydrofracture experiment in the Michigan deep well. Lines are linear-regression fits to stress-depth relationships. (Courtesy of B.C. Haimson, Dept. of Metallurgy and Mining Engineering, University of Wisconsin)

of alteration of the flow rock may require re-examination. Regardless of ultimate interpretations, studies of cores from far beneath the Phanerozoic cover in a sedimentary basin illustrate the potential that such samples hold for understanding the complex history and processes of plate-interior geodynamics.

Stress Measures. The Michigan deep well presented an opportunity for application of hydrofracture techniques to crustal stress measures at depths not previously attempted. B.C. Haimson reports on the results of four test points in the borehole, the deepest at 5105 m, as shown by Figure 9.1. Note that the least principal stress (σ_{Hmin}) is clearly less than the vertical component except at the shallowest point. The latter point overlies thick salt units which may account for relaxation of horizontal stresses present in deeper strata. Haimson is seeking sites for further shallow testing on the basin periphery away from discontinuities introduced by salt. In all other respects the results are compatible with those expected in a cratonic-interior position under mild flexure accompanying subsidence. Comparative data from other basins, including those of quite different tectonic histories, are eagerly awaited.

New Madrid Seismotectonic Study

An area within a 200-mile radius of New Madrid, Missouri, is being intensively studied by geologists, geophysicists, and seismologists representing six state surveys, the U.S. Geological Survey, and individual scientists from at least five universities. The investigation is under the sponsorship of the Nuclear Regulatory Commission and is designed to evaluate earthquake-risk factors at the sites of planned nuclear power plants but will obviously produce a mass of data of broad geodynamic significance.

Hildenbrand and others (USGS) have mapped the regional gravity and magnetic fields. A version of the total magnetic intensity map is shown in Figure 9.2; the positions of recent seismic events (from Stauder and others, St. Louis University) are shown in Figure 9.3. Integrating the gravity, magnetics, and seismicity, the USGS group believes that they can demonstrate the existence of a down-faulted, basalt-floored rift zone as shown in Figure 9.4. Comparison with the Midcontinent and Michigan features of the Keweenawan age is invited. Inasmuch as the northwest boundary of the putative rift parallels the margin of the deeply subsided Mississippi Embayment there appears to be additional evidence that the tectonic history of this important element of the cratonic interior is at least 1000 m.y. old and that ancient events have determined the position, if not the mode, of neotectonic activity.

Continuing work (T.C. Buschbach, Illinois Survey, coordinator) will include the installation and monitoring of seismic arrays in the New Madrid seismic zone and in the Wabash Valley, completion of gravity and magnetic coverage of the area, refraction and reflection (including COCORP deep reflection) surveys of critical areas, updating of subsurface structure and stratigraphy, basement rock studies, detailed field mapping, and geomorphic evaluation of recent vertical movements.

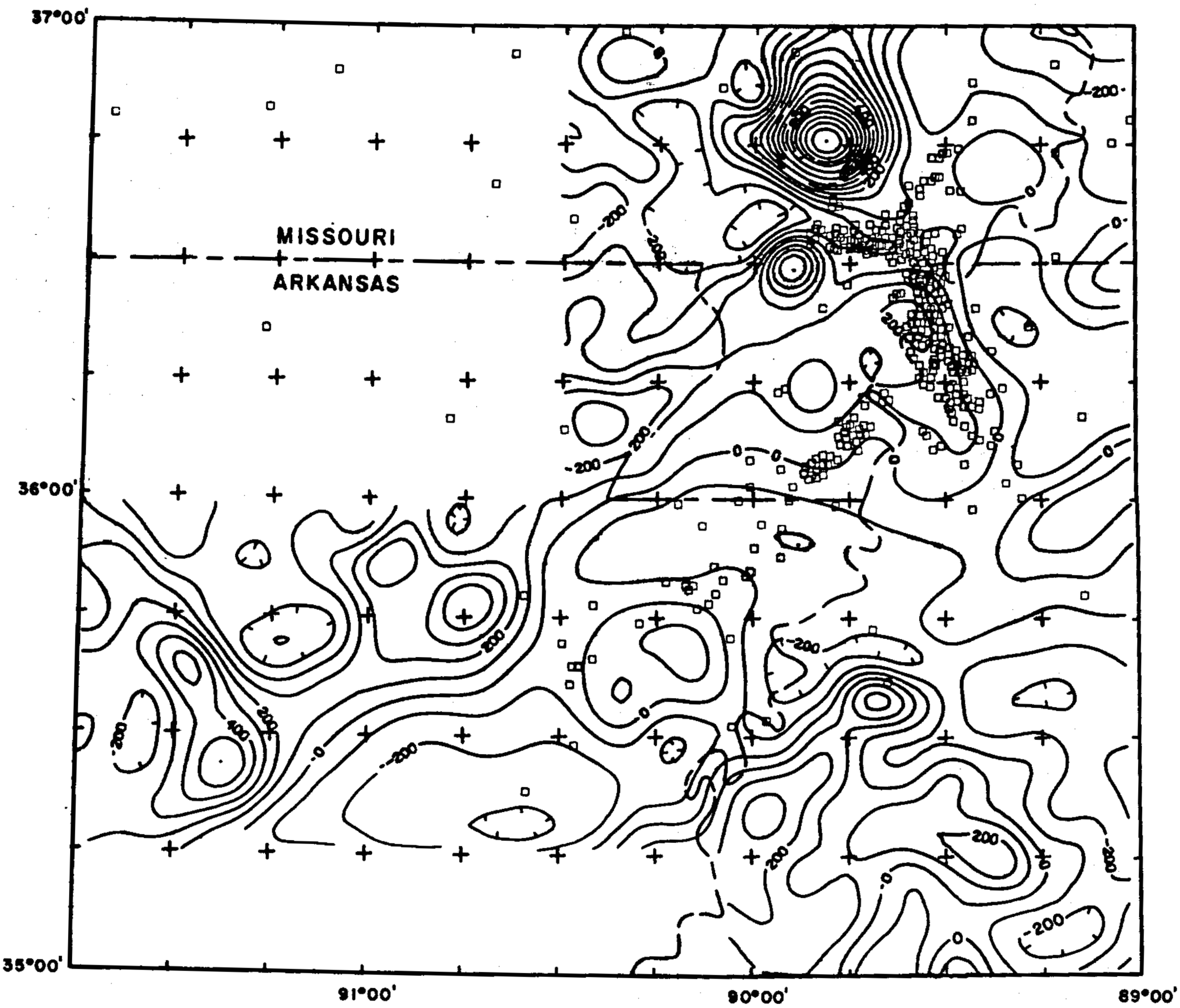

FIGURE 9.2 Total magnetic field intensity in the area of the northern end of the Mississippi Embayment. Contour interval is 100 gammas. Squares indicate earthquake epicenters shown in greater detail in Figure 9.3. The magnetic survey was flown at an elevation of 0.305 km barometric and with flight line spacings of 1.609 km. The total magnetic field intensity was obtained by removing the IGRF (1965 version) after updating to the years in which the surveys were flown. The data were digitized with a spacing of 2 km. An 8-unit Zurflueh filter was applied to the digitized data to suppress effects of sources at the surface or at shallow depth while essentially preserving the significant deeper geological effects. The smallest wavelength transmitted by this filter is around 16 km. (Courtesy of T.G. Hildenbrand, U.S. Geological Survey)

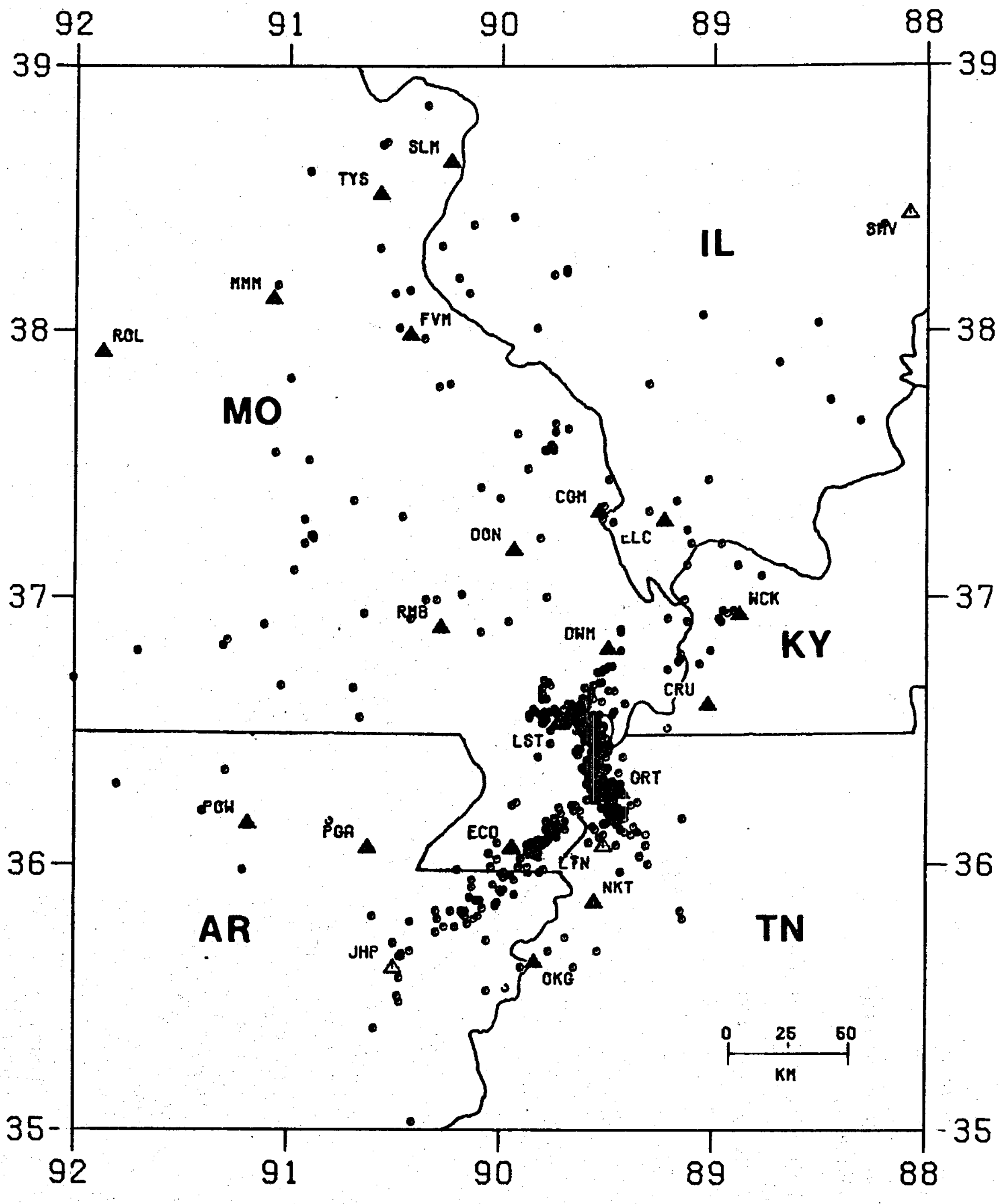

FIGURE 9.3 Seismic events recorded 1 July 1974 - 30 June 1977 in the New Madrid area, Missouri, and surrounding region. Circles = epicenters; triangles = stations. (Courtesy of W.V. Stauder and associates, Department of Earth and Atmospheric Sciences, St. Louis University)

