APPENDIX 2B

Seismological Studies
of the
Continental Lithosphere

National Academy Press, Washington, D.C., 1984

Seismological Studies of the Continental Lithosphere

Panel on Seismological Studies of the Continental Lithosphere
Committee on Seismology
Board on Earth Sciences
Commission on Physical Sciences, Mathematics, and Resources

NATIONAL ACADEMY PRESS
Washington, D.C. 1984

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its Congressional charter of 1863, which established the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This study was performed by the Panel on Seismological Studies of the Continental Lithosphere of the Committee on Seismology in the National Research Council's Commission on Physical Sciences, Mathematics, and Resources. The work of the Committee is supported by the Defense Advanced Research Projects Agency, the Division of Problem-Focused Research of the National Science Foundation, the U.S. Geological Survey, the U.S. Air Force Office of Scientific Research, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Division of Earth Sciences of the National Science Foundation, the U.S. Nuclear Regulatory Commission, and the Department of Energy. The Panel wishes to express its appreciation for the interest and support of these agencies. Valuable assistance was obtained from many individuals regarding specific details of the report.

<u>Available from</u>

Board on Earth Sciences
National Research Council
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

COMMITTEE ON SEISMOLOGY

PAUL W. POMEROY, Rondout Associates, Stone Ridge, New York, Chairman
LAWRENCE W. BRAILE, Purdue University
C. ALLIN CORNELL, Stanford University
ROBERT S. CROSSON, University of Washington
RICARDO DOBRY, Rensselaer Polytechnic Institute
ROBERT B. HERRMANN, St. Louis University
THOMAS H. JORDAN, University of California, San Diego
HIROO KANAMORI, California Institute of Technology
FRANKLYN K. LEVIN, Exxon Production Research Company, Houston
DAVID W. SIMPSON, Lamont-Doherty Geological Observatory
ROBERT E. WALLACE, U.S. Geological Survey, Menlo Park

Ex Officio Member

THOMAS V. McEVILLY, University of California, Berkeley

Liaison Members

RALPH W. ALEWINE, III, Defense Advanced Research Projects Agency
LEON L. BERATAN, U.S. Nuclear Regulatory Commission
MICHAEL A. CHINNERY, National Oceanic and Atmospheric Administration
JOHN R. FILSON, U.S. Geological Survey
EDWARD A. FLINN, National Aeronautics and Space Administration
JOHN G. HEACOCK, Office of Naval Research
LEONARD E. JOHNSON, National Science Foundation
GEORGE A. KOLSTAD, U.S. Department of Energy
PAUL F. KRUMPE, Agency for International Development
JAMES F. LANDER, National Oceanic and Atmospheric Administration
RICHARD A. MARTIN, JR., U.S. Bureau of Reclamation
UGO MORELLI, Federal Emergency Management Agency
GERALD B. MORRIS, Office of Naval Research
EDWARD SCHREIBER, U.S. Department of Energy
JOSEPH W. SIRY, National Aeronautics and Space Administration
JAMES W. SMITH, Air Force Office of Scientific Research
K. THIRUMALAI, National Science Foundation

Staff

JOSEPH W. BERG, JR., Staff Director
ROY E. HANSON, Staff Officer

PANEL ON SEISMOLOGICAL STUDIES OF THE CONTINENTAL LITHOSPHERE

GEORGE A. THOMPSON, Stanford University, Chairman
LARRY D. BROWN, Cornell University
B. CLARK BURCHFIEL, Massachusetts Institute of Technology
NIKOLAS I. CHRISTENSEN, Purdue University
WILLIAM L. ELLSWORTH, U.S. Geological Survey, Menlo Park
ROBERT P. MEYER, University of Wisconsin at Madison
ROBERT B. SMITH, University of Utah
RALPHE WIGGINS, Schlumberger-Doll Research, Ridgefield, Connecticut

Ex Officio Member

PAUL W. POMEROY, Rondout Associates, Stone Ridge, New York

Liaison Members

RALPH W. ALEWINE, III, Defense Advanced Research Projects Agency
LEON L. BERATAN, U.S. Nuclear Regulatory Commission
EDWARD A. FLINN, National Aeronautics and Space Administration
FREDERICK E. FOLLOWILL, Lawrence Livermore National Laboratory
JOHN G. HEACOCK, Office of Naval Research
LEONARD E. JOHNSON, National Science Foundation
JAMES F. LANDER, National Oceanic and Atmospheric Administration
UGO MORELLI, Federal Emergency Management Agency
GERALD B. MORRIS, Office of Naval Research
JAMES W. SMITH, Air Force Office of Scientific Research
K. THIRUMALAI, National Science Foundation
MARK D. ZOBACK, U.S. Geological Survey

Staff

JOSEPH W. BERG, JR., Staff Director
ROY E. HANSON, Staff Officer

BOARD ON EARTH SCIENCES

WILLIAM R. DICKINSON, University of Arizona, Chairman
DON L. ANDERSON, California Institute of Technology
PAUL A. BAILLY, Consultant, Lakewood, Colorado
THOMAS D. BARROW, Standard Oil Company (Ohio), Houston
LLOYD S. CLUFF, Woodward-Clyde Consultants, Walnut Creek, California
W. GARY ERNST, University of California, Los Angeles
MICHEL T. HALBOUTY, Michel T. Halbouty Energy Company, Houston
MELVIN J. HILL, Gulf Oil Corporation, Houston
CARROLL ANN HODGES, U.S. Geological Survey, Menlo Park
JOHN IMBRIE, Brown University
V. RAMA MURTHY, University of Minnesota
JACK E. OLIVER, Cornell University
STEPHEN C. PORTER, University of Washington
C. BARRY RALEIGH, Lamont-Doherty Geological Observatory
J. WILLIAM SCHOPF, University of California, Los Angeles
E-AN ZEN, U.S. Geological Survey, Reston

Ex Officio Members

CLARENCE R. ALLEN, California Institute of Technology
P. BUFORD PRICE, JR., University of California, Berkeley

Liaison Members

LEON L. BERATAN, U.S. Nuclear Regulatory Commission
JOHN D. BOSSLER, National Oceanic and Atmospheric Administration
PHILIP COHEN, U.S. Geological Survey
KENNETH DAUGHERTY, Defense Mapping Agency
PAUL R. FISHER, U.S. Army Corps of Engineers
BRUCE B. HANSHAW, U.S. Geological Survey
JAMES F. HAYS, National Science Foundation
JOHN G. HEACOCK, Office of Naval Research
LINN HOOVER, U.S. Geological Survey
GEORGE A. KOLSTAD, U.S. Department of Energy
IAN D. MacGREGOR, National Science Foundation
DALLAS L. PECK, U.S. Geological Survey

BOARD ON EARTH SCIENCES (continued)

MARK SETTLE, National Aeronautics and Space Administration
A. G. UNKLESBAY, American Geological Institute
KENNETH N. WEAVER, Maryland Geological Survey
FRANK J. WOBBER, U.S. Department of Energy
ARTHUR J. ZEIZEL, Federal Emergency Management Agency

Staff

JOSEPH W. BERG, JR., Staff Director
WILLIAM E. BENSON, Staff Officer

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

PREFACE

The "lithosphere," as used here in the generally accepted sense, includes the crust of the earth and that part of its upper mantle that, together with the crust, constitute the moving tectonic plates. These are underlain by the more easily deformed "asthenosphere" at a depth on the order of 100 km. The seismic low-velocity zone (LVZ) in the mantle is usually identified with the asthenosphere.

We are convinced that (1) a better understanding of the continental lithosphere is vital to society, (2) much of that understanding can only be gained by the application of modern seismological methods, and (3) to accomplish these objectives the United States needs urgently to upgrade its seismological capability.

Our aim in this report is to convey to the reader our convictions with the hope that they will be translated into action. We suggest specific studies that should be undertaken now and some actions that, if taken, should realize the full potential of seismological techniques.

The coming years will be rich and exciting with regard to seismic exploration of the continental lithosphere. The problems are first order and the instrumentation and methods of analysis are within reach. Reflection, high-resolution refraction, and array seismology are making important breakthroughs. To bring this potential to fruition will require planning, cooperation, and support. The effort is timely in relation to both national and international programs for the 1980s.

George A. Thompson, Chairman
Panel on Seismological Studies of the
Continental Lithosphere

CONTENTS

EXECUTIVE SUMMARY

The U.S. earth sciences community has identified the continental lithosphere as the focus for major national and international programs of research in the 1980s. As seismology is by far the most effective technique for mapping the earth's interior, exploration of the continents will undoubtedly be seismology's most important role in the coming decade. However, U.S. seismology currently lacks adequate instrumentation, organization, and, above all, a national commitment to implement the necessary effort. The Panel on Seismological Studies of the Continental Lithosphere notes that, unlike the exploration of the oceans, where major research programs involving ships and facilities focus the human and national resources, no such focusing has yet occurred for the exploration of the continental lithosphere.

Crucial problems about the continental lithosphere await solutions using seismological methods as described in this report. For example, a better understanding of the geologic details of plate boundaries and interiors is needed both for scientific purposes and for resource exploration; the decoupling of the lithosphere from the rest of the earth needs to be described by studying deep geologic structures, variations in physical and chemical properties of the deep earth materials, and changes in the deep regions related to place, time, and temperature; and the upper regions of the lithosphere require much more detailed description for purposes of geologic hazard mitigation, resource discoveries, and scientific insight. Indeed, there is a large gap in our knowledge between the fine detail provided by shallow seismic exploration for petroleum and the general large-scale knowledge of the whole earth provided by the study of earthquakes using the worldwide network of seismographs.

Filling this information gap is important to the future of our society and will require dedicated program funding. Large arrays of modern refraction seismic instruments are needed so that spacings of instruments can be made commensurate with the deep features (geologic structures, velocity anisotropies, energy absorption, etc.) to be studied; new and innovative methods of experimentation and data analyses must be developed that more completely utilize the information contained in the seismic recordings; equipment must be obtained that takes advantage of most recent advances in seismic instrumentation and computation facilities; sufficient standardization of data formats should be required to facilitate easy data exchange and handling; and the organization must allow for individuals to make scientific discoveries based on individually specified studies as well as group experimentation for large investigations. This is a set of very large goals, but many things attest to the reasonableness of them: instrumentation and supporting data equipment are within current capabilities; new analytical methods are awaiting use; and the emphasis on the earth systems of the lithosphere is timely and is required to plan for resource exploration and land use and to guide science to new heights of knowledge. Thus, the following recommendations are directed toward a national effort for seismic exploration of the continental lithosphere.

Recommendation 1. We believe that advancement of our understanding of the structure, composition, and evolution of the continental lithosphere will require a program of major field experiments. The Panel recommends that long-range coordinated field programs targeted on specific geologic problems be started immediately. These field programs will need to combine a spectrum of seismological imaging methods, including reflection, refraction, and earthquake sources, to develop a three-dimensional understanding of the lithosphere.

Recommendation 2. The U.S. seismological community currently lacks the instrumental capability to implement large-scale seismic investigations of the continental lithosphere. Thus, the Panel recommends a substantial increase in the number and quality of portable digital seismographs dedicated to lithospheric seismology. Arrays of 1,000 instruments (up to 6,000 channels) are required to study the lithosphere on a scale comparable to its geologic heterogeneity. The 150 existing instruments of various designs that are available for lithospheric studies are inadequate to various degrees. They should be supplemented and eventually replaced by versatile digital portable seismographs that have capabilities for controlled source (explosives, vibrators, etc.) and earthquake source recording. We note that several recent reports of the National Research Council (NRC) have strongly recommended mobile seismic arrays for earthquake monitoring. The proposed instruments are applicable for this purpose, and will undoubtedly be utilized in this way (NRC, 1977; NRC, 1980c).