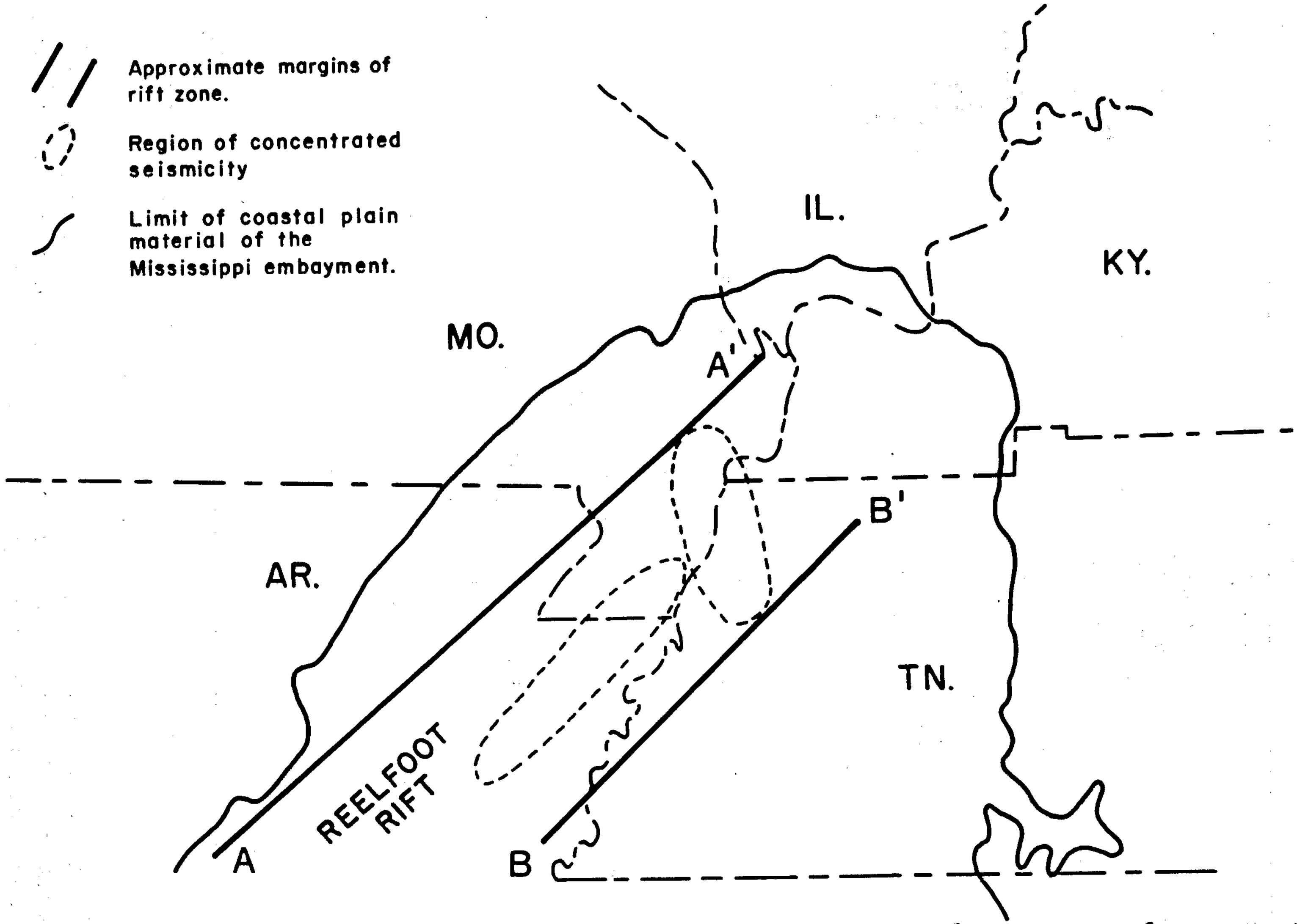

FIGURE 9.4 Northern end of the Mississippi Embayment. Dashed lines enclose regions of concentrated seismicity shown in Figure 9.3. Solid lines (A-A', B-B') indicate assumed margins of rift zone. (Courtesy of T.G. Hildenbrand, U.S. Geological Survey)

Forecast of Plate-Interior Activity

Documentation of activity in the Michigan Basin and in the Missisippi Embayment provides but two examples of intense investigative effort devoted to the dynamics of plate interiors. Equally significant projects, some unidentified by this reporter and his informants, are also operating in a time of greatly revived interest and concern for the tectonics and resources of cratons and their margins. It is becoming increasingly clear that the dynamics of plate interiors are manifestations of processes and events of much greater scope and that rational solutions to plate-interior problems cannot be found without consideration of the evolution of continental plates through global-tectonic history or without taking into account the concurrent effects of ocean dynamics on continental interiors. Examples of pressing problems would include:

Cratonic Flexure. Sedimentary basins and intervening arches represent flexural deformation of continental plates. Global episodes of flexure appear to coincide with episodes of sea-floor spreading maxima. Is stress applied at continental margins transmitted to interiors or are accelerated spreading and flexure independent responses to an unidentified "driving force"? Loci of upwarp and subsidence remain relatively fixed yet shift about within the limits of arch/basin domains. Is there a predestination of positive and negative elements as a result of crustal evolution? If so, why are there 100 km and greater migrations of basin centers?

Cratonic Fracture. Cratons are subject to episodes of large-scale vertical movements along fractures, sometimes in concert from craton to craton, sometimes more or less independently. In places and at times fracture is accompanied by vulcanism and plutonism, elsewhere or at different times no thermal activity is involved. It is convenient to consider midcontinent rifts and aulacogens as related to incipient spreading axes, yet the number of "failed" examples suggests that a quite different process is involved. It is possible to envisage a continuum from cold/rigid deformation of "Ancestral Rocky" or Arbuckle type to high-T/low-P "Germanotyp" or Hercynian mountain building. Is the continuum real? If not, what distinguishes and determines the end members and intervening states? The implications of cratonic fracture in terms of cratonic seismicity indicate the need for continuing study.

Passive Margins. Atlantic-type margins are parts of the interiors of present-day lithospheric plates but tend to fall between the jurisdictional stools established by oceanic and continental investigators, perhaps because of differences of approach, philosophy, tools, and funding agencies. Observations accumulate to show a strong interdependence and concomitance between shelf/upper-slope tectonics and sedimentation and that of continental interiors but little is known about the stratigraphy and internal geometry of the lower-slope/rise prism, where enormous volumes of sediment, perhaps containing vast resources, reside. Theoretically, there should be a complementary relationship between cratonic erosion and slope/rise sedimentation; that is, episodes of continental-interior uplift should be matched by major depositional events on slopes, rises, and adjacent fans. If so, there exists an unexplored and unexploited sedimentary mass whose stratigraphy, petrology, and resource potential may find no ready analogs among the familiar sediments of continental interiors and shallow margins.

Approach to this question will demand the coordinated effort of land-lubbers and oceanographers, of geophysicists and geologists, of government, industry, and academia.

May 1977

10B
DATA CENTERS AND REPOSITORIES

ALAN H. SHAPLEY

Editor's Note: Various international bodies will be discussing international data exchange (through the World Data Centers and other mechanisms) during meetings in 1977. These include various associations and commissions of IUGG--IASPEI, IAVCEI, IAGA, Commission on Recent Crustal Movements, Tsunami Committee, Commission on Practice, Heat Flow Committee, Commission on Earth Tides, IAGA Working Group on Collection and Dissemination of Data (and several IAGA WG's concerned with specific aspects of magnetic data), Working Group on Radiogenic Isotopes and Their Geophysical Applications, Working Group on Volcanological Data Files, and others--that are concerned with solid-earth data relevant to geodynamics.

The Inter-Union Comission on Geodynamics (ICG) was asked by ICSU to name the representative for solid earth on the ICSU Panel on World Data Centers. In addition, ICG established a Committee on World Data Centers and Data Exchange to take initiative in encouraging the relevant associations and committees to develop recommendations for the solid-earth data exchange through the World Data Centers.

The following report regarding collaboration between World Data Center A and World Data Center B was prepared for a general audience. It pertains not only to the solid earth, but to other areas of geophysics. However, in view of the increasing interest of the solid-earth community in international data exchange, the chairman of the U.S. Geodynamics Committee invited inclusion of this report in the USGC progress report for 1977.

In May and June of this year, there was a significant step forward in the efforts to improve the effectiveness of the international exchange of observational data in the environmental sciences. After several years of planning, a delegation of five scientists representing World Data Center B (two of them were full-time staff workers at that center) spent four weeks in the United States visiting and working at the several components of World Data Center A and associated national centers.

This was not the first visit between representatives or staff of the World Data Centers, which were established at the time of the International Geophysical Year, IGY, 1957-1958, and have continued to serve very effectively since then for exchange of data under the auspices of the International Council of Scientific Unions (ICSU). But almost all such visits before this one have been brief visits of opportunity--when scientists involved in data management or data center staff were passing through on other business. Such short visits have helped very much to resolve specific questions and have provided opportunities for overview of facilities, but the 1977 working visit of WDC-B representatives to WDC-A allowed enough time for both discussion on many more details and in-depth observation of techniques and procedures with the people actually doing the work.

The leader of the WDC-B delegation was Vladimir Kotliakov, a distinguished Soviet glaciologist, a corresponding Member of the USSR Academy of Sciences and Vice Chairman of the IUGG Commission on Snow and Ice. He was assisted by Dr. Artyom Powsner, Secretary of the Soviet Geophysical Committee which oversees the activities of World Data Center B and actually operates WDC-B2, the center which treats solar-terrestrial and most solid-earth data. The other component of the center, WDC-B1, is operated by the hydrometeorological department and covers meteorology, oceanography and related disciplines, including glaciology, Dr. Kotliakov's speciality. The other scientists were Dr. Ye. Kharin, Deputy Director of WDC-B2, Dr. Yu. Tiupkin who is head of the WDC-B2 mathematical and computer group, and Dr. Natalia Dreyer, a hydrologist experienced in data matters. The group was exceedingly well prepared for the visit with many well focused, written questions on data handling procedures and scores of specific questions. It was indeed a working visit.

The visit was responsive to a recommendation of the ICSU Panel on World Data Centers in a 1972 report which was endorsed by ICSU itself. This was followed by an exchange of letters between the Presidents of the U.S. and USSR Academies of Science and the inclusion of the visit in the formal exchange plans of the two Academies. The arrangements in the U.S. were the responsibility of Dr. P. J. Hart, Secretary of the Geophysics Research Board and Director of WDC-A.

Unlike the WDC-B centers, both of which are located in Moscow, the WDC-A centers, all of which the Soviet delegation visited, are located in three cities--Washington, D.C., Asheville, North Carolina and Boulder, Colorado. In the Washington area there are WDC's for Oceanography, Rockets and Satellites, and Rotation of the Earth; WDC-A for Meteorology and GARP is in Asheville. The most time spent was at Boulder, the location of the WDC-A centers for Solar-Terrestrial Physics, Solid Earth Geophysics and Glaciology. The first two are operated by the NOAA Environmental Data Service along with the corresponding national centers, while the University of Colorado operates WDC-A Glaciology under contract with EDS. Doctors Kotliakov and Dreyer also visited the key glaciological activity of the U.S. Geological Survey at Takoma, Washington, the former site of WDC-A Glaciology, to work on an international data compilation project concerning snow and ice.