We recommend that 400 new instruments be acquired by the university community over an initial 5-year period. We recommend that the additional 600 instruments needed for large-scale experiments be procured, based on the success of the program as it develops. The new instruments should constitute a national resource, which can be used as a "telescope" to look downward into the earth.

Recommendation 3. The Panel recommends accelerating U.S. efforts to survey continental structure by reflection profiling. Major contributions to our understanding of the structure and evolution of continents are being made by applying the existing reflection technology of the oil industry. The outstanding academic example is the program directed by the Consortium for Continental Reflection

Profiling (COCORP), which has spawned similar programs in the United States and other countries.

Recommendation 4. The Panel recommends the establishment of a working committee, composed of members of academia, industry, and government. The role of this group would be fourfold: (1) to plan and coordinate new large-scale field programs; (2) to recommend guidelines and standards for state-of-the-art instrumentation, and for data acquisition and handling, including compatible formats for ease of data exchange; (3) to organize scientific symposia on continental seismology; and (4) to coordinate activities with other national and international programs.

Recommendation 5. The Panel recognizes that the advice, cooperation, and support of industry are vital to attaining the goals of this program. To that end, we recommend that the working committee include one or more petroleum industry members and that it meet annually in conjunction with meetings of the Society of Exploration Geophysicists (SEG).

Recommendation 6. The Panel recommends that a national workshop be held as soon as possible, to recommend characteristics of "standardized" instruments and to examine methods of organization and management applicable to the U.S. seismological community.

Recommendation 7. The Panel recommends that ongoing research include (1) integrating narrow-angle (reflection) and wide-angle (refraction) methodologies using controlled and natural sources to exploit the full range of seismic recording in a unified manner, and (2) carrying on accelerated laboratory and rock physics studies to help in identifying the materials and understanding the processes in the lithosphere.

1

INTRODUCTION

CONTINENTAL LITHOSPHERE: A FOCUS FOR EARTH SCIENCE IN THE 1980s

The earth sciences are approaching, for the first time, a consistent and comprehensive perception of how the earth works. The earth is now seen as a dynamic convecting body, driven by its internal heat and characterized by horizontal movements at the surface of a small number of rigid plates at relative velocities of only a few centimeters per year. Although seemingly insignificant, these rates accumulate with dramatic results over intervals of many millions of years. It is generally accepted that new ocean crust is created along major rift zones, where hot, buoyant material from the earth's mantle rises to the surface. It cools, contracts, and subsides as it flows away from the zone of upwelling. Thus, the oceanic lithosphere is viewed as the upper boundary layer of the convection circulation. It underlies 70 percent of the earth's surface and is young--generally fewer than 200 million years old (representing only the last 5 percent of the earth's history). Oceanic crust is destroyed when it is forced back into the mantle at zones of convergence.

Continents are fragmented along rift zones, and the fragments drift apart as the ocean basins form between them; but they grow by accretion where fragments collide, and become welded together when intervening ocean basins disappear. The continents, because of their much different composition and age, have a lower mean density, remain buoyant in the mantle, and survive over major portions of the earth's history. As a result, the evolutionary history of the continental lithosphere is much more complex than that of the oceanic lithosphere in that the rocks of the continents often contain superimposed records of a multitude of thermal and deformational episodes.

The International Council of Scientific Unions (ICSU) considers the study of the lithosphere to be one of the most important scientific activities for the future of mankind. In September 1980 the Eighteenth General Assembly of ICSU approved the establishment of the Inter-Union Commission on the Lithosphere (ICL), with the objective of undertaking an international program of interdisciplinary research for an improved understanding of the earth, especially those aspects upon which human society depends for its well-being. The program--Dynamics and Evolution of the Lithosphere--The Framework for Earth Resources and the Reduction of Hazards--is outlined in ICL Report No. 1 (ICL, 1981). It is concerned primarily with the current state, origin, evolution, and dynamics of the lithosphere, with special attention to the continents and their margins. Investigations of the lithosphere beneath the oceans and of parts of the earth below the lithosphere will also be required in order to meet the scientific objectives of the program.

In addition to purely scientific achievements, this research will contribute knowledge and techniques needed in the search for additional supplies of nonrenewable energy and mineral resources and in their optimum utilization; but by the same token, the research program will benefit from the detailed knowledge of the nature and evolution of the outer part of the earth's lithosphere that has been accumulated in the course of exploration for and development of mineral and energy resources.

The assessment, prediction, and mitigation of geological, geophysical, and geochemical hazards, natural and induced by human activities, make up another of the principal areas of immediate applicability of the research results to be achieved under this program. The research will contribute to the development of improved methods for assessing the most likely locations of future great earthquakes and volcanic eruptions, and perhaps of better ways of estimating the time intervals between their occurrences. It will also support other research directed to learning how to make timely predictions of specific events.

In 1976 the Geophysics Research Board of the National Academy of Sciences was assigned the responsibility of developing a statement of the objectives of geodynamic studies in the 1980s and the corresponding research directions-- continuing and new. <u>Geodynamics in the 1980's</u> (NRC, 1980b), the report of that group, is the result of 3 years of effort. It sets forth a program of continuing and new activities that the committee believes to be of first-order importance during the opening years of the decade. The principal focus that emerged for studies of geodynamics for the United States in the 1980s was crustal dynamics, with emphasis on

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

The proposed U.S. program is considered completely consistent with the international program of ICSU.

The interested reader is further referred to an excellent and up-to-date scientific treatise recently released by the Geophysics Study Committee of the Geophysics Research Board entitled <u>Continental Tectonics</u>. The study makes the following recommendation:

> To remove a major gap in man's understanding of his environment, and to provide an adequate scientific basis for geological hazard and waste-disposal evaluation and for exploration,

> assessment, and appropriate utilization of earth resources, a broad multidisciplinary effort based on modern technology should be directed toward the exploration and understanding of the dynamics, structure, evolution, and genesis of the continents. This effort should be a major component in programs for geodynamics in the 1980s [NRC, 1980a, p. 9].

The following are four main targets of this effort:

1. three-dimensional structure of the continents
2. timing of the evolution of continental crust and associated mantle
3. nature and origin of the stress fields within the continents
4. thermal processes and thermal structure of the continents and underlying mantle

Other national programs that will rely heavily upon components of lithospheric seismology include (1) the Continental Deep Drilling Program, 2) the National Earthquake Hazards Reduction Program, and (3) a newly proposed program by the NRC's Geophysics Study Committee dealing with explosive volcanism. The delineation of specific geologic targets to be tested by deep continental drilling will rely heavily upon deep-seismic sounding to determine the composition, depth, and structure and to assist in location of drill sites. Earthquake recording for both temporal and spatial variations including the relationships between epicenters and faulting and detailed crustal structure are an integral part of the National Earthquake Hazards Reduction Program. The utilization of large numbers of digital instruments will provide important new information on the source properties of earthquakes as well as sufficient detail to reveal time-space variations that are integral to a program of earthquake precursor evaluation. Accelerated efforts to distinguish naturally occurring sources from nuclear explosions rely primarily upon determination of location, size, and critical spectral information of sources as deduced by digital seismographs. A new program to evaluate and predict the occurrence of explosive volcanic eruptions will require detailed earthquake investigations primarily because the location and occurrence of small earthquakes and earthquake swarms are important precursors and hence can reveal the "most likely time and occurrence" of volcanic eruptions. A recommendation of the NRC (1984) Explosive Volcanism report specifically recommends the implementation of modern seismological arrays for detection of volcanic eruptions and related phenomena.

THE UNIQUE ROLE OF SEISMOLOGY

The Committee on Seismology, aware of the development of the above reports and programs and of the ground swell of scientific and practical interest that generated them, quickly recognized that seismology potentially provides the most powerful tools for attacking most of these problems. However, it also felt that certain difficulties impede realizing this potential, and that they should be examined. Although classical techniques of seismology have been critical in the development of current concepts of the crust and lithosphere, these concepts have not led to solutions of a number of fundamental questions about the composition, structure, formation, and evolution of continental crust. What is required is vastly improved resolution of deep structure at a scale comparable to the true geological complexity. Rapidly developing advances in microelectronics and computer technology have led to enormously increased power in the acquisition and processing of large amounts of data, potentially revolutionizing seismological investigations by providing the increased resolution required to solve fundamental geological questions.

Thus, at its meeting in St. Louis on October 26-27, 1979, the committee recommended the establishment of a Panel on Seismological Studies of the Continental Lithosphere. The Panel was charged with examining seismology's role, past, present and future, in the investigation of the continental crust and lithosphere. Included would be a critical review of the accomplishments and limitations of classical methods including both active and passive techniques, an assessment of recently developed methods, and consideration of the most promising lines of future development. Input from other relevant technological fields and from the oil exploration industry would be especially valuable. In the future one can imagine close interaction of seismological studies with increasingly accurate and realistic geological models of crustal dynamics and structure. Geological input will thus be quite important in guiding the design of experiments and in the development of new techniques of instrumentation, data processing, and interpretation. The Panel could perform a valuable service by stimulating ties between fundamental geological investigations and development of new seismological techniques.

It is important to emphasize, in today's funding climate, that the earth sciences community has firmly established the study of the continental lithosphere as a top-priority item for the next decade. There is little doubt that a major subset of the community will eagerly support a series of major cooperative seismological experiments.

SEISMOLOGY AND NATIONAL NEEDS

Seismological studies of the lithosphere can be expected to produce new concepts and data that are of fundamental interest to those involved in mineral and energy resource exploration and development. The key role played by seismology exploration for petroleum is already well known; a major fraction of the oil and gas industry's exploration budget is typically devoted to the seismic reflection method. Yet seismology also contributes to resource exploration in a broader but equally important sense by refining our understanding of the basic issues in the evolution of the continental lithosphere. The investigation of the nature, origin, and evolution of Archean lithosphere (2.5 billion years old) should provide new information on heterogeneities in the distribution of metals in the ancient lithosphere as well as on the origin and distribution of specific types of mineral deposits. Many of the world's mineral resources occur in these older rocks, and the investigation of the relationships among tectonic regimes, magmatism, and metallogenesis in these rocks will aid in the exploration for these types of mineral deposits.

The evolution of Phanerozoic (<600 million years old) sedimentary deposits will be of significance for fossil fuel exploration. Most of the world's fossil fuel resources and much of its mineral resources occur in rocks that were formed or profoundly modified by Phanerozoic orogenesis. Many important geothermal areas are located within Phanerozoic orogenic belts. The exploration for these resources will be facilitated by the investigation of Phanerozoic orogenesis. Clarification of the basic processes involved in subduction, collision, and accretion; in the evolution of magmatic and metamorphic processes through the whole span of geological time; and in the nature and evolution of the oceanic lithosphere--all these are of fundamental importance in metallogenetic studies. Studies of the evolution of sedimentary basins that have formed within lithospheric plates and at their margins are important in the exploration for both fossil fuel and mineral resources.

Natural hazards arising from the dynamic behavior of the earth pose a serious threat to many people throughout the world. A better understanding of the dynamic state and evolution of the lithosphere offers a framework for the reduction of these hazards.

Volcanic eruptions, earthquakes, tsunami, landslides, flash floods, climatic changes, the gradual subsidence and submergence of coastal areas, and slow deformation of the foundations of engineering structures are natural manifestations of the dynamic behavior of the earth and are part of the normal process of evolution of the lithosphere. The assessment, prediction, and mitigation of these natural hazards can be facilitated by an enhanced understanding of the nature, dynamics, and evolution of the lithosphere.

The discharge of waste products, including toxic chemicals, radioactive materials, and substances that affect the natural state of dynamic equilibrium in the biosphere, has become a serious problem. Several kinds of engineering activities are known to be able to stimulate processes in the lithosphere that are potentially hazardous. The filling of reservoirs behind high dams may produce earthquakes. The pumping out of underground fluids may unintentionally deplete essential groundwater supplies and cause subsidence of the ground surface. The pumping of fluids into the subsurface may pollute water supplies or induce earthquakes. The assessment and mitigation of these hazards require analysis of the relation of these processes to the structure and properties of the rocks, the state of stress in the rocks, local geological factors, and hydrogeological conditions.

2

CONTINENTAL GEOLOGY AND SEISMOLOGY

To place seismology's role in perspective, this chapter outlines a number of fundamental geological problems of the continents and their margins. It explores what we think we know, what we think we need to know, how seismology can contribute to the answers, and, as examples, recommends particular field experiments.

It is realized, of course, that the full scientific potential of such studies can be achieved only with the close interaction of scientists concerned with application of geology, geophysics, geochemistry, and geodesy toward framing increasingly accurate and realistic geological models of crustal dynamics and structure. Research must be global, because no continental region contains a complete spectrum of well-developed features that can be studied to yield answers about the formation and evolution of continents. However, the United States itself is rich in geological features that represent excellent targets for investigating fundamental questions of lithospheric structure and evolution. All applicable facets of seismology must be focused simultaneously on each of the geological problems.

PLATE TECTONICS AND CONTINENTAL GEOLOGY

Over the past 20 years great advances in the geological sciences have been made from the seismological study of the earth's lithosphere, mostly restricted to the depth of the Mohorovičić (Moho) discontinuity (no more than the upper one-third of the lithosphere). Nevertheless, a major accomplishment has been the development of the theory of plate tectonics. Data derived largely from the oceans show that the present lithosphere consists of six large and five or six smaller moving plates. These plates include large areas of relatively undeformed lithosphere bounded by narrow interconnecting zones of deformation marked by earthquake activity. Geophysical studies show three types of plate boundaries depending on the direction of relative motion of the plates: (1) divergent, (2) transform, and (3) convergent. Figure 2.1 shows the results of a pioneering study of seismic slip vectors at plate boundaries. Along the first type of boundary, plate motion is horizontal and divergent and is characterized by shallow tensional earthquakes. Within oceanic areas, new oceanic lithosphere is created

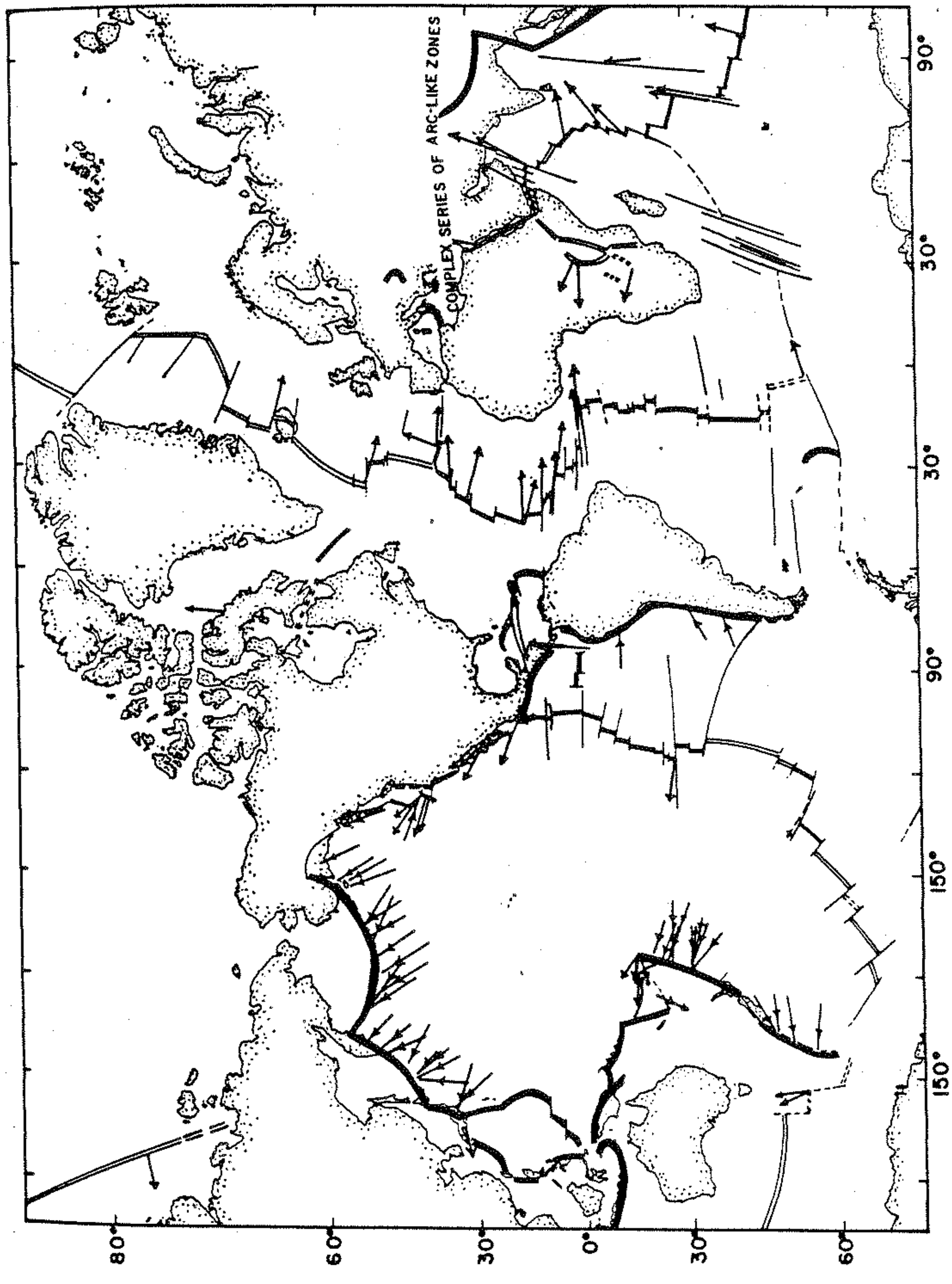


FIGURE 2.1 Summary map of slip vectors derived from classical earthquake mechanism studies. Reprinted, with permission, from Isacks et al. (1968). © 1968 by the American Geophysical Union.

by upwelling of mantle material along divergent boundaries at divergent rates of up to 20 cm/yr. Within continents, these boundaries are seen as zones of extensional rifting which, if continued, would lead to separation of continental fragments and formation of new oceanic crust between them. Seismic velocities in such rift zones are more characteristic of the oceans than of the continents. Along transform boundaries, lithospheric plates slide past each other horizontally and are characterized by shallow earthquakes with vertical fault planes and strike-slip motion. At convergent boundaries, oceanic lithosphere of one plate commonly moves beneath another and returns into the mantle. An ensemble of shallow, intermediate, and deep earthquakes is characteristic.

These lithospheric motions define a global system--plate tectonics--whose basic concepts are simple. Oceanic lithosphere is formed at divergent boundaries, slides past itself along transform boundaries, and plunges back into the mantle at convergent boundaries along subduction zones. Plate boundaries are the locus of deformation and plate interiors are relatively undeformed. Although plates may contain continental or oceanic lithosphere or both, the process of lithospheric generation and destruction acts almost exclusively upon the oceanic lithosphere. The usual mode of subduction is for oceanic lithosphere to be returned to the mantle where it is partially or wholly assimilated. The subduction of oceanic lithosphere leads to the recycling of oceanic lithosphere at such a rate that no oceanic crust in the present oceans (over 70 percent of the earth's surface) is older than 200 million years. Continental lithosphere, because of its less dense cap of continental crust, is more difficult to subduct, and remains a long-lived but evolving feature of the earth's surface.

One major area where plate tectonics has only begun to scratch the surface has been in the study of the formation and evolution of continental crust and lithosphere. Whereas only the last 5 percent of geologic history is recorded in oceanic crust, the remaining 95 percent must be obtained from a study of continental crust where rocks as old as nearly 4 billion years are present.

An examination of continental geology shows that the continental crust is largely composed of broad belts of deformed and variously metamorphosed rocks intruded by igneous rocks that are locally overlain by a thin veneer of younger sedimentary rocks. The geologic relations preserved in these belts directly reflect the kinematic, thermal, and dynamic events that affected these rocks and form a first-order heterogeneity of continental crust. Each belt has evolved over a specific span of time that distinguishes it from adjacent belts. Within these age belts, the rocks and associated structures are similar to those formed along modern plate boundaries.

Recent studies of the still-evolving, seismically active western part of the North American continent have shown the complexity of one of these age belts. Here the continent consists of fragments of ancient island arcs, oceanic ridges, seamounts, plateaus, and continental crust (Davis et al., 1978; Coney et al., 1980; and Jones et al., 1982). These fragments contain rock sequences, structural histories, igneous rock assemblages, and associated ore deposits that are different from adjacent fragments or from North American rocks. From some of these fragments, paleomagnetic and faunal data indicate that they originated far from North America and were added to North America at various times during the last 400 million years. Between some of the fragments are narrow belts of highly disrupted rocks that represent the remnants of oceanic regions scraped off against the continent as large tracts of ancient oceanic crust were subducted. Some of the accreted fragments have been carried thousands of kilometers on oceanic plates before their addition to North America.

Plate boundary motions can change rapidly (Dewey, 1980), so the accreted fragments can be subsequently deformed by plate boundary activity different from that which caused accretion. Geologic data indicate that the fragments have been disrupted by large horizontal motions along strike-slip faults, shortened by thrust faulting and folding, extended by normal faulting, intruded by igneous rocks, and metamorphosed at various times since their addition to North America. During these subsequent deformations not only were the fragments disrupted, but parts of the North American continent were deformed as well. Similar "collages" of accreted fragments can be recognized well within continents where ancient plate boundary activity has brought large continental masses together as an oceanic region was eliminated by subduction. Such continent-continent collisions are known in the Urals, several Paleozoic mountain chains in China, and the Caledonides of Scandinavia and Greenland (Gee, 1975). Studies of these belts indicate that collisions profoundly rework not only all the fragments accreted from the ancient oceanic realm, but the rocks of the two colliding continents formed during yet earlier periods of plate tectonic activity.

Studies of these age belts within continents and their reconstructed plate boundary activity have led to two important conclusions: (1) plate boundaries are generally well defined and relatively narrow within oceanic lithosphere, but are very broad, diffuse, and poorly defined within continental lithosphere; and (2) reworking of continental lithosphere profoundly alters older accreted fragments and continental rocks so that the processes of continental evolution are very difficult to decipher. These conclusions suggest that (1) plate boundaries within continents must be treated as dynamic systems that generate broad zones of deformation, (2) active plate boundaries must be studied to understand how these dynamic systems function and what the three-dimensional arrangements of rock assemblages and structures are before they are disrupted by younger plate boundary activity, and (3) a careful three-dimensional study of older, continental crust is necessary to decipher the evolution of the continent.

From such investigations a detailed picture of the structure, composition, and evolution of continental crust could emerge. This will require a thorough analysis of modern plate boundary systems where the maximum amount of data on these is available. Seismological studies are an important key to a better understanding of the physical properties, rock associations, compositions, structure, geometry, and the dynamics of the lithosphere in active settings. From measurements of compressional and shear waves, we can arrive at better estimates of structure, composition, temperature, mineral orientation, and fluid content in the deep lithosphere and asthenosphere. Seismic waves from earthquakes also carry information on the strength and state of stress at the earthquake hypocenter. These data on modern boundaries can then be used to unravel by analogy the older and more complex parts of the continental crust, using the same seismological techniques (with the exception of local earthquakes) employed in the study of the active regions.