There were three main themes for the WDC-B/A visit: (1) sharing experience on detailed procedures for data acquisition, processing, archiving, and dissemination; (2) agreeing on formats and other particulars to enhance the exchange of data, particularly in machine readable form; (3) sharing information on and experience with equipment used in all aspects of the data service function. In all three, a great deal of progress was made. The WDC-B scientists went away with dozens of pages of organized notes and there are several pages of jointly agreed understandings in the record.

Of special interest were the very detailed discussions and written understandings as regards machine readable data, thanks to the comparable expertise of Dr. Tiupkin and the many computer specialists at the various U.S. centers. This bodes well for the future as data from modern sensors, especially from the newer international data-intensive programs (such as the IMS and GATE), flow into the WDC's in great quantity. There have always been problems of compatibility of data from one kind of computer to another. This causes problems even for exchange of data among centers and institutions in the United States, and is amplified for international exchanges. The USSR computer at WDC-B2 is not compatible with U.S. computers, but WDC-B2 has limited time access to another computer in Moscow which, in general, is compatible. Shortly before the visit of the WDC-B scientists, each center had successfully read pilot tapes from the other, so the discussions during the visit were conducted with the background of actual successful experience. The exchange of these experiences, with the kinds of details and interactions which can only be done between experts, cannot help but accelerate manyfold the progress in treating the respective magnetic tapes even more expeditiously and effectively in the future.

The timing of this exchange visit was also influenced by the fact that there are active plans to relocate and re-equip WDC-B in a central location in Moscow, including, hopefully, a compatible computer. To the extent possible, there will be an attempt to achieve compatibility also in copying machines, microform and other data handling equipment. The WDC-B scientists have now seen the equipment used or available in the U.S. and have had opportunities to use many items themselves. In the long run, this will reduce the reformatting effort with data exchanged between the centers and improve services to users in the many countries served by WDC-A and WDC-B. It has been the general experience of both centers that in quantity of data, the data from other countries are the most wanted.

Perhaps it would be useful, for putting the importance of this exchange visit into perspective, to briefly summarize the general mechanism of data exchange through the World Data Centers. The principles were laid down for the IGY program and continue virtually unchanged. The WDC's supplement the traditional scientist-to-scientist exchange of the kinds of data usable by scientists other than the original observers. The type and quantity of data and, in many cases, the format, are detailed in data exchange recommendations compiled by the cognizant groups in the ICSU scientifc organizations (unions, associations, committees) and relevant intergovernmental bodies; they are collected in a publication, *Guide to International Data Exchange through the World Data Centers*, issued by the ICSU Panel on WDC's. Participation is fully voluntary, but the cooperation of the scientific community has been remarkable. The individual WDC's were designated by the overseeing ICSU group, acting on the offers from the national bodies (Academies) adhering to ICSU. For reasons of safety of the data collections and the convenience of data contributors and users, three duplicate WDC's in different parts of the world were designated for most disciplines and at least two in all cases. The WDC's are operated with national funds and agree to follow the ICSU principles and guidelines. In general the contributors of data are entitled to an equivalent amount without cost; other data are made available at no more than the copying cost. In practice the WDC-A centers are in the U.S., the WDC-B centers in the USSR, in each case covering all disciplines covered in the ICSU *Guide*. The WDC-C centers for various disciplines are in different countries in Western Europe and in Japan. The *Guide* calls for data to be sent by the observer either to all of the WDC's for that discipline or to only one of them; in the latter case the WDC receiving the data is to send copies to the others or at least make them available upon request. In this way, the core data collection is available at all the relevant WDC's; all the rest of the data are available on request through any of the WDC's.

In the U.S., the WDC-A centers have now been co-located with the corresponding national centers. This simplifies the carrying out of another recommendation in the ICSU *Guide*, namely that WDC's will undertake to obtain for requestors data which are not specifically provided for inclusion in the WDC archives. The WDC-B and WDC-C centers also have responded to such requests.

It has been remarkable how well this loose, almost informal arrangement for international data exchange has worked out. WDC-B reports about 10,000 requests serviced per year and the WDC-A level of activity is about the same, although it is harder to distinguish between the WDC-A and the national center activity. Some of the WDC-C centers are proportionately active, while many concentrate on subsets of the data for particular disciplines and on data processing or summarization. Of course, the quantity of requests is not necessarily the most meaningful parameter. Many important scientific jobs just could not be done if data requests and data copying were not centralized to a certain extent. What if one has to write to the 35 solar flare patrol stations every time one wanted data on a particular flare? Or to 150 ionospheric sounding stations to know what the electron density of the F2 layer was at 1300 UT on a given day? Or to 100 oceanographic laboratories to find out if they had cruise data near the Galapagos Islands? Similar considerations apply for seismology, geomagnetism--indeed, most geophysical disciplines.

The ICSU *Guide* is continually, if slowly, being revised to try to correspond to the real and modern needs of scientists using the WDC mechanisms. But it is important for the data exchange recommendations to be practical for the data contributors and the data centers as well as for the data users. If experience shows that there is rather small, albeit important, call on a given type of data, it may make sense for the archive to stay at the originating institution and the role of the WDC's be to advertise the existence of the data but refer requests to the holding institution rather than incur effort and expense to get the whole data file into a central archive. And if a WDC gets many requests for data which it cannot fill, it should take steps to get the data more conveniently available by having it brought to the center. In many cases the WDC's have made suggestions on the basis of this kind of experience to the scientific organizations responsible for sections of the ICSU *Guide*.

One of the fruits of the WDC-A/B exchange visit was the sharing of their experiences and plans to communicate on data exchange matters with the various specialized international scientific committees which influence observing programs. One thing the two groups realized was the need to constantly renew information about the WDC mechanism to scientific leaders in the various disciplines and countries, particularly the developing countries. The older scientists, many of them veterans of the IGY, are quite familiar with the WDC's, but the turnover of potential users and contributors is perhaps 5% per year; since it has been almost five years since the last mass mailing of the ICSU *Guide*, almost a quarter of the present scientific community may not have heard directly about the WDC's. We discussed a number of ways the WDC's themselves could help in renewing such information in the community.

It was generally agreed that this should be only the first working visit of this kind. We are determined to explore the possibilities of a reciprocal visit of WDC-A workers to WDC-B at an appropriate time in the planned evolution of WDC-B activity. It was also considered that there was a need for some more specialized working visits on data-related activities and that visits of opportunity would continue to be encouraged, not only involving A and B, but also the various centers C. At the concluding session at Boulder, which involved several of the members of the U.S. National Academy advisory committee concerned with the WDC's, it was generally agreed that the visit had inaugurated a new era in cooperation in data service activities of the respective countries. This should benefit the entire community of users of the WDC's.

Scientific Disciplines Included in Data Exchange through World Data Centers

Solar-Terrestrial Physics
- Solar and Interplanetary Phenomena
- Ionospheric Phenomena
- Flare-Associated Events
- Geomagnetic Variation
- Aurora
- Cosmic Rays
- Airglow

Rockets and Satellites

Meteorology

Oceanography and Marine Geology and Geophysics

Glaciology
- Snow Cover, Avalanches
- Glaciers and Glacier Fluctuation
- Sea, River and Lake Ice
- Permafrost
- Polar Ice Masses
- Paleoglaciology

Solid-Earth Geophysics
- Seismology
- Tsunamis
- Gravity
- Earth Tides
- Recent Movements of the Earth's Crust
- Rotation of the Earth
- Magnetic Measurements
- Paleomagnetism and Archeomagnetism
- Volcanology
- Heat Flow and Geothermics

11

GEODYNAMIC ACTIVITIES IN THE CARIBBEAN AREA

JOHN D. WEAVER

The tectonic and bathymetric maps of the Caribbean at 1:2,500,000 by J. Case (USGS) and T. Holcombe (U.S. Naval Oceanographic Office) are now completed and in course of publication.

The Puerto Rico seismic network has continued operation. Some interesting results are a possible southward-dipping Benioff zone under the Puerto Rico Trench and Puerto Rico. The Mona Canyon continues to be the most active, though anomalously high activity is found in the southwest of the island. A line of events heading NE from the NE corner of Puerto Rico suggests a hitherto unnoted fault.

In volcanology, Smith and Roobol (University of Puerto Rico) continued their studies of alternating sequences of eruptive styles in Mt. Pelee and Statia and hope to carry out similar studies on other West Indian volcanoes. This work should be of considerable value in prediction of volcanic hazards. The continued eruption of the Soufriere in Guadeloupe gave a team from Los Alamos Scientific Laboratory an opportunity to study various aspects of its eruptive activity. H. Sigurdson (University of Rhode Island) is studying tephrochronology in cores taken close to volcanic islands.

A Department of Geology and Mining has been started at the Universidad Catolica Madre y Maestra in Santiago, Dominican Republic, with substantial aid from the United Kingdom. J. Lewis (George Washington University) has spent his sabbatical year there and continues study of the structure and plutonic rocks of the western part of the Republic.

J. Watkins (University of Texas), A. Bellizzia (Venezuela), J. Galavis (Venezuela), J. Saunders (Natural History Museum, Basel), and J. Weaver (University of Puerto Rico) are compiling three N-S geological and geophysical profiles from the Outer Ridge of the Puerto Rico Trench, through eastern Dominican Republic, western Puerto Rico, and the Virgin Islands, across the Venezuela Basin and into the Venezuela mainland (Figure 11.1). A preliminary draft was displayed at the Caribbean Geological Conference in Curacao in July 1977 (see below).

In July 1976, the Caribbean Study Group of Working Group 2 met in Mayaguez, Puerto Rico. Six critical problems and/or areas were agreed upon as foci of future coordinated efforts. These were:

(a) The four corners or "hinge" areas of the region, beginning with the SE (Barbados)
(b) Hispaniola