SEISMOLOGICAL STUDIES OF CONTINENTAL EVOLUTION

We will focus our attention on a limited number of research studies that illustrate what can be accomplished with present and foreseeable seismic technology and that indicate likely useful directions toward the ultimate goal of understanding the structure, composition, and evolution of continental lithosphere. The examples presented here are intended to typify the role that the three types of modern plate boundary systems play in continental evolution.

Continental Accretion at Convergent Boundaries

As indicated above, one of the primary mechanisms of continental growth during geologic time is through the addition of lithospheric fragments from ocean regions by collision and suturing. Many of these fragments (such as island arcs, aseismic ridges, sea mounts, and oceanic plateaus), while formed in the oceanic realm, are less dense than typical oceanic crust. They resist subduction and thus represent a net addition to continents by their accretion. Some accreted fragments may be only the upper part of the lithosphere, being decoupled from the remainder of the subducting slab so that the continental crust grows by stacking of thin slices by low-angle thrusting. Fragments that include the entire oceanic lithosphere may also be accreted, in which case the continent grows by lateral addition of thick fragments. The effects of such accretion can be profound, with genetically related deformation extending far into both the subducting and overriding plates. At the earth's surface brittle faulting and folding are a common expression of the deformation, but the processes at depth during accretion are essentially unknown. Study of older, more deeply eroded terranes shows that in similar convergent boundaries the continents have behaved in a ductile mode at depth, for folding and flow have been observed. It is thus critical to know where and how the brittle-ductile transition takes place within the lithosphere, what is the level of decoupling during accretion, and what is the relation between the two. Such transitions should be marked by low-velocity zones, the base of the seismogenic volume, a decrease in Q, and increased-velocity anisotropy. Seismological data can thereby reveal the probable depth of decouplings during accretion and a considerable amount about the properties of the brittle and ductile regions. Answers to such questions will lead to a better understanding of the development and modification of the lower crust, upper mantle, and the Moho at accreting convergent boundaries.

Classical seismology has already played an important role in characterizing the kinematics and structure of convergent plate boundaries and of island arcs. Seismic refraction and reflection profiles shot at sea across many oceanic subduction zones worldwide have led to the construction of a detailed picture of oceanic crustal structure and tectonic processes active in noncollisional subduction environment. For example, refraction experiments utilizing seaborne explosions and land-based recordings, such as off the Pacific coast of Colombia, have been particularly effective because they combine the economy, speed, and flexibility of oceanic profiling with the data integrity of onshore recording. Some measure of the scope of these experiments can be gained from their extent--from the unsubducted oceanic plate to the Central Andes, more than 700 km along the profile. Deep-penetration reflection profiles provide even greater resolution of upper crustal structure, particularly within the accretionary prism lying between the volcanic arc and trench (e.g., Hamilton, 1979). (See Figure 2.2.) These examples of artificial source studies show the advantages of two seismological methods, but as yet they have not been applied to a common detailed study of the same subduction zone. Further, the concept of calibrating the subduction zone by detailed artificial source studies has rarely been combined with the process of locating and studying the associated natural events. To date there has been no utilization of high-density, closely spaced seismographs to record simultaneously the numerous natural and closely spaced artificial sources in the same subduction zone. This results largely from the lack of suitable seismographs. Unfortunately, studies of comparable scope and magnitude have been conducted only infrequently on land where the comparison with geologic data can be made more directly, partly because of the lack of suitable experimental facilities (primarily insufficient numbers of seismographs) and funds.

As fragmentary and incomplete as our knowledge of the subduction process is, far less is known about its termination. What processes and rates control the transition from a stable subduction boundary configuration to a new type when subduction is arrested or disrupted by the entrance of an island arc or continental margin into the subduction zone? Where and how does the collision disrupt the affected plates? How is surficial and shallow lithospheric activity related to deep lithospheric and asthenospheric motions? Following the suturing of an arc system to a continent, or to another arc, how do the crust and mantle interact with the convergent zone to achieve a new equilibrium? Such questions are central to our understanding of the formation of continental lithosphere by accretion. Answers will depend on three-dimensional studies of such zones designed to find the seismic velocity distribution as well as on longer-term studies of seismicity that use a much larger number of seismographs than are currently available.

A contemporary example of arc-continent collision, suitable for seismological study, is the subduction of the northwestern part of the Australian continent beneath the southeastern margin of the Asian plate (Carter et al., 1976). The part of the Asian plate that is presently

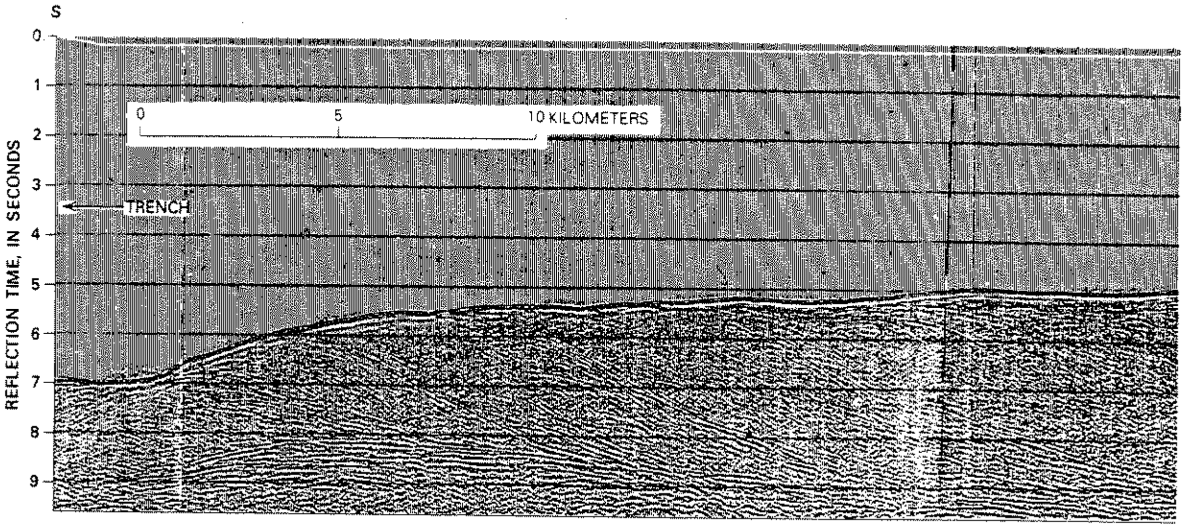


FIGURE 2.2 Marine seismic reflection line across the subduction zone of the Java Trench, Indonesia. Subducting oceanic lithosphere appears as a prominent, gentle-dipping reflector, but can be followed for more than 50 km beneath the landward slope of the trench. From Hamilton (1979).

colliding with Australia comprises many island arc and continental fragments surrounded by oceanic lithosphere, which is itself being contemporaneously reworked by collisional processes. If the present-day plate motions between the Asian and Australian cratons are maintained for another 30 million years, they will collide and compress Indonesia and the Philippines into a broad orogenic belt (Hamilton, 1979), thus forming a new continental mass.

A different type of collision awaiting detailed study is that currently active along the Pacific-North American plate boundary in the Gulf of Alaska. This is the latest in a series of collisions that has built most of Alaska (Jones et al., 1982). Using earthquake focal mechanism data, Perez and Jacob (1980) have defined a borderland terrane, the Yakutat block, that is both impinging upon the Gulf coast of Alaska and overriding the Pacific plate that carries it northward. Analysis of earthquake focal depths suggests that this allochthonous block, made largely of sedimentary rocks, is horizontally decoupled from the underlying Pacific plate along listric thrust faults. High-resolution refraction and reflection profiling is needed to determine the seismic velocity distribution that must be known in order to define earthquake locations along listric faults, etc. The Yakutat block may very well be accreted to North America as thin fragments stripped from its lithospheric underpinnings.

> Alaska represents a timely, and in many ways unique, opportunity to investigate accretionary tectonics using all seismological tools. Multidisciplinary interest in Alaskan tectonics is currently high, and the Alaska pipeline road and circum-Alaska oceans provide fortuitous access. Therefore, it is recommended that a detailed seismic reflection/refraction traverse across Alaska coupled with array studies of natural events be considered a priority program, to be planned and executed during the coming decade.

Lithospheric Dynamics at Continent-Continent Collisions

Subduction of oceanic lithosphere often leads to collision between two continental plates, following which continent-continent convergence between the two plates may stop or may continue, producing a wide zone of deformation that may extend far into the continental interior. The surficial expression of collision is deformation by shortening, manifested by folds, thrust faults, strike-slip faults, and igneous activity, but it is not known how the deeper lithosphere accommodates continued convergence. In such settings intermediate and deep seismicity is generally lacking, so the kinematics and dynamics of converging lithosphere at depth are virtually unknown. Here, deep refraction and reflection observations from both artificial and the shallow natural sources may provide critical structural details of the deep structure in the collision zone.

Continent-continent collisions are active in many places along the Alpine-Himalayan chain where the Indian, Arabian, and African plates have collided with the Eurasian plate. In the eastern Mediterranean region, the active collisional system is more than 500 km wide. The geologic evolution of the region suggests that several small fragments of continental lithosphere were swept together between two large converging plates (for example, see Burchfiel, 1980). The oceanic tracts were subducted, while at least parts of the buoyant continental fragments remained at the surface. Continued convergence has deformed both the small continental fragments and the margins of the larger plates, so the collisional system now extends across a very broad zone. Because convergence has taken place along very irregular boundaries, the disruption of continental lithosphere has resulted in complex motions of small fragments. Motions along different fragment boundaries, as determined by earthquake focal mechanism studies, are divergent, transform, and convergent (McKenzie, 1972). Relative motion between some fragments is at right angles to the overall convergent motion of the two large plates. Motion of the small fragments suggests that they are decoupled from the large plates not only along their lateral boundaries but also at some unknown depth from their underlying lithosphere. The presence of such coupling and the nature of the forces that drive the small fragments are clearly first-order problems for which we have few answers.

The most spectacular example of an active, broad convergent boundary system is in eastern Asia. About 50 million years ago, convergence between the Indian and Asian plates produced a collision between the continental lithospheres of India and Asia. After collision, continued convergence of perhaps more than 2,000 km has been absorbed principally by disruption of the former Asian plate (Molnar and Tapponnier, 1975); additionally, the rocks at the northern edge of the Indian plate have been detached within or near the base of the continental crust to form south-directed faults (see Figure 2.3). According to this interpretation, Asia has absorbed massive intracontinental deformation and fragmented into numerous small blocks bounded by strike-slip, thrust, and extensional faults. Simplistically, Asian crust has shortened longitudinally and extended latitudinally to accommodate the northward movement of India. Faulting within Asia extends nearly 3,000 km from the former collision boundary and, coupled with deformation of the Indian plate, forms a wide, complex convergent system. Yet the relationship between the motion of the smaller blocks within Asia to the motion of the deeper lithosphere and asthenosphere remains uncertain.

Geological studies in continent-continent collision zones have suggested that the magnitude of horizontal shortening in shallow-level thrust faulting may reach several hundred kilometers. This has led some workers to suggest that continental crust, or at least the lower part of the continental crust, can be subducted (Bird, 1978; Molnar and Gray, 1979; Burchfiel, 1980). Are there ways in which such a hypothesis can be tested seismologically in active collisional zones?

Recent studies of earthquake focal mechanism in Himalayan foreland (Seeber and Armbruster, 1981) and seismic wave attenuation in Tibet (Chen and Molnar, 1981) have lent credence to the hypothesis of substantial underthrusting of the Indian continental plate. It remains to

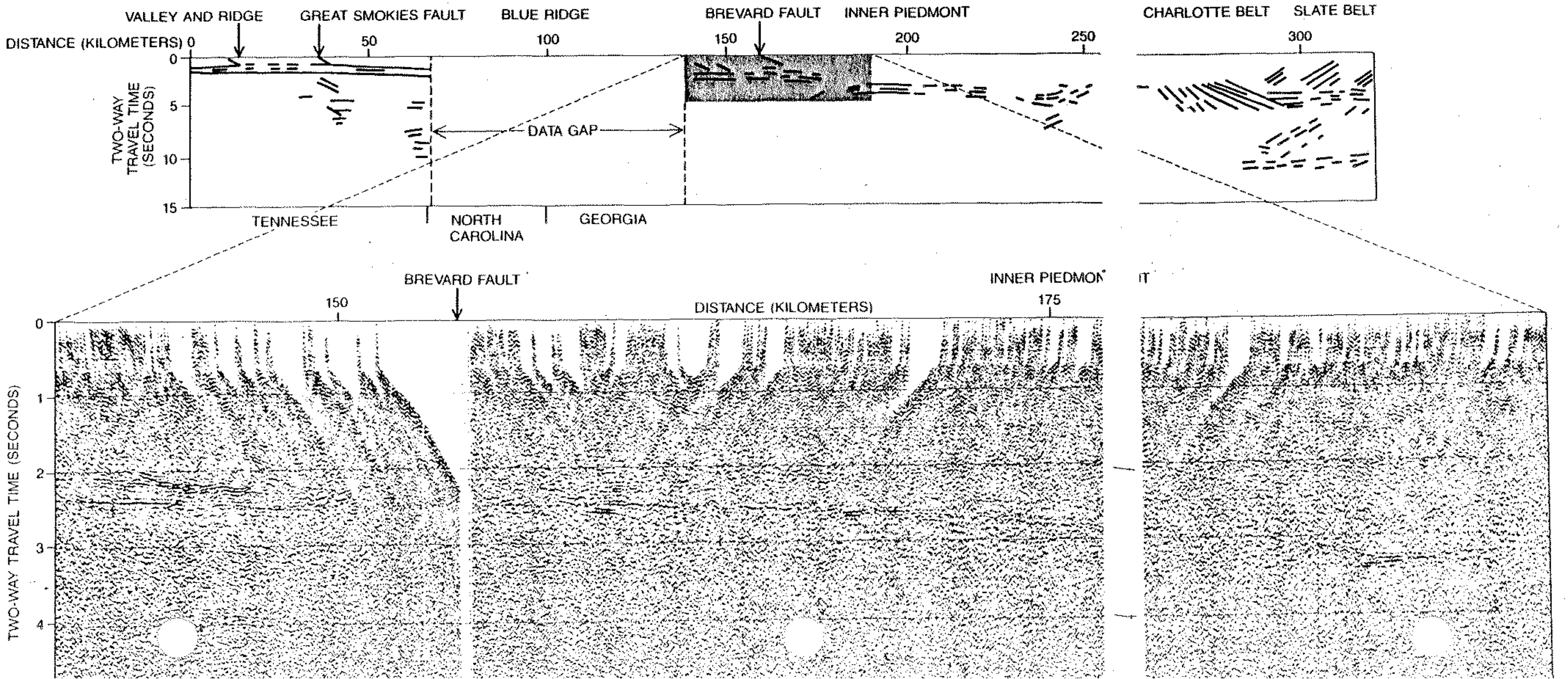
FIGURE 2.3 ERTS photo of portion of central China showing part of the Altyn Tagh fault, one of the greatest strike-slip faults in the world. This fault is believed to be driven by the Indian-Asian continental collision that is occurring nearly 1,000 km to the south. Reprinted, with permission, from Molnar and Tapponnier (1975). © 1975 by American Association for the Advancement of Science.

be determined at what level in the lithosphere the decoupling occurs, separating potentially subductable lower crust from shallower crust that is imbricated by thrusting faults and remains in the upper crust. Would this mean that orogenic belts as known in the upper crust are basically superficial and differ fundamentally from the deeper lithosphere?

Seismic reflection data from the southern Appalachian Mountains have shed light on some of these questions (Harris and Milici, 1977; Cook et al., 1980). Deep-crustal reflection profiles revealed that crystalline rocks exposed in the Blue Ridge and at least part of the Piedmont provinces form an allochthonous thrust sheet that is underlain by relatively flat-lying layered rocks. (See Figure 2.4.)

The crystalline rocks are inferred to have been thrust at least 250 km to the west during episodes of continental collision between the North American and African plates. The underlying layered rocks visible in the reflection cross sections at depths varying from 6 to 10 km are probably Paleozoic sedimentary rocks that extend eastward from the foreland beneath the crystalline terrane. In fact, Cook and Oliver (1981) have suggested the ancient Proterozoic-early Paleozoic continental margin may still be present beneath the thrust sheet. Major questions raised by this discovery involve (a) the disposition of the remains of the lithospheric section that originally formed the lower part of the allochthonous sheet, and (b) the processes of crustal decouplings. It would appear to be difficult, if not impossible, to answer these questions without investigating active continent-continent collision zones.

Geology is intrinsically a global science, and solutions to domestic geologic problems often must be sought in other parts of the world. Nowhere is this aspect better displayed than in the scientific debate over the nature of continent-continent collisions. Many important geologic structures in the United States are believed to be the result of such collisions (e.g., the Appalachian and Grenvillian orogenic belts, the former a significant petroleum province, the latter an important ore-producing region). Yet the most promising, and in many respects unique, area for investigating the most fundamental aspects of continent-continent collision is in the Himalayas. There the Indian continent appears to be underthrusting the Asian continent. In fact, the central role of the Himalayan/Tibetan region in the debate over continent collision virtually demands a major initiative to probe the lithosphere in this area. The beginnings of such an effort are already underway in several quarters, including, for example, a Chinese wide-angle reflection/refraction program in Yunnan Province, in which the United States has been invited to participate under the U.S.-Chinese 1980 Ewtt Studies Protocol. Recently studies using broad-scale Chinese telemetered network earthquake data in Yunnan Province suggest that in the Mekong Foldbelt, adjacent to the Tibetan region, the upper crust as identified by low velocities is more than twice as thick as expected, up to 30 km (Mooney, 1983). How this apparent thickening is achieved is unknown, and cannot be addressed with the present data. However, it is important that seismological exploration of this critical region be carried out in a manner adequate to fully addressing the fundamental issues involved in an unambiguous fashion.


VALLEY AND RIDGE
GREAT SMOKIES FAULT
BLUE RIDGE
BREVARD FAULT
INNER PIEDMONT
CHARLOTTE BELT
SLATE BELT
DISTANCE (KILOMETERS)
0
50
100
150
200
250
300
TWO-WAY TRAVEL TIME (SECONDS)
0
5
10
15
DATA GAP
TENNESSEE
NORTH CAROLINA
GEORGIA
BREVARD FAULT
INNER PIEDMON
150
175
DISTANCE (KILOMETERS)
TWO-WAY TRAVEL TIME (SECONDS)
0
1
2
3
4

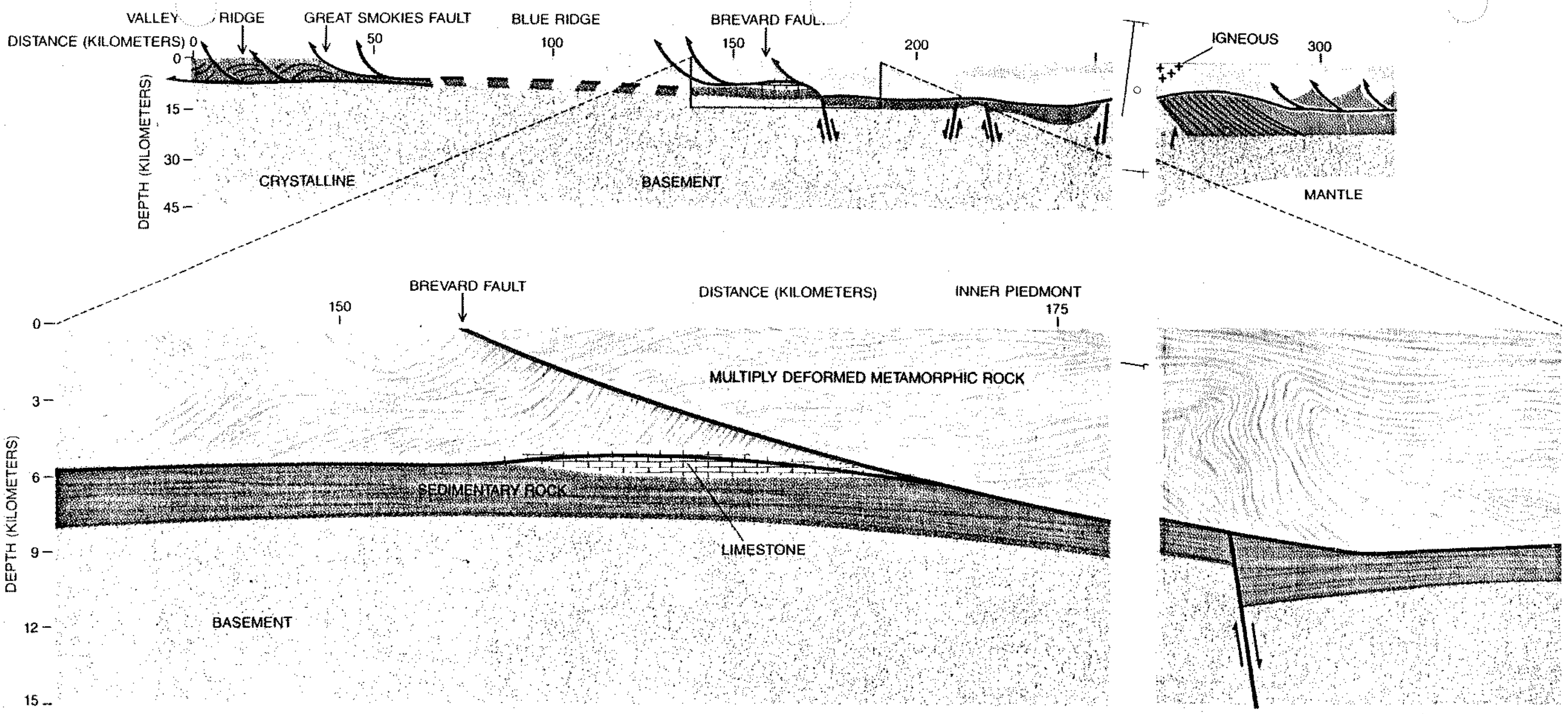


FIGURE 2.4 Seismic reflection survey and geologic interpretation across the Brevard fault zone in Georgia. Reprinted, with permission, from Cook et al. (1980). © 1980 by Scientific American, Inc. All rights reserved.

Thus, it is recommended that current and future efforts to explore the lithosphere in the area of the Himalayas and Tibet be coordinated and augmented in such a way as to constitute a realistic yet effective program to map the lithosphere starting on the Indian Craton south of the Himalayan Foreland and traversing northward across the Himalayas and ending well into the Tibet Plateau. This transect should include the full range of seismic methodologies, not only vertical reflection and refraction/wide-angle profiles, but surface-wave studies as well, so that gross as well as detailed lithospheric structure is mapped.