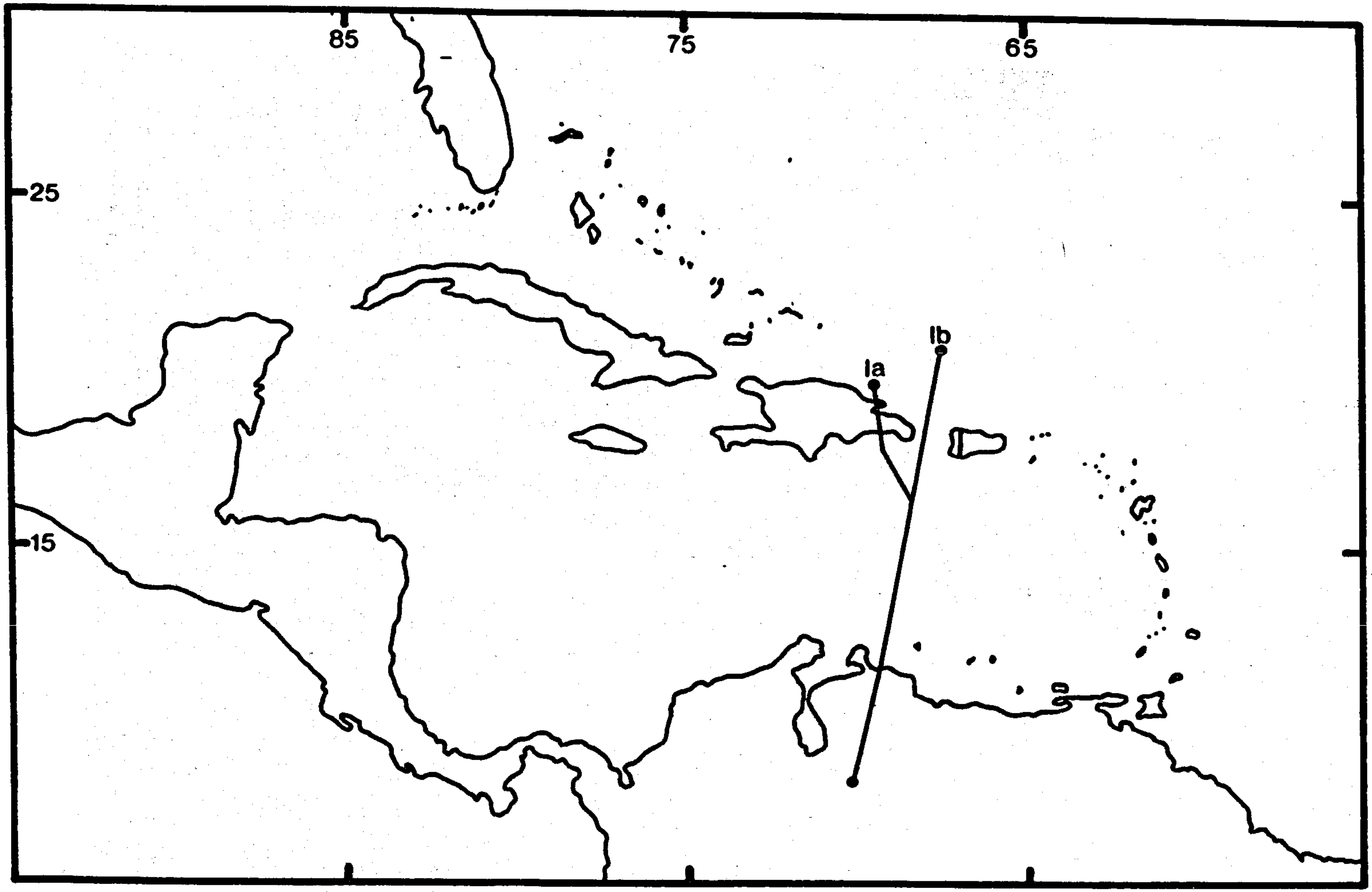

FIGURE 11.1 Location of preliminary cross section presented at the 8th Caribbean Geological Congress, July 1977.

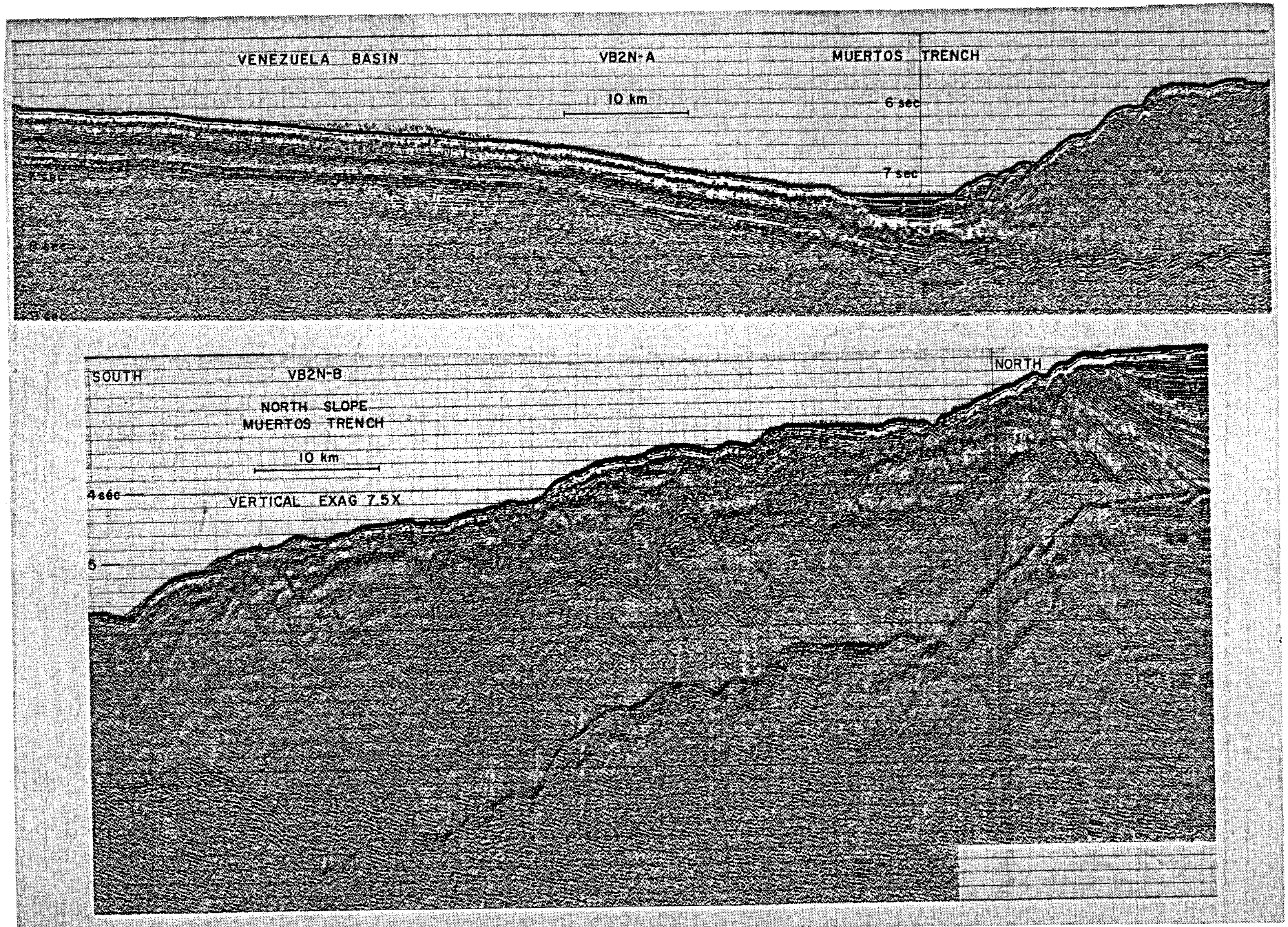

FIGURE 11.2 Reflection profile across the Muertos Trench showing evidence of underthrusting of the Venezuela Basin under the slope south of Hispaniola.

(c) Exposed "basement" areas
(d) Recent crustal movements and seismicity
(e) Metallogenesis related to tectonics and petrology
(f) Volcanic activity

In April 1977, a Caribbean Workshop was held at SUNY, Albany, organized by K. Burke and P.J. Fox and funded by the National Science Foundation. Its recommendations followed quite closely those of the Caribbean Study Group, though emphasis was placed more strongly on land studies. It was noted that there is a serious lack of workers interested in carrying out studies on land involving mapping.

The suggested possibility of oil in the northern shelf of Puerto Rico and imminent drilling by Venezuelans in eastern Dominican Republic may encourage interest in geology and geophysics locally.

The following report on the Caribbean cross section was provided by Joel Watkins.

Geological-Geophysical Section across the Caribbean

At the 8th Caribbean Geological Conference in Curacao, 9-24 July 1977, the Caribbean Study Group (of ICG Working Group 2) presented a preliminary version of Section 1 from the outer high north of the Puerto Rico Trench to the interior of Venezuela. The section was drawn on a scale of 1:250,000 with no vertical exaggeration.

John Weaver of the University of Puerto Rico contributed sections through Puerto Rico and Hispaniola based on published geology and geophysics of the region. John Saunders of the Natural History Museum in Basel, Switzerland, contributed a section across the coastal ranges and continental margin of Venezuela northward to Curacao. Dirk Beets of the Geology Institute in Amsterdam, the Netherlands, contributed a section across Curacao incorporating the results of his latest mapping. John Ladd of the University of Texas Marine Science Institute (MSI) contributed a section from the outer high north of the Puerto Rico Trench to the island of Curacao using published geophysical information and multichannel data collected by MSI. The display at the Caribbean conference included examples of multichannel data along the line of section (Figure 11.2) as well as data connecting the section to John Weaver's Hispaniola section.

The contributors at the Caribbean Conference felt that the display was only a preliminary attempt since it is hoped that scientists from Venezuela will contribute more detailed information to a Venezuela section and that Lamont will contribute data from their Caribbean work. The contributors plan to display their sections again at the Latin American Geological Congress in Caracas in November 1977.

July 1977

12

SEISMICITY AND DEEP STRUCTURE OF THE CONTINENTAL MARGIN

THOMAS H. JORDAN

Introduction

Most of the earth's seismic activity is concentrated along the continental margins (Figure 12.1). Destructive or potentially destructive earthquakes occurring at shallow depths within these margins account for well over three fourths of the planet's total seismic energy production. These earthquakes are evidence of the continuing violent processes which have shaped the continents over the aeons of geological history. Plate tectonics has provided an explanation for why so many of the great earthquakes are concentrated in these narrow zones: most continental margins are, or have been at some time in the past, the boundaries between major lithospheric plates engaged in geologically rapid relative motion. These motions give rise to the stresses responsible for large earthquakes and continually modify the face of the planet.

To understand fully the dynamics of destructive earthquakes, as well as the fundamental mechanisms that cause them, we need to increase our knowledge of the structure and dynamics of the continental margins. It appears that an adequate understanding of these problems will not emerge if we confine our attention to the upper levels of the crust; our studies must extend deeply into the earth's mantle.

Besides being directly relevant to dynamic questions, the information gleaned from these studies of deep structure of the margins is critical to any theory of the evolution of continents. The nature of the subsurface transition from the oceanic to the stable continental environment is not well understood. Geophysical data indicate that profound differences between the oceans and the stable continental platforms extend below the crust, well into the upper mantle. At these depths the transition zone includes not only the present-day continental margins but nearly all of the tectonically active regions of the continents--generally regions that have been continental margins at some time in the relatively recent geological past.