Continental Rift Zones

Plate divergence within continental lithosphere results in long linear, arcuate, or branching zones of localized crustal extension, exemplified by the currently active Rio Grande Rift or the late Precambrian Midcontinent Rift of North America. Other rift zones, such as the Basin and Range province, are broad and complex. Seismological and related geological and geophysical studies have shown that regions of continental divergence are characterized by shallow seismicity, extensional faulting, lithospheric thinning, broad topographic upwarp, high heat flow, and characteristic assemblages of volcanic and sedimentary rocks. Rift depressions contain thick sedimentary accumulations, some of which are major petroleum producers (e.g., the Anadarko Basin, Oklahoma). The passive margins of continents (see next section) left by those rifts that evolve into ocean basins are especially important regions for exploration (e.g., the Gulf Coast of the United States). Moreover, igneous and hydrothermal activity associated with rifting has generated both ore deposits and geothermal prospects, as in the Basin and Range province. The North American continent has a wide range of both active and inactive rifts in various stages of development, so we are in a favorable position to study processes in their evolution.

Shallow focal depths of earthquakes (generally 10 km or less) suggest that high heat flow renders the lower crust ductile. Brittle deformation observed at the surface is believed to merge downward into ductile flow and subhorizontal zones of decoupling on detachment faulting. The transition is under active study in "metamorphic core complexes" (Coney, 1980), but whether these findings apply to rift zones in general is debatable. A few deeper earthquakes (15 km or more) and active basaltic volcanism, presumably from a mantle source, suggest that high-angle fracturing of some type may penetrate the entire crust. Reflection seismic data in western Utah show a prominent subhorizontal detachment fault underlying, and uncut by young normal faults of the shallow crust. This detachment can be followed westward and downward to midcrustal depths.

Several processes have been proposed for the formation of continental as well as oceanic rifts. These processes generally involve lithospheric thinning over hot rising plumes of asthenospheric material and plate extension driven in part by the "slab-pull" of a distant subduction zone or (in a back-arc environment) by more localized convection. Many problems related to these hypotheses remain unanswered: What localized the initial rifting, and are the thermal and convective processes a cause or an inevitable accompaniment of rifting? Why do some continental rifts, such as the Red Sea Rift, evolve into oceans, while others like the Midcontinent Rift are aborted and "frozen" in an early stage of development?

What is known of the deep structure of rifts suggests that high-velocity materials characteristic of the deeper ocean crust are intruded into the lower continental crust, forming a broad zone of altered lithosphere. Geophysical evidence from both the Rhine Graben of southern Germany and the Mississippi Embayment indicates that both of these rifts are underlain by an extensively modified lower crust and mantle. The latter is a Precambrian rift that has been reactivated by the present intraplate stress regime (Ervin and McGinnis, 1975; Zoback et al., 1980) and is one of the most active earthquake sources within the eastern United States. This region was the site of the devastating major earthquakes of 1811 and 1812.

> It is recommended that major emphasis be placed on integrated seismological study to asthenospheric depth in the Mississippi Embayment. The embayment offers an ideal site for studying the tectonic reactivation process in an intraplate environment, a process with no clear relationship to plate tectonics, but nonetheless central to the evolution of continents. In societal terms, the potential for widespread earthquake damage is great in this densely populated region. Because of the efficiency of seismic energy transmission in this portion of the craton, prediction is critical.

The Basin and Range rifts began to form during a time of active subduction at the western continental edge. Arc-type (andesitic) magmatism was widespread throughout the rifted region. Rifting has continued in the present stage, but the plate boundary has changed from subduction to transform and the magmatism has changed from andesitic to basaltic. Although the deep crust and the mantle lithosphere are clearly involved in contemporary tectonism (Thompson and Zoback, 1979), little is known of the seismic properties and details of seismic boundaries at these depths.

Recent geophysical investigations of the Rio Grande Rift (Riecker, 1979) have been successful in identifying probable magma chambers in the middle and upper crust of the rift, and in characterizing the geometry of the faulted flanks of the rift. Midcrustal shear-wave reflections from accurately located microearthquakes indicate the presence of a magma layer within the central region of the rift (Sanford et al., 1977; Rinehart et al., 1979). Important additional controls from P-wave reflection data indicate that the magma occurs in a thin, flat sill covering about 1,700 km^2 at a depth of 19 to 20 km (Brown et al., 1980) (Figure 2.5). Regional-scale surface-wave (Keller et al., 1979) and seismic refraction studies (Olson et al., 1979) show

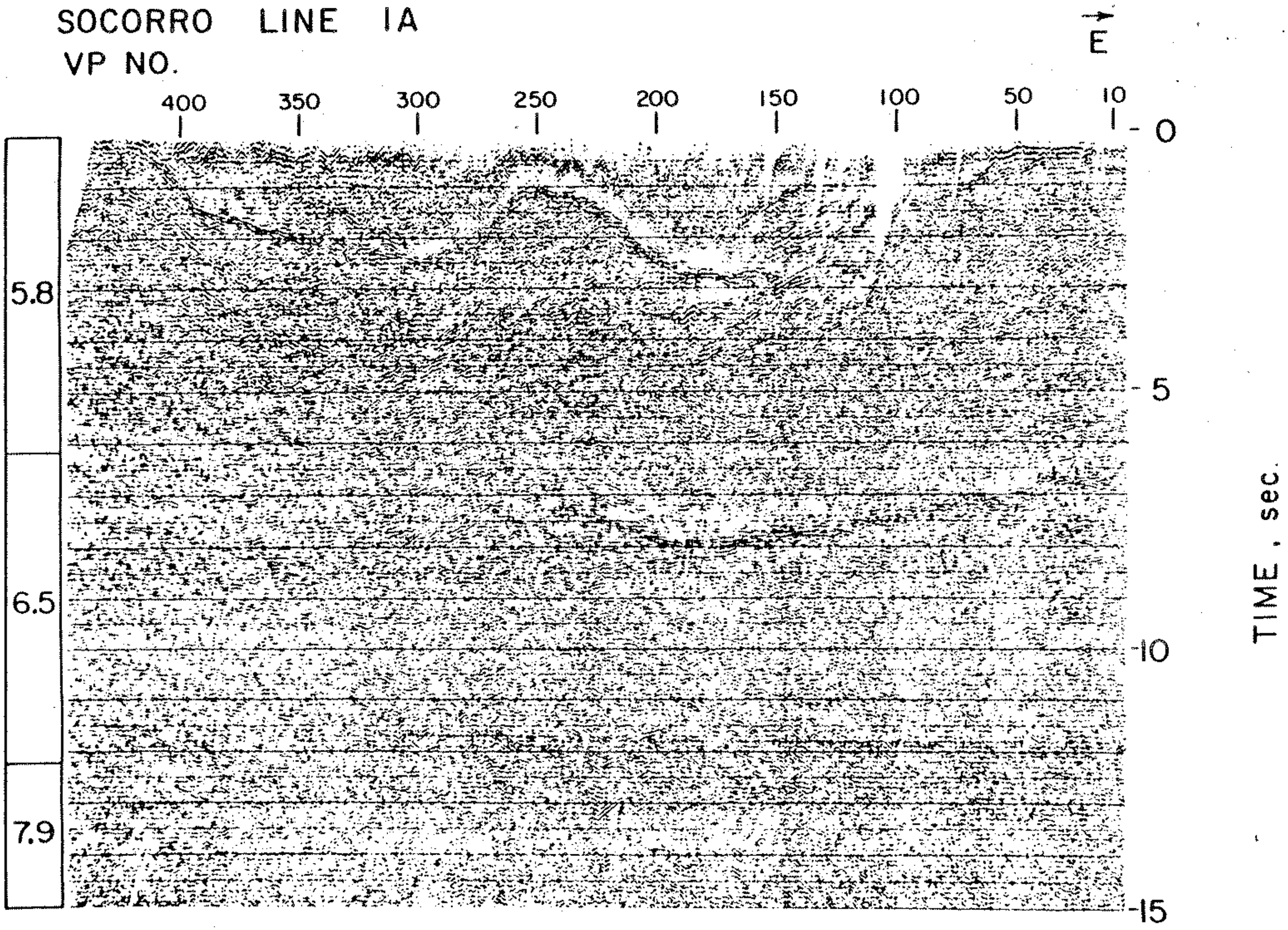


FIGURE 2.5 Seismic reflection profile across the Rio Grande Rift, New Mexico. Note intergraben horst beneath vibrating points 200-300. Deep reflector at 7.5 to 8.0 seconds time is believed to come from the top of a lower crustal magma body. Reprinted, with permission, from Brown et al. (1979). © 1979 by the American Geophysical Union.

that the crust has been thinned by 10 to 15 km beneath the rift. High-resolution reflection profiles (Cape et al., 1983) appear to resolve some of the major crustal features of rifts, such as buried intragraben horsts, detachment faults, and intrusive bodies.

Wide-angle reflection profiling of the crust within rift zones is one effective approach to some of these problems. An extensive program of such profiles recently completed in the Imperial Valley of California by the U.S. Geological Survey (USGS) provided both a remarkably detailed picture of structure and clues to the evolution of the Salton Trough, an obliquely spreading basin at the southern end of the San Andreas fault (Fuis et al., 1981). Improved analysis techniques, primarily for the computation of ray travel times and synthetic seismograms in a two dimensionally varying crust (Cerveny et al., 1974) have been of great value in constraining both the lateral and vertical velocity structure. A major discovery was that the basement in the trough consists of metasedimentary rocks. Crustal rifting has separated the older granitic crust, allowing for the accumulation of sediments that are metamorphosed by intrusives in the lower crust. Thus, the Salton Trough is believed to be an active example of the continental rifting process.

> The Rio Grande Rift and the Basin and Range province are potential sites for key seismic experiments. In both regions significant new vertical reflection profiling is underway or has been completed. A complementary effort is recommended using dense one- and two-dimensional arrays of instruments with both artificial and earthquake sources to further define details of the middle and lower crust, the Moho discontinuity, and the anomalous upper mantle.

Passive Continental Margins

If plate divergence along rift zones continues, oceanic lithosphere forms within the rift and the ruptured edges of the continent undergo a long-term evolutionary sequence that results in the formation of a passive continental margin. The Atlantic coast of North America is an example of this type of margin. Three main stages in the development of a passive margin are generally recognized: (1) initiation of continental rifting involving thinning or rupture of the continental lithosphere and graben formation as a prelude to continental breakup, (2) youthful opening of a new ocean basin and concurrent rapid subsidence of the rifted continental margin, (3) subdued but long-lived regional subsidence and development of thick depositional sequences of miogeosynclinal and eugeosynclinal deposits across the continent-ocean transition zone.

Seismology has already played a key role in the development of this evolutionary model of passive margins, particularly for the mature stage. Shallow-penetration seismic reflection profiles have been an essential and widely employed tool for use in mapping the seismic stratigraphy of the continental shelf and borderland (e.g., Tucholke and Mountain, 1979). Such studies, when coupled with lithostratigraphic and biostratigraphic control from Deep Sea Drilling Project borehole data, have permitted the unraveling of the sedimentary history of passive margins.

Major problem areas that will require new data include questions relating to the mechanisms of continental splitting and subsidence, particularly in the youthful stages of passive margin development. Comparatively little is known about the processes that thin the continental crust, and even less is known about the evolution of the deeper portions of the lithosphere, although these processes should introduce clear geophysical fingerprints. The most primitive asthenospheric materials intruded from below are (at the same pressure and temperature) both of higher density and velocity than the more generally reworked sedimentary and metamorphic rocks and the igneous rocks that form the bulk of the continents' upper crustal material. Therefore, if not masked by the accumulating light sediments overlying them, rifts are ultimately marked by linear zones with positive gravity anomalies. Disturbed magnetic fields also mark the lithosphere composed of now-cool asthenospheric material. Hot intrusives should be seismologically distinguishable during early phases of rifting by anomalous zones of high seismic attenuation, and during late phases by linear zones of higher-than-normal wave velocity.

Preliminary interpretations of data from recent refraction and reflection surveys conducted across the continent-ocean transition suggest that crustal thinning may occur by ductile flow in the lower continental crust. Surveys across the ancient eastern Atlantic margin off of France revealed that the upper continental crust can be traced continuously to the continent-ocean boundary (Montadert et al., 1980). As the continent-ocean join is approached, the upper continental crust is cut by listric normal faults, but is otherwise not attenuated. The lower continental crust, on the other hand, becomes thinner gradually over a distance of more than 100 km across the passive margin. How this thinning takes place is still controversial (Bott, 1980; McKenzie, 1978). For example, surveys conducted across the young margin of the Red Sea to the Saudi Arabian Shield indicate that the transition zone is remarkably abrupt, occurring in a distance of about 20 km. The details of how such a sharp boundary might evolve into more typical, broad Atlantic-type margins are still unknown and in need of further investigation.

The Atlantic coast of the United States is the classic example of a passive continental margin (see Figure 2.6). Industry exploration, as well as USGS activities, has generated an impressive data base of shallow reflection results across and along the Atlantic. Offshore drilling has provided additional geologic control. Although many aspects of postrift stratigraphy across the Atlantic margin are now well known, the deeper and more fundamental aspects of crustal thinning and compositional transition (continental to oceanic) remain poorly known. Imaging, even locating, the buried continent-ocean transition is complicated by the logistical problems of collecting data with sufficient density in an onshore-offshore experiment where the underlying structure--both shallow and deep--is changing rapidly. In spite

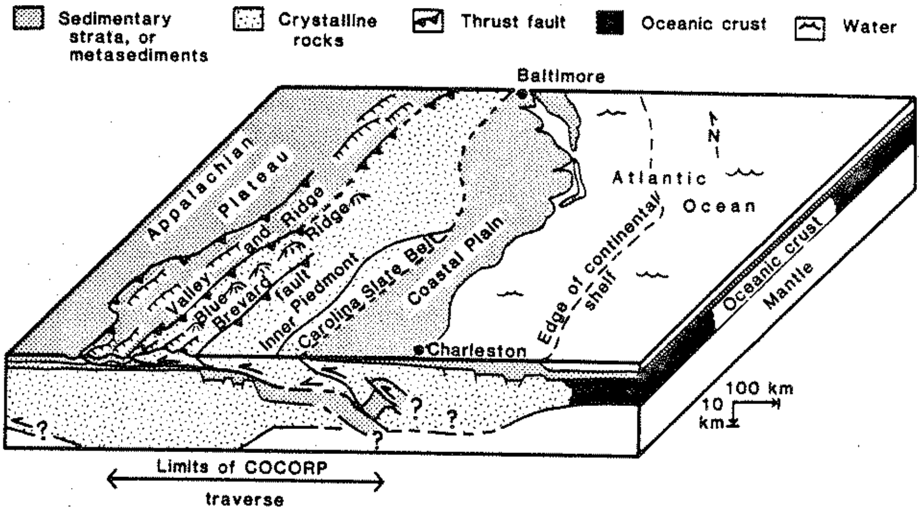


FIGURE 2.6 Diagram illustrating the modern Atlantic margin of the southeastern United States. Cross section shows how rocks of the southern Appalachian thrust sheet now overlie a former continental margin, which before burial resembled the modern margin. Reprinted, with permission, from Oliver (1982b). © 1982 by American Association for the Advancement of Science.

of numerous past attempts using both reflection and refraction methods, delineation of deep structural and compositional changes has largely been unsatisfactory. Effective resolution of the deep nature of such a transition should not, however, be beyond the capabilities of a modern, multichannel onshore-offshore seismic experiment employing sufficiently large sources, sufficiently dense recording, and appropriate data processing techniques.

> An adequately instrumented, combined reflection/refraction traverse should be conducted across the Atlantic continental margin with the aim of unambiguously defining the nature of the continent-ocean transition at lower crustal and upper mantle depths. Results of such a traverse would have implications beyond its intrinsic scientific merit, since the evolution of potential hydrocarbon resources in the sedimentary basins that characterize passive margins is undoubtedly controlled by processes at depth. Furthermore, a clearer picture of passive margin structure could contribute significantly to the understanding of the infrequent yet significant seismicity of the eastern United States.

Transform Boundary Systems

In the framework of plate tectonics, transformlike boundaries between lithospheric plates might appear, upon first consideration, to represent the simplest type of plate boundary. In nature they typically appear as complex zones of anastomosing fault strands. Their internal structures are complex on both local and regional scales, commonly containing such diverse features as pull-apart basins and folded mountain ranges formed in response to shearing of the braided fault system. Many of these structures are important oil habitats.

The present strain pattern along the Alpine fault of New Zealand, for example, suggests a 200-km-wide zone of pervasive deformation (Walcott, 1978). In some parts of the zone relative motion is taken up by faulting, whereas along other parts of the zone, ductile flow is the dominant strain mechanism. The diffuse nature of earthquake activity also supports the idea of a broad zone of plate interaction.

The San Andreas transform system of the southwestern United States is equally, if not more, complex (Allen, 1981). Within the San Andreas transform system, numerous anastomosing strike-slip faults have cut the continental crust into many long narrow slivers, particularly in its western part. Movement on these slivers has greatly disrupted the earlier geologic framework generated by older plate boundary systems. The total displacement some blocks have undergone within the San Andreas system may be large, amounting to several thousands of kilometers. Motion on the modern San Andreas fault, within about the past 15 million years, accounts for no more than about 300 km of the total. (See Figure 2.7.)

Detailed seismological studies of earthquake locations and focal mechanisms in central California clearly define some of the boundaries

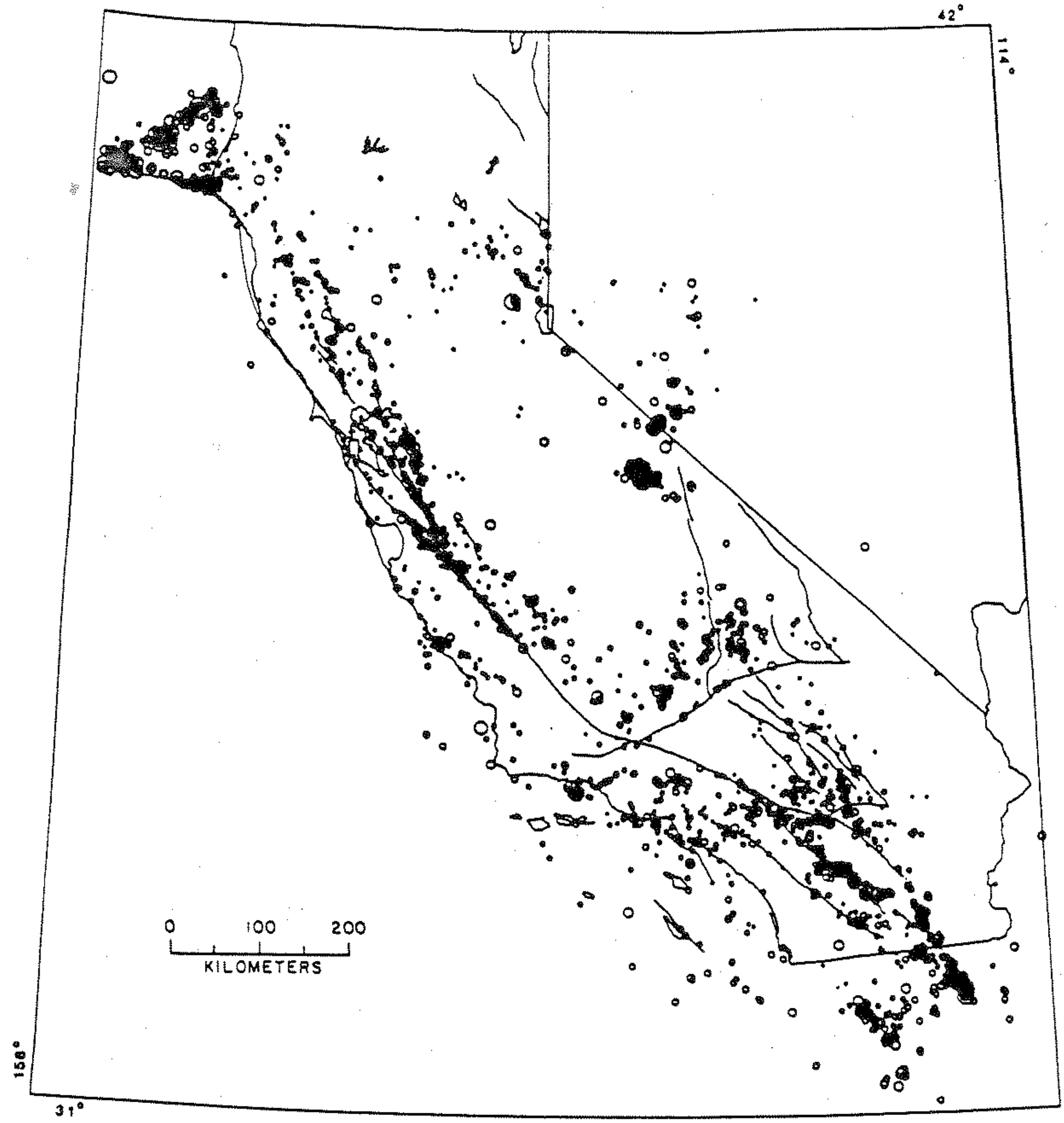


FIGURE 2.7 Seismicity of California and western Nevada for 1980 from seismographic networks of the U.S. Geological Survey, California Institute of Technology, and the University of Nevada.

of the principal blocks as vertical strike-slip faults within the upper 15 km of the crust. The nature of the boundaries at greater depths and the thickness of the displaced blocks are purely conjectural at present. Such blocks could be thin rafts of the upper crust (Lachenbruch and Sass 1980; Zandt, 1981) or they could be more deeply rooted slices of the lithosphere. The forces that drive the earthquake-producing brittle upper crust are also not yet understood. The interplay between the brittle and ductile parts of the system is another central question that has not been fully explored. An understanding of these elements is essential if we are to learn how surficial processes conform with or differ from deeper-seated processes.

One way in which seismology can help place constraints upon possible models is through the comparison of the distribution of earthquakes with predictions from specific rheological models. Sibson (1982), for example, found a good correlation between the cutoff depth of microearthquakes in various heat flow provinces of the western United States and the frictional/quasi-plastic transition modeled for different geotherms. The very abrupt drop in shear resistance below the transition predicted by the model from experimentally derived flow laws for quartz suggests that decoupling and decollement beneath the seismic zone could be the pervasive mode of deformation of the lower crust.

As one of the most important and best-studied earthquake faults in the world, the San Andreas is an ideal target for bringing to bear both active (reflection and refraction) and passive (earthquake source) techniques for investigating a lithospheric fracture. As the changes in structure and composition with depth near the fault must be intimately related to its mechanical behavior, effective imaging of the fault zone at depth may prove instrumental in evaluating attendant earthquake hazards. Previous attempts to study the fault using active seismic techniques have lacked sufficient sampling to avoid spatial aliasing.