Seismicity of the Margins

Global networks of seismometers are capable of locating most potentially destructive earthquakes (magnitude > 4.5) with a precision of about ±25 km. However, much can be learned about the tectonics of seismically active regions by monitoring smaller events and locating these with increased precision. This usually requires the deployment of local or regional networks

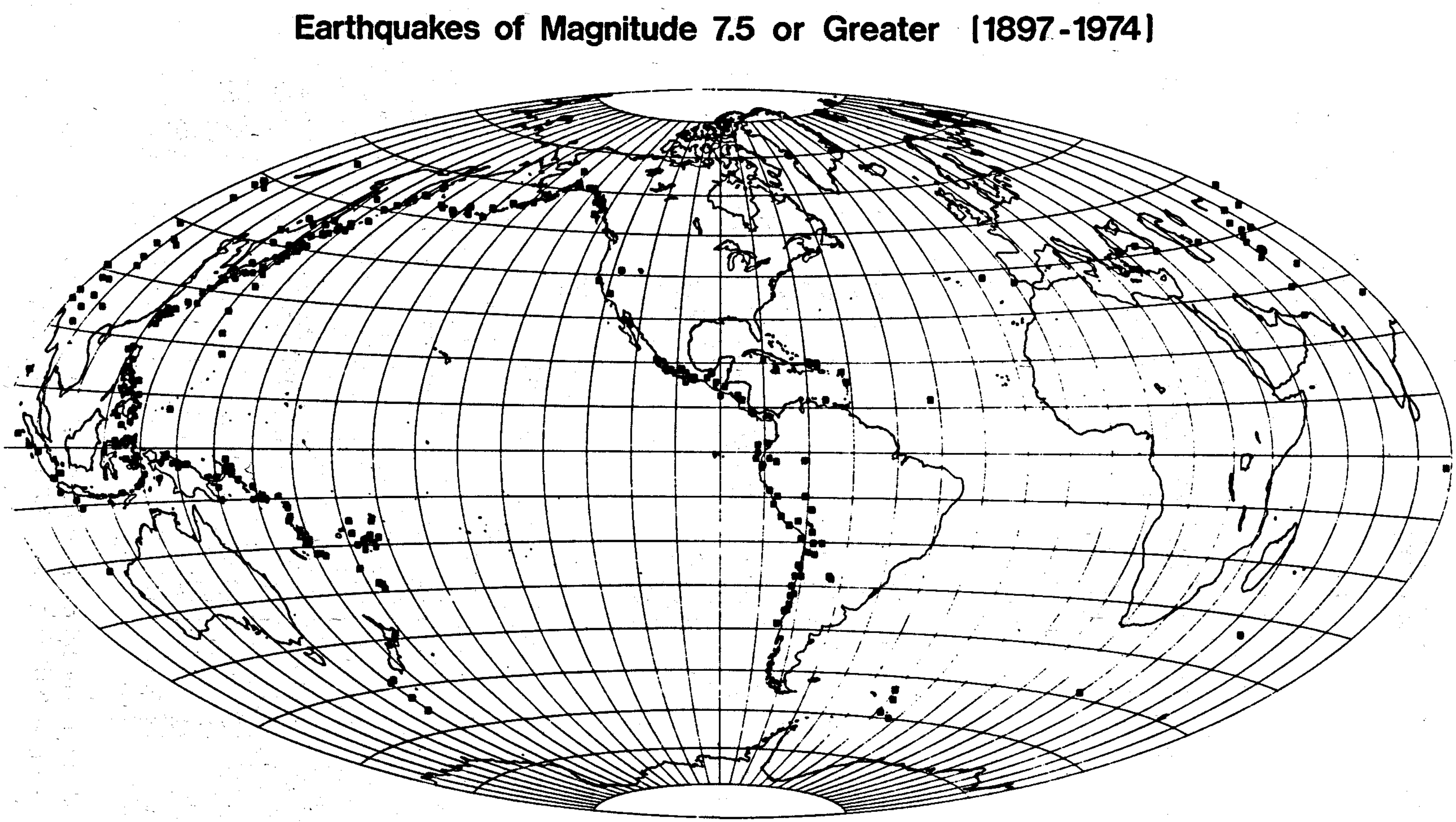

FIGURE 12.1 The distribution of large earthquakes, 1897-1974. (Prepared by National Oceanic and Atmospheric Administration)

Fracture Zone Microearthquakes

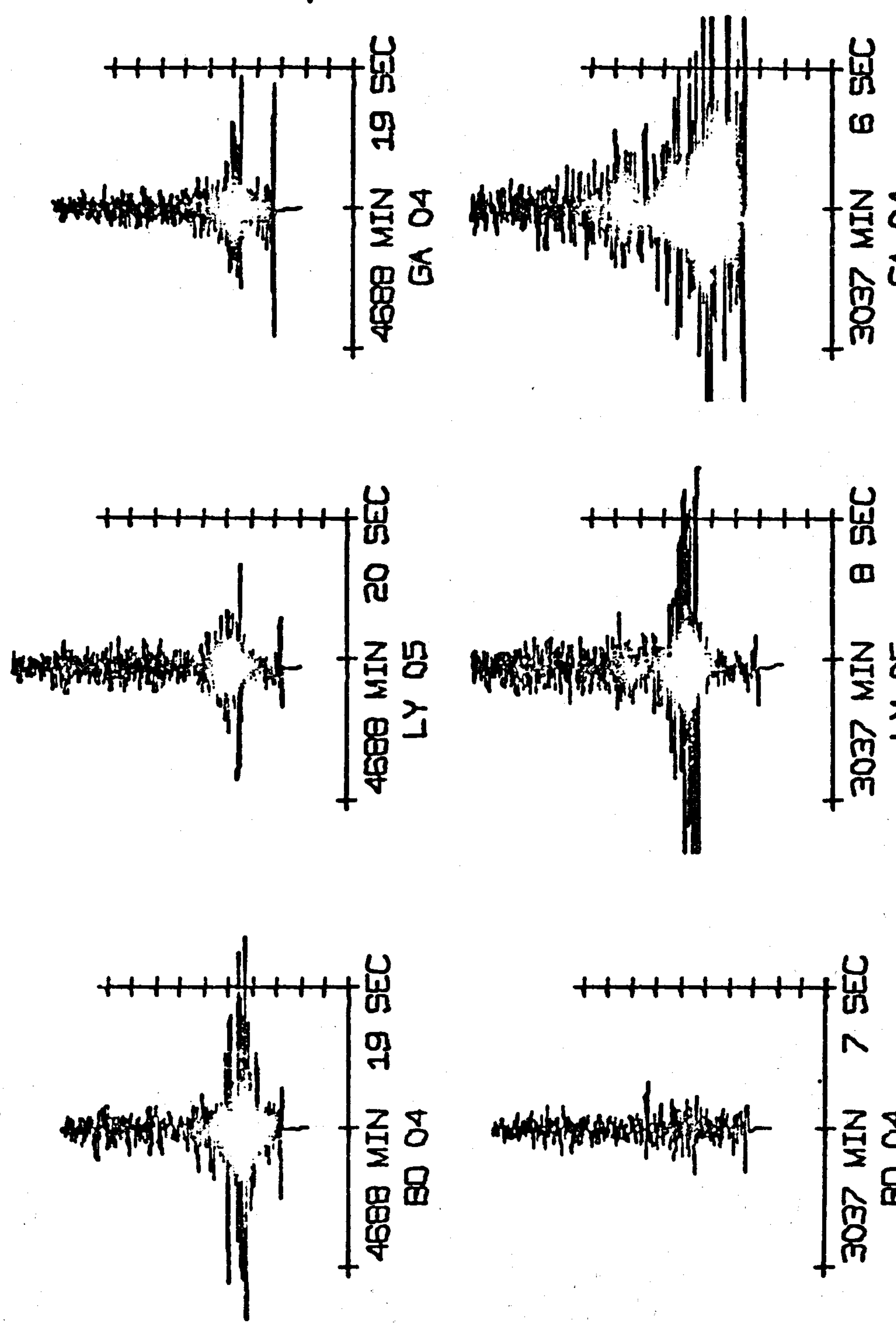

FIGURE 12.2 Microearthquakes recorded by ocean-bottom seismometers near the mouth of the Gulf of California. (Courtesy Scripps Marine Seismology Group)

with seismometers separated by tens to several hundreds of kilometers. Accurate location also requires good azimuthal distribution of seismometers around the source region. For continental margin seismicity, this coverage is difficult to achieve with land-based stations alone. The land-based networks must be augmented by seismometers capable of being deployed in the marine environment.

Recent advances in ocean-bottom seismometer (OBS) technology at a number of universities and oceanographic institutions now permit such deployments to be done routinely. OBS packages are essentially miniaturized, self-contained seismic stations capable of withstanding the harsh environment of the deep ocean. In some OBS designs, incoming signals activate the recording device. Magnetic tape or digital memory buffers are used to obtain complete recording of the event and some sample of the preceding noise activity. This event-recording mode permits the long deployment times (1 month or more) necessary to sample adequately the microseismic activity. In the more advanced packages, the data are logged in digital format. Such logging increases the seismometer's dynamic range and greatly facilitates the analysis of the data. At the end of the recording period the OBS packages are recalled to the surface by acoustic command or released from the bottom at a preset time. Figure 12.2 illustrates some microearthquake data collected by an array of ocean-bottom seismometers deployed on the East Pacific Rise near the mouth of the Gulf of California.

The OBS technology is new and is only now being used to study continental margin seismicity and structure. More instrumental development is needed, especially in the direction of increasing bandwidth and low-frequency sensitivity. This is necessary if full use is to be made of OBS capabilities for the study of shear waves and surface waves from the larger magnitude seismic events.

Use of ocean-bottom seismometers in conjunction with land-based arrays will considerably increase our knowledge of the major and minor seismicity of the continental margins. Particular questions that should be addressed include:

1. What are the spatial and temporal relationships between minor seismicity and the occurrence of large earthquakes?
2. Is the minor seismicity of the active margins concentrated along major faults or distributed within large volumes of the lithosphere?
3. What is the nature of the seismicity gap between the trench and island arc apparent in some subduction zones?
4. What is the minor seismicity of the passive margins? What features along the passive margins are seismically active?

Tectonic Stresses along the Margins

At present, little is known about the state of stress within the earth, despite the obvious importance of stress fields in earthquake processes. This is especially true about the absolute magnitude of stresses within tectonically active regions. For example, there is no consensus among geophysicists about the average absolute stress fields present immediately prior to the occurrence of large earthquakes: estimates vary by more than one order of

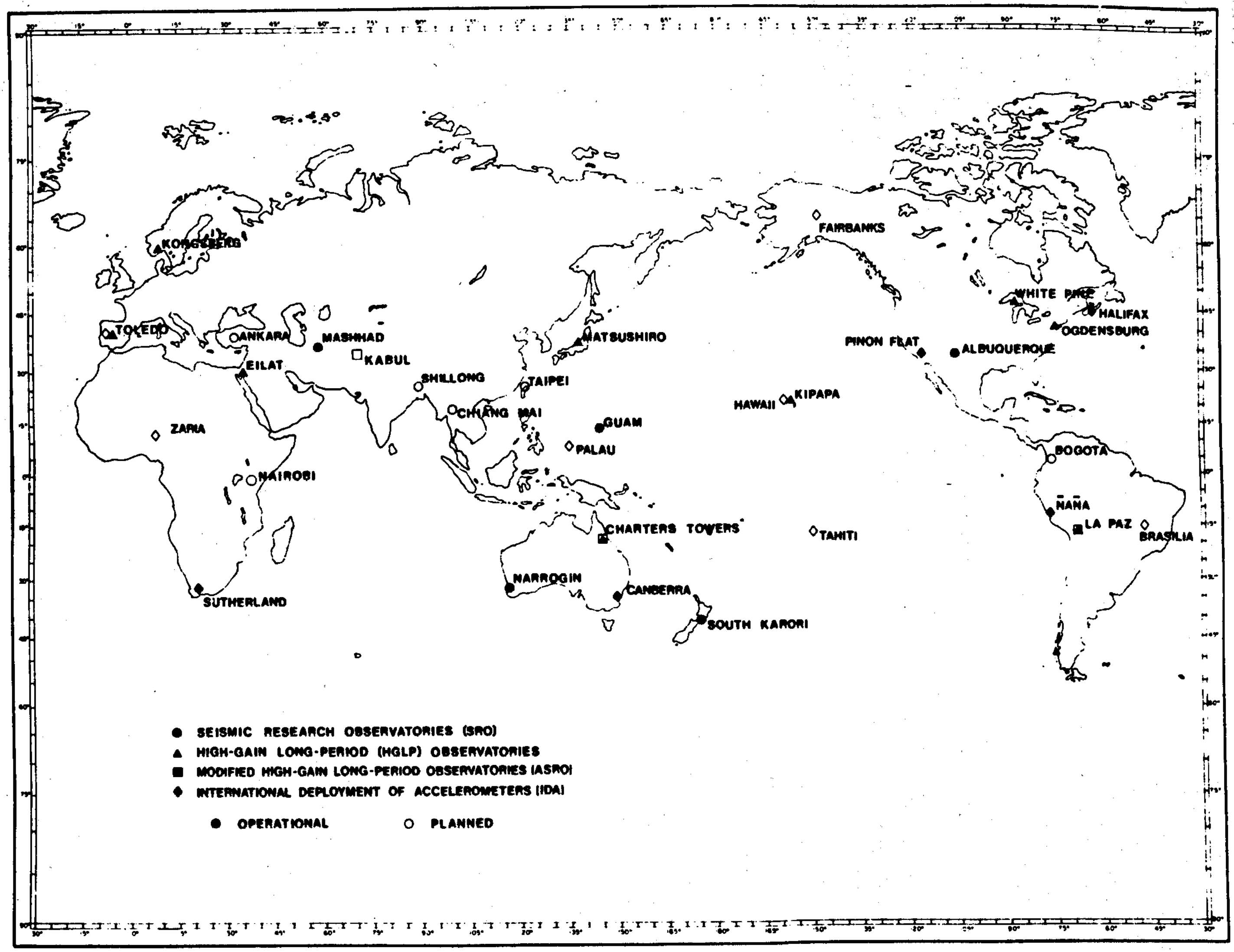

FIGURE 12.3 The distribution of digitally recording seismic stations. (Courtesy U.S. Geological Survey)

magnitude. On the one hand, seismologists routinely measure stress drops (i.e., the difference between initial and final stress) for earthquakes which generally are less than 100 bars. These numbers have been used as measures of absolute stress. On the other hand, rock mechanics experiments suggest that, at lithostatic pressures appropriate for the middle to lower crust, absolute deviatoric stresses exceeding several kilobars are necessary to fracture crustal rocks. Until the controversy surrounding these questions is resolved, it will be difficult to attain any precise understanding of earthquake dynamics. These questions also have an important bearing on the theories of the plate-tectonic driving mechanism.

Studies of the stress fields along active margins should be a cornerstone for any research program on earthquake dynamics. Stress estimates have been made on convergent active margins from seismic measurements (i.e., stress drop and stress tensor orientation), but the techniques employed by these studies need further development. In particular, computational schemes for properly handling surface tractions during the rupture process (important for very shallow events) and spatially and temporally complex sources (important for large events) need to be implemented.

For these studies, the data collected by global networks of digitally recording, broad-bandwidth seismometers will be critical. At present, there are three such networks deployed or in the deployment stage (Figure 12.3):

1. High-Gain Long Period (HGLP) Network
2. Seismic Research Observatory (SRO) Network
3. International Deployment of Accelerometers (IDA) Network

In addition, the United States Geological Survey is proposing to upgrade 15 to 20 Worldwide Standardized Seismograph Network (WWSSN) stations to 7-channel, digital recording capability. These networks will provide the high-quality data base necessary for the study of continental margin earthquakes, and they deserve strong federal support.*

For the study of small earthquakes, such as the aftershock sequences of large events, the deployment of local networks including ocean-bottom seismometers is necessary.

Ocean-bottom topography outboard from the trenches is influenced by the stress regime at convergent active margins. This topography places independent constraints on the model of stress regime of those margins. Using elastic plate models, a number of workers have estimated that the stresses within the descending slab necessary to support the topographic elevation of the so-called "outer rise" are on the order of several kilobars, values similar to the strength of rocks studied under laboratory conditions, but an order of magnitude or so greater than stress drop estimates derived from seismology. These values, however, are sensitive to the assumptions of the

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*For further information on these networks, consult the reports *Trends and Opportunities in Seismology*, 1977 and *Global Earthquake Monitoring: Its Uses, Potentials and Support Requirements*, 1977, issued by the Committee on Seismology, National Academy of Sciences, Washington, D.C.

elastic plate model and further studies employing nonlinear plastic rheologies should be attempted.

To model earthquake dynamics, it is necessary to know not only the ambient stress field, but also the nature of temporal changes in the stress and strain fields of seismically active areas, especially on a time scale of one to several tens of years. Measurements of these changes require precise geodetic techniques capable of sensing very small vertical and horizontal motion displacements and the development of new stress monitoring devices. Recently developed satellite-ranging and lunar-laser ranging techniques and the techniques of very long baseline interferometry are promising. Temporal changes can also be monitored by ultra-stable strainmeters and gravimeters which employ laser and cryogenic technologies. In the study of U.S. margins, more program coordination among the various responsible federal agencies should be achieved.

The direct measurement of stresses at shallow depths by down-hole hydraulic fracturing may also shed some light on the problems associated with stress fields. However, these techniques are difficult to implement even on land and are subject to errors and interpretive uncertainties. Nevertheless, the feasibility of collecting such measurements on the continental margins should be studied.

Besides addressing the general problems of earthquake dynamics and global tectonics, stress field and associated strain field studies are needed to answer the following specific questions:

1. How far into the continental/island arc region does the deformation associated with the subduction of oceanic plate irregularities extend?
2. Which portions of the subduction zone are under tension and which are in compression?
3. Do the different arcuate structures of subduction zones correspond with different conditions of stress within the volcanic arc?
4. What determines the equilibrium position of the overriding plates with respect to the surface of the underthrust lithosphere?
5. How are the orogenic forces in convergence regions transmitted from the subduction zone to the mountains on the overriding plates?
6. How important, deep, and extensive are the high-friction regions that are presumed to heat up the upper surface of the subducted slabs to produce magmas?
7. What is the stress field in marginal basins?
8. What are the strengths of rocks in continental margin fault zones and how are these strengths affected by volatile content?

The Nature of the Continent-Ocean Transition

The continental margins represent a region of transition between two very different crustal types--the thin, simatic crust of the oceans and the thick, sialic crust of the continents. The differences between these two lithospheric types are not confined to the crust: profound variations extend to an as yet undetermined depth into the mantle. Furthermore, the margins are thought to be the site of continental accretion, the most spectacular surface manifestation of the long-term chemical evolution of the earth. The exact nature of the continent-ocean transition is a fundamental problem confronting modern earth science. The detailed understanding of this transition will place severe constraints on models of earth dynamics.

The probing of this transition zone is not an easy task. By its very nature the continental margin is laterally heterogeneous, and the heterogeneity extends over many scales. The techniques used to map this heterogeneity must have high lateral and vertical resolution and must be capable of great depth penetration. No one geophysical technique can provide this resolution; a combination of techniques is required.

The highest resolution methods are seismic surveys using compressional waves and artificial sources. These can be broadly classified into two types: reflection and refraction.

Reflection profiling with artificial sources has been extensively developed in the search for petroleum, and its capabilities using advanced multichannel systems are detailed elsewhere (e.g., *Multichannel Seismic Reflection System Needs of the U.S. Academic Community*, Ocean Sciences Board, National Academy of Sciences, Washington, D.C., 1976). High resolution and increased signal-to-noise ratio are achieved by stacking procedures that take full advantage of data redundancy. This method seems to be ideally suited for the study of the upper 10 km of the crust. By two-ship, constant-offset profiling, the recording can be extended to even greater depths, perhaps allowing the entire crustal column and even the uppermost mantle to be sampled. Further development of the reflection profiling method deserves a high priority.

The seismic refraction technique makes use of greater separation between the source and receiver. It has the advantage that very deep penetration (200 km or more) can be achieved with artificial sources. The development of reliable ocean-bottom seismometers has re-awakened the interest of the scientific community in the use of refraction techniques for the study of continental margin structure.

The geometry of refraction profiling using OBS's is illustrated in Figure 12.4. A ship firing explosive charges steams away from the OBS, and the seismic energy turned or reflected at depth is recorded for later recovery. To conserve magnetic tape, the shots are fired and recorded at prearranged intervals. Recording in digital format is preferred, since it facilitates subsequent data processing. To maximize the use of the information obtained in this fashion, sophisticated analysis techniques are employed in the interpretation of the data. The most successful of these has been the time-domain modeling of the arrivals by the computation of synthetic seismograms. The use of amplitude and waveform information greatly enhances the resolution of the refraction method.

Further information can be obtained by shooting to an array of ocean-bottom seismometers instead of a single sensor. Frequency-wavenumber processing can then be employed to extract the horizontal phase velocities of various arrivals, which further constrains the class of acceptable velocity models, especially in regions characterized by large vertical velocity gradients. The use of OBS arrays can also provide constraints on the lateral structure beneath the array. An example of the application of frequency-wavenumber analysis to data from an OBS array is illustrated in Figure 12.5.

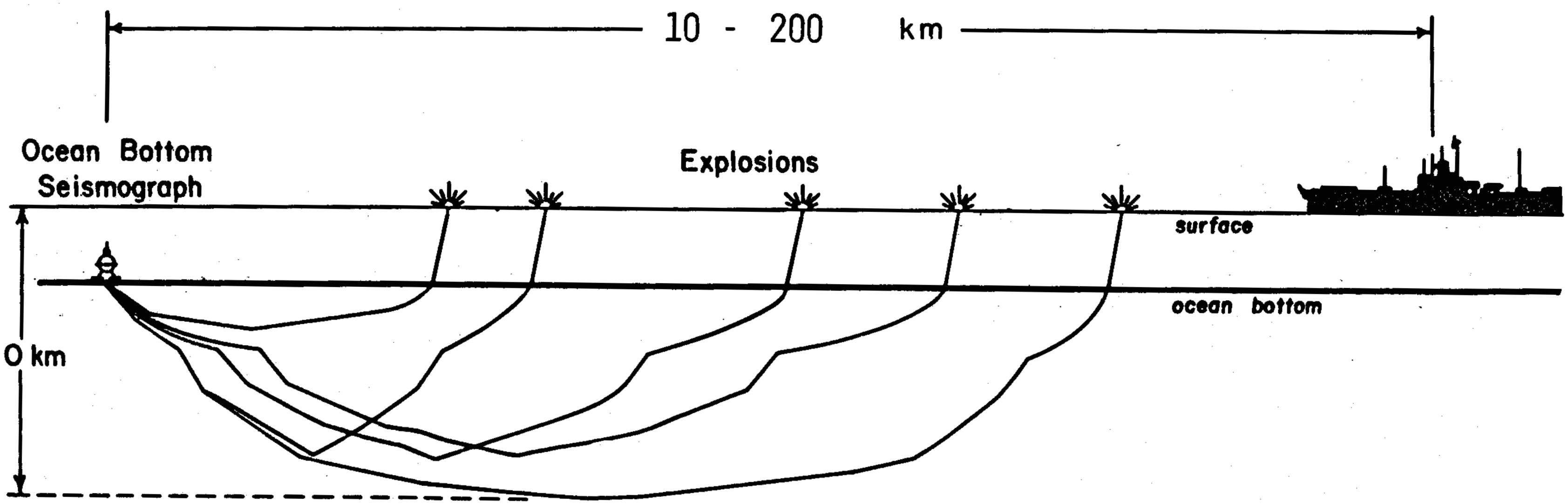

FIGURE 12.4 The geometry generally used in refraction profiling with ocean-bottom seismometers. The separation between sources and receivers can be extended to 1500 km, allowing penetration to depths exceeding 200 km. (Courtesy Scripps Marine Seismology Group)

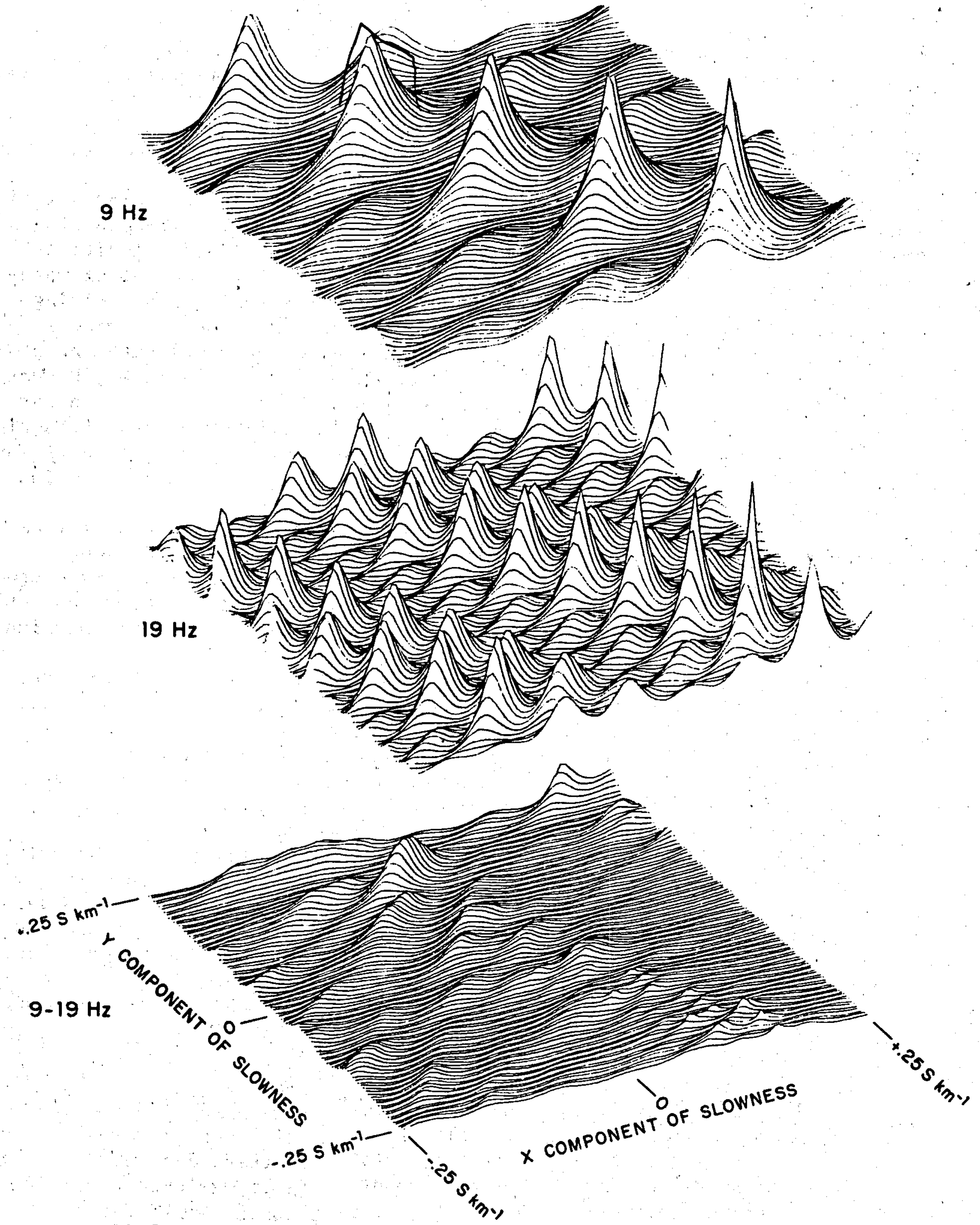

FIGURE 12.5 Example of spatial filters applied to digitally recorded data from an OBS array used to isolate the direction of an incoming signal. (Courtesy L. Dorman, Scripps Marine Seismology Group)

The advantages and disadvantages of the reflection and refraction profiling techniques are complementary. The reflection technique has high spatial resolution but has a limited depth of penetration and a limited ability to resolve compressional velocities. The refraction technique can achieve deep penetration and good vertical velocity resolution but involves the extensive horizontal averaging of structure.

Neither of these techniques has yet been very useful for shear velocity studies. Shear velocities are critical parameters for the determination of the composition and state of crustal and mantle rocks, shear velocities being particularly sensitive to the temperature and fluid content of materials. Artificial sources of seismic energy are inefficient in exciting shear waves, especially in the marine environment, and methods that rely on artificial sources have so far provided very little shear velocity information. There is some hope that the study of converted phases (i.e., P energy converted to S energy at sharp interfaces) can be used to constrain shear velocity profiles. Converted phases have been identified on both reflection and refraction profiles of oceanic crust. Because of the importance of shear wave information to continental margin studies, efforts in this direction should be encouraged.

However, the precise delineation of shear velocity structure will undoubtedly require the use of nature's own seismic sources, earthquakes. Shear-wave travel times and surface-wave velocities are particularly useful in modeling shear velocity structures. The development of broader-band OBS packages would permit the recording of these waves directly on the margins of the continents and should be given high priority.

For the studies of the nature of the continent-ocean transition, the information from global seismic networks is again critical. Seismic surface waves and free oscillations are sensitive to lateral variations at great depths, and advanced theoretical techniques for modeling these variations on a global scale are rapidly being developed. Body waves other than first arriving P and S waves are proving to be quite useful in describing these variations. For example, Figure 12.6 illustrates the large-scale variations in shear velocity associated with the passive continental margin bordering northern Siberia as expressed in the travel times of shear waves multiply reflected from the core-mantle interface (multiple ScS waves). These data were obtained from the WWSSN. The data emerging from the more advanced digitally recording networks will allow signals such as these to be processed in a routine fashion and considerably expand the data base.

Structural studies of the continental margins should be directed toward the following questions:

1. What are the properties and the lateral variabilities of the major discontinuities (sediment-rock interface, M discontinuity, upper mantle discontinuities)? What are the variations in physical properties of the lithologic units between these discontinuities?
2. What is the configuration of the Gutenberg low-velocity zone beneath the margins? Do other low-velocity zones exist within the crust and upper mantle? If so, what are the velocities within these zones and what is their lateral variability?

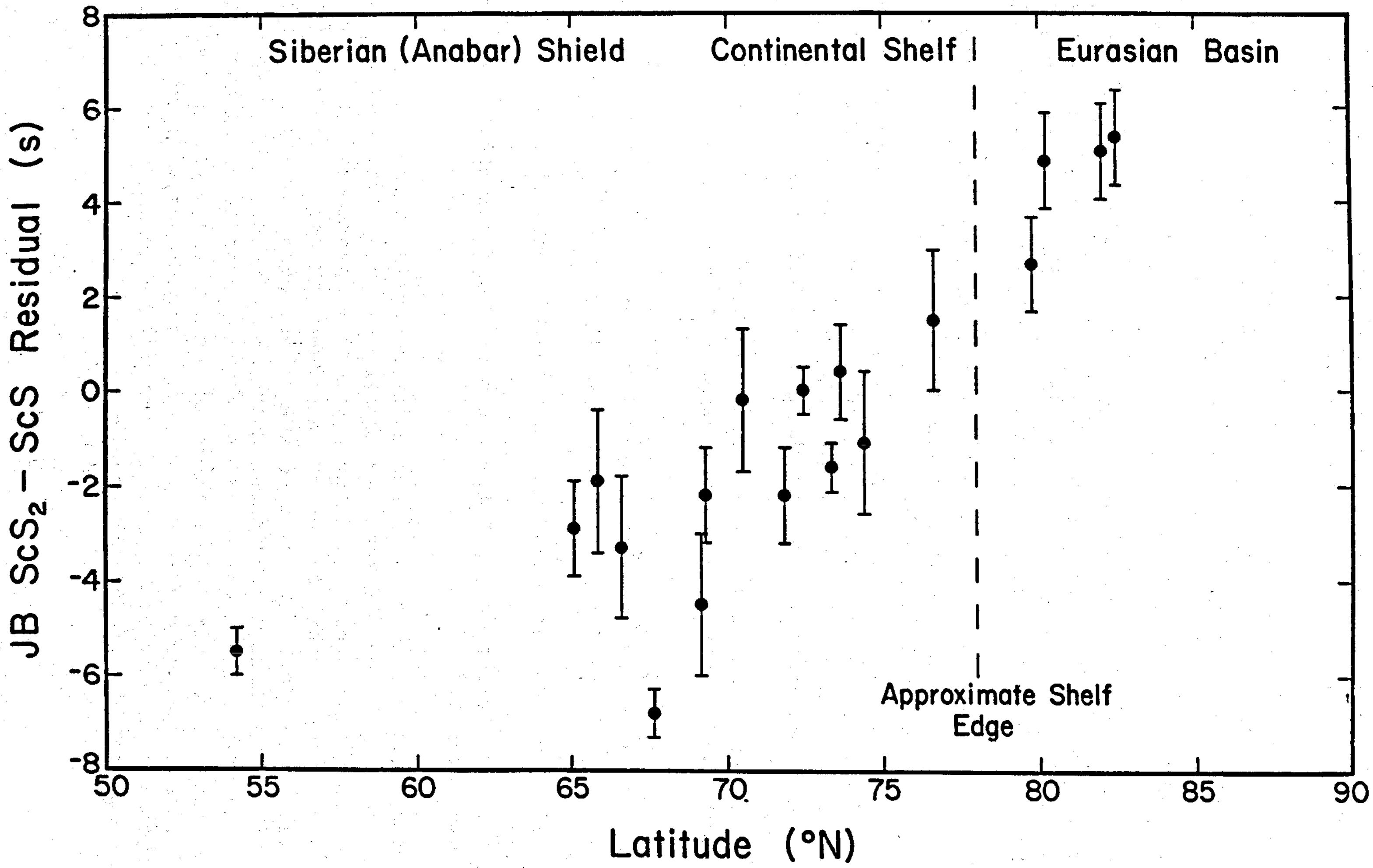

FIGURE 12.6 The variation of vertical shear-wave travel times across the passive continental margin of northern Siberia. The large magnitude of the residuals and the monotonic trend observed in this figure are indicative of a broad continent-ocean transition zone extending to great depth. (Courtesy S.A. Sipkin and T.H. Jordan)

3. Are the seismic velocities in these regions anisotropic? If so, what are the orientation and magnitude of the anisotropy? What is the relationship between anisotropy and ambient tectonic stress?
4. What is the attenuation structure of the margins?
5. To what depth into the mantle do the lateral variations associated with the continent-ocean transition extend?

The Fate of Subducted Lithosphere

Beneath the convergent active margins oceanic lithosphere is thrust deeply into the mantle beneath the continents. Any theory of crustal and mantle dynamics must explain the eventual fate of this material. At present, the data are not sufficient for definitive answers to the following questions:

1. Does the lithospheric slab retain its identity below the Benioff zone? If so, how deeply into the mantle does it extend before it is thermally equilibrated?
2. What are the dynamics of phase changes within the slab? Are any upper mantle discontinuities elevated or depressed within the slab?
3. What mechanical factors determine the angle of subduction? What processes are responsible for changes in this angle laterally and vertically?
4. What is the mechanism of deep focus earthquakes? What factors determine the magnitude of seismic-energy release in the deep focus zones?
5. What are the variations of elastic, anelastic and rheological properties across the slab-mantle interface? To what extent is frictional heating important in determining the thermal regime of the slab?
6. What is the fate of volatiles and sediments subducted with the slab?
7. What is the relationship between Benioff zone seismicity and volcanic activity?

Seismology provides powerful methods for answering these questions. Teleseismic studies of Benioff zone earthquakes can yield information about the nature of these earthquakes and the physical properties of the slab. Some information about deep-focus events has been interpreted to indicate that mechanisms involving changes of volume (phase changes) may be responsible for initiating these earthquakes. Other studies using deep-focus events have shown that the high seismic velocities associated with the lower temperature slab extend below the earthquake zone, perhaps far into the lower mantle. If these hypotheses are substantiated, then we have direct evidence that the lower mantle participates in the convection which drives the plates, a critical constraint on geodynamic models.

Structural studies of the lithospheric slab and studies of Benioff zone seismicity will be facilitated by the use of ocean-bottom seismographs. With these instruments the signals from deep earthquakes can be recorded seaward of the trench, and should provide information complementary to that obtained with land-based networks.

Recommendations

The effective monitoring of continental margin seismicity, the studies of earthquake dynamics, and the investigations of the deep structure of continental margins depend critically on the collection of high-quality, broad-band seismic data from both global and local networks of instruments. The recommendations contained in the recent reports by the Panel on Seismographic Networks and the Committee on Seismology should be supported. Specifically, with regard to the global networks:

Recommendation 1. Stable funding should be established to assure the continuing operation of the WWSSN as a basic research facility for U.S. investigators.

Recommendation 2. Stable funding should be established to continue operation, maintenance, and improvement of the digitally recording HGLP, SRO, and IDA seismograph stations. Furthermore, a number of WWSSN stations should be upgraded to include digital recording capability. Facilities for the organization, storage, retrieval, and distribution of digital data from the above observatories should be provided.

The study of the structure and seismicity of the continental margins on local and regional scales requires the use of ocean-bottom seismometers. Therefore:

Recommendation 3. A strong national program in ocean-bottom seismology should be established and maintained. Elements of this program should include sufficient funding for instrumental development.

May 1977

13
AEROMAGNETIC SURVEY

WILLIAM J. HINZE

The National Magnetic Anomaly Map (NMAM) Committee has been actively engaged in refining and implementing the recommendations of the Committee as detailed in the report of the NMAM Workshop. This report, which defines the benefits, objectives, and requirements of a NMAM as well as a three-stage program for producing the map, has been widely distributed to the geoscience community to develop interest in the program and to elicit reaction to the procedural recommendations of the workshop. The general response to the objectives of the program has been excellent. The USGC (see Part 2, Section 13) and the Advisory Board of the Office of Earth Sciences of the National Research Council approved the following resolutions pursuant to the three-stage NMAM program:

1. A major effort should be made to produce a regional national magnetic anomaly map and consistent data set by utilizing available data to the extent possible, and by flying additional aeromagnetic surveys for that purpose as needed.
2. In view of the time required to complete the national magnetic anomaly survey, an interim national map and quasi-consistent data set should be prepared from existing available data and magnetic data currently being collected by the Energy Research and Development Administration as part of the National Uranium Resource Evaluation Program.
3. Since neither 1 nor 2 will be accomplished in the near future, a colored photo-mosaic of available magnetic data should be prepared as a preliminary magnetic anomaly map.

The Executive Committee of the Society of Exploration Geophysicists has approved 2 and 3 in a similarly worded recommendation, but has asked the NMAM Committee to re-evaluate the recommendation for a national aeromagnetic survey of the nation because of the proposed detailed nature and resulting cost of the survey. Similar concerns have been raised by others in responding to the Workshop Report. As a result, the NMAM Committee is working with representatives from the minerals and petroleum exploration industries to refine and more completely define the recommended technical specifications of the aeromagnetic survey of the United States. These decisions in effect will also establish what existing magnetic data are acceptable for the map.

The U.S. Geological Survey has agreed to prepare, print, and distribute the colored photo-mosaic magnetic anomaly map at a 1:2.5 x 10^6 scale. Subcommittees of the NMAM Committee are acquiring data for this map from nongovernment sources and will assist in editing the map. The Society of Exploration Geophysicists has prepared a proposal for funding to cover the expenses of these subcommittees. The NMAM Committee is also investigating the feasibility of combining this map with those of other countries to prepare a North American Magnetic Anomaly Map. The U.S. Geological Survey is developing and testing procedures and computer codes for preparing a quasi-consistent magnetic data set of Nevada which can be considered a prototype of the recommended interim data set and map. Two tasks related to the NMAM aeromagnetic survey hold the attention of the committee. The first is the refinement of the technical specifications as already discussed and the second is the identification of a lead agency or group to conduct the aeromagnetic survey.

The NMAM Committee, recognizing the need for research into the most cost effective method(s) for reducing or eliminating the effect of magnetic temporal variations on magnetic survey data, has encouraged the appropriate granting agencies to foster research on this subject.

Finally, the U.S. Naval Oceanographic Office is conducting an aeromagnetic survey of the conterminous United States at approximately 750 meters above mean terrain with north-south oriented tracks spaced 110 km apart and east-west tracks spaced at 330 km apart. Total field intensity values of this survey at 1-second (0.1-km) intervals and accuracies of ±1.0 gamma with a resolution of 0.01 gamma will be made available through the National Geophysical and Solar-Terrestrial Data Center of NOAA by April 1978.

Reference

National Magnetic Anomaly Map, Report of the National Magnetic Anomaly Workshop held in Golden, Colorado, 17-19 February 1976. Copies of the report are available from the U.S. Geodynamics Committee.

May 1977

APPENDIX A

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Galveston	Marine Science Institute	J. Lamar Worzel
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
University of Washington	Geological Sciences	Bernard Evans
	Oceanography	Ronald T. Merrill
Wesleyan University	Geology	Jelle deBoer
West Virginia University	Geology and Geography	Russell L. Wheeler
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
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.

GEOSCIENCE SOCIETIES

During the planning period for the U.S. program for the Geodynamics Project, many geoscience societies indicated their continuing interest in the U.S. program. These geoscience societies, their current presidents, and the persons designated by these societies for continuing communication with the U.S. Geodynamics Committee are listed below:

Society	President*	Representative
American Association of Petroleum Geologists	Edd R. Turner	Georges Pardo, chairman, AAPG Research Committee
American Geological Institute	William A. Oliver, Jr.	
American Geophysical Union	Arthur E. Maxwell	AGU Committee for the Geodynamics Project Daniel Karig (chairman) Shelton S. Alexander Peter L. Bender Gerry H. Cabaniss William R. Dickinson Mark Landisman Peter H. Molnar
Geochemical Society	Edwin Roedder	
Geological Society of America	Charles L. Drake	
Mineralogical Society of America	F. Donald Bloss	
Seismological Society of America	George W. Housner	
Society of Exploration Geophysicists	Roy O. Lindseth	Sidney Kaufman

*August 1977.

APPENDIX C

FEDERAL COORDINATING COUNCIL FOR SCIENCE, ENGINEERING, AND TECHNOLOGY COMMITTEE ON SOLID-EARTH SCIENCES*

Member	Alternate	Organization
James R. Balsley, chairman	Anthony W. England Dallas Peck	Department of the Interior
Francis L. Williams, vice-chairman	Edward A. Flinn Joseph W. Siry	National Aeronautics and Space Administration
Leonard E. Johnson	Donald F. Heinrichs	National Science Foundation
Alexander Malahoff	Dennis G. Carroll	Department of Commerce
Carl Romney	William J. Best Fernand P. dePercin John G. Heacock	Department of Defense
Robert G. Morris	John G. Dardis	Department of State
George A. Kolstad	Jerry Harbour	Energy Research and Development Administration
	Observers	
	Robert D. Lanza	Department of Health, Education, and Welfare
	Arthur J. Zeizel	Department of Housing and Urban Development
	Jack W. Keely	Environmental Protection Agency
	David Katcher	National Advisory Committee on Oceans and Atmosphere

* see footnote, page 3

COUNTRIES PARTICIPATING IN THE GEODYNAMICS PROJECT *

NATIONAL COMMITTEES

Argentina

Australia

Austria

Belgium

Bolivia

Botswana

Brazil

Canada

Central American Regional Committee

Chile

Colombia

Czechoslovakia

Denmark

Ecuador

Federal Republic of Germany

Finland

France

German Democratic Republic

Ghana

Greece

Hungary

Iceland

India

Iran

Ireland

Israel

Italy

Japan

Korea

Mexico

Netherlands

New Zealand

Nigeria

Norway

Poland

South Africa

Spain

Sweden

Switzerland

Taiwan

Turkey

Union of Soviet Socialist Republics

United Kingdom

United States

Venezuela

Yugoslavia

COUNTRIES WITH NATIONAL CORRESPONDENTS

Cuba

Indonesia

Pakistan

Philippines

Rhodesia

Thailand

*According to information published by the Inter-Union Commission on Geodynamics in *Geodynamics International* - *9*, June 1976.

APPENDIX E

ABBREVIATIONS

AAPG	- American Association of Petroleum Geologists
AFGL	- Air Force Geophysical Laboratory
AGU	- American Geophysical Union
COCORP	- COnsortium for COntinental Reflection Profiling
CPMP	- Circum-Pacific Map Project
CRIB	- Computerized Resource Information Bank of the U.S. Geological Survey
DSDP	- Deep Sea Drilling Project
EDS	- Environmental Data Service
ERDA	- Energy Research and Development Administration
FAMOUS	- French-American Mid-Ocean Undersea Study
FCCSET-CSES	- Federal Coordinating Council for Science, Engineering, and Technology - Committee on Solid Earth Sciences
FCST-IGP	- Federal Council for Science and Technology - Committee for the International Geodynamics Project
GARP	- Global Atmospheric Research Program
GATE	- GARP Atlantic Tropical Experiment
GIPSY	- General Information Processing Systems of the University of Oklahoma
GSA	- Geological Society of America
IAGA	- International Association of Geomagnetism and Aeronomy
IASPEI	- International Association of Seismology and Physics of the Earth's Interior
IAVCEI	- International Association of Volcanology and Chemistry of the Earth's Interior
ICG	- Inter-Union Commission on Geodynamics
ICSU	- International Council of Scientific Unions
IGC	- International Geological Congress
IGP	- International Geodynamics Project
IGY	- International Geophysical Year
IMS	- International Magnetospheric Study
IPOD	- International Program of Ocean Drilling
IUGG	- International Union of Geodesy and Geophysics
IUGS	- International Union of Geological Sciences

LASL	- Los Alamos Scientific Laboratory
NAVOCEANO	- U.S. Naval Oceanographic Office
NMAM	- National Magnetic Anomaly Map
NOAA	- National Oceanic and Atmospheric Administration
NSF	- National Science Foundation
OAS	- Organization of American States
ONR	- Office of Naval Research
SEG	- Society of Exploration Geophysicists
USGC	- U.S. Geodynamics Committee
USGS	- U.S. Geological Survey
WDC	- World Data Center
WWSSN	- Worldwide Standardized Seismograph Network