> A well-planned, thorough, multitechnique seismic experiment to image a key volume at the San Andreas fault in three dimensions is long overdue and recommended. A unique aspect of such an experiment should be the integration of newly deployed mobile recording instruments such as called for in this report, with existing earthquake monitoring networks in California. Such an experiment is a natural opportunity to combine these equally necessary yet complementary seismic networks to best advantage. The experiment should also employ and integrate vertical reflection with wide-angle reflection/refraction recording, both carried out in a three-dimensional imaging mode.
>
> The societal benefits from an experiment such as envisioned here extend beyond the issue of earthquake risk. Many of the geologic structures associated with the San Andreas fault contain known or potential hydrocarbon resources whose full exploitation is contingent upon proper understanding of an evolutionary history intimately related to the fault itself.

Basins and Uplifts in the Continental Interior

Basins and uplifts located within the "stable" core of continents present a particularly difficult problem for geodynamics studies, as their relationship to plate tectonic models is obscure. Two of the type examples for such intraplate deformation in the United States are the Michigan Basin, a remarkably circular Paleozoic subsidence feature, and the Adirondack Mountains of New York, an equally remarkable circular uplift formed some time after the middle Paleozoic and exposing Precambrian basement.

The Michigan Basin is the focus of much active hydrocarbon exploration and drilling. However, despite numerous geophysical studies including gravity and magnetic surveys (Hinze et al., 1978), seismic reflection surveys (Brown et al., 1982), and a deep scientific well (Sleep and Sloss, 1978), the cause of its subsidence remains unknown. Several geomechanical models have been proposed to explain the shape and sedimentary history of the basin (e.g., Haxby et al., 1976), but all involve thermal perturbations to the lithosphere that are both ad hoc and lacking in supporting evidence.

Although the deep-well measurements (Sleep and Sloss, 1978), the potential field data, and the seismic reflection data indicate that a late Precambrian rift underlies the Michigan Basin, its relationship if any to the late Paleozoic subsidence has yet to be established. A particularly puzzling aspect of the basin is its apparent synchroneity with other basins worldwide, including some Appalachian basins that are believed to be related to plate-boundary phenomena.

In spite of the geologic importance of the Michigan Basin, detailed seismological information on its deep structure that could shed light on its origin is virtually nonexistent. Not even a reconnaissance refraction survey across the basin to establish such basic parameters as depth to Moho have been conducted.

The Adirondack Dome has not been studied any more completely. Unlike the Michigan Basin, it has no sedimentary record to document its history of vertical movement. Like the Michigan Basin, the Adirondack Dome, with its mineral resources such as zinc and titanium, is of substantial commercial interest. Uplift of the Adirondacks is believed to be post-Devonian, and geodetic data have been used to argue that it is still rising (Isachsen, 1975). Although the basement rocks exposed in the dome are providing important information on the nature of the late Precambrian Grenville orogeny during which they were formed or modified, geological and geophysical evidence relevant to the much more recent formation of the dome is sparse. The only deep refraction data are almost 30 years old, and recently completed COCORP reflection surveys in the area appear to be too limited in extent to shed much light on the mechanism of uplift.

In view of the importance of understanding intraplate basins and uplifts and the relative lack of seismological data across such features, a major seismologic effort to examine the lithosphere beneath the Michigan Basin and Adirondack Dome should be given high priority. Study of these features will require both high structural resolution and accurate measurement of rock properties (e.g., seismic velocity), so a unified strategy employing both near-vertical reflection and wide-angle reflection is needed. The exploration program must be extensive enough to include the flanks of these structures. In view of previous experience with Vibroseis reflection data in the Michigan Basin, consideration should be given to an explosion reflection survey to enhance penetration. The fortuitous existence of major bodies of water on three sides of the Michigan Basin suggests that long-range fan-shooting of the basin by a circumscribed set of marine shot points should also be considered.

Magma Chambers, Batholiths, and Volcanism

Igneous rocks can provide insights into major features of continental tectonics for which little other record exists. Bodies of magma develop and are emplaced in the crust buoyantly (as batholiths), in response to tectonic extension (as dikes), or from other physical imbalances of sometimes obscure origin. Upon cooling, large magma bodies become plutons that range in surface exposure from a few to hundreds of square kilometers. Over several million years, continued intrusion of plutons leads to the formation of batholithic terranes that crop out over thousands of square kilometers and must occupy a significant volume within the continental crust. Data from refraction seismology have generally indicated that batholithic terranes are underlain by rocks of higher velocity at depths of less than half the crustal thickness. Subhorizontal reflections from the basal contacts of a few batholiths have also been detected (Lynn et al., 1981).

Considerable controversy exists as to how large plutons intrude into the crust. The three-dimensional geometry of the pluton and its relation to its host rocks is one of the most important pieces of data in deciphering the problem. Are the plutons flat sheets, do they have flat floors and irregular or domed tops, or are they large irregular three-dimensional bodies? Have they intruded only at shallow crustal levels or can they be intruded at any crustal level? Can the compositions of plutons be distinguished by seismically determined physical properties?

Several recent coordinated geological and geophysical investigations have begun to provide partial answers to some of these questions. The Coso Range of southeastern California, which has been characterized by basaltic to rhyolitic volcanism and extensional tectonism for approximately the last 3 to 4 million years, bears many similarities to other continental intraplate volcano-tectonic systems in the western United States (see Figure 2.8, left). The region is one of high heat flow, high seismicity, and fumarolic hot spring activity. Geologic, seismic, gravity, and heat flow data indicate that its geothermal system is driven by deep circulation of fluids through fractured hot rocks above a relatively small, midcrustal silicic magma reservoir. Seismological studies of teleseismic P-waves recorded above

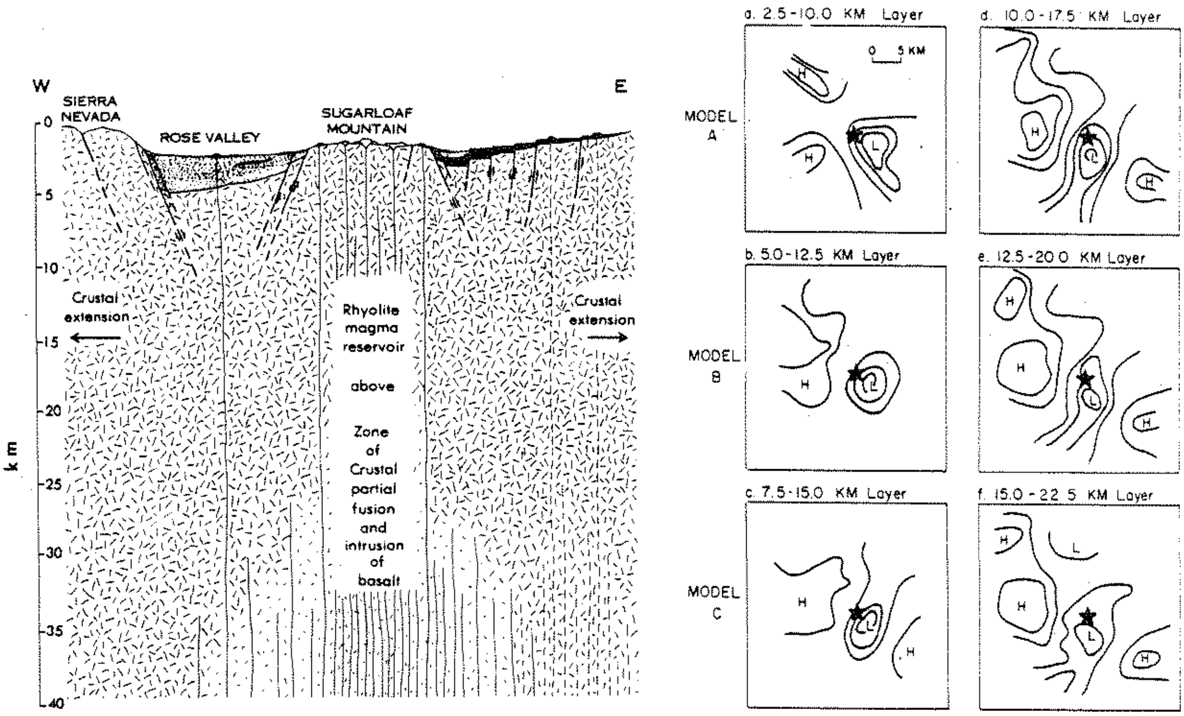


FIGURE 2.8 Comparison between geologic cross section of the Coso Range, California, rhyolite field (from Duffield et al., 1980), and three-dimensional velocity structure determined by Reasenberg et al. (1980). Note the coincidence of the vertical low-velocity zone with the proposed magma reservoir and zone of basaltic intrusion.

LEFT: Schematic east-west cross section of Coso Range through Sugarloaf Mountain; horizontal scale equal to vertical scale with some exaggeration at surface. Patterned area, pre-Cenozoic rocks and possibly plutons coeval with Pliocene volcanic rocks; less dense pattern where partial melting inferred to have taken place during Quaternary. Shaded area, basalt, largely Pliocene on eastern third of section, mainly Pleistocene elsewhere. Stippled area, Pliocene and Pleistocene sedimentary rocks. Unpatterned area, Pleistocene rhyolite. Thin dashed vertical lines, inferred Pliocene dikes; thin solid vertical lines, inferred Pleistocene dikes; and heavy lines, faults.

RIGHT: Smoothed inversion solutions for the second and third layers of the three-block layer divisions modeled. Velocity variation contours at 1% intervals (0% contour omitted) are shown. High-velocity and low-velocity zones are indicated by H and L, respectively. Shaded areas indicate compressional wave velocity 1% or more slower than average layer velocity.

the geothermal field have provided the most definitive evidence on the location, size, and shape of the magma reservoir (Figure 2.8, right). The reservoir is expressed at the surface by a travel time delay shadow that shifts position with changing source azimuth. Three-dimensional velocity models contructed by inversion of the travel-time data localize the lowest velocities within a narrow vertical column at depths between about 8 and 15 km. At greater depths, the low-velocity body becomes elongated along a north-northeasterly azimuth, suggesting that the ultimate heat source for the rhyolitic volcanism is related to intrusion of basaltic magma into an extending lower crust.

The inferred correspondence between the region of low compressional-wave velocity and the presence of magma has not as yet been confirmed by independent means. Similar low-velocity bodies localized beneath other silicic volcanic fields--at the Geysers in California, Roosevelt Hot Springs in Utah, and Yellowstone caldera--lend support to the association. Recent results from a two-dimensional teleseismic imaging study of San Francisco Mountain stratovolcano in Arizona by Stauber (1982) suggest that other explanations for the observed low-velocity features must be considered.

While the teleseismic body wave analysis method has been very successful in defining the gross configuration of some magmatic systems, it cannot resolve features smaller than a few kilometers in size. Other techniques with better spatial resolution, such as refraction and wide-angle refraction or vertical reflection profiling are needed to refine structural relations. Shear-wave and amplitude data are also critically needed because of their sensitivity to the presence of molten or partially molten rock.

In the 1978 Yellowstone-Snake River Plain cooperative seismic project, a two-dimensional array of portable seismographs was used to record refraction and wide-angle reflections. With a station spacing of 3 km, this experiment provided detailed information on the P-wave velocity structure of this large Quaternary silicic volcanic system. The primary results show a low-velocity upper crustal volume that coincides with the outline of the Yellowstone caldera. At least one very low velocity body, with a 30 percent decrease, was shown to be present beneath the caldera at depths from 3 to 10 km and was interpreted to result from a large volume of either a steam-water-dominated system or a partial melt of 10 to 50 percent (Smith, 1981; Smith et al., 1982).

> Because much of our mineral wealth and virtually all of our geothermal resources are derived from igneous rocks and their associated hydrothermal systems, and because of the need for accurate assessments of volcanic hazard, seismic studies of the configuration and emplacement of igneous bodies and batholiths have considerable societal importance.
>
> Numerous excellent targets for detailed seismological studies of active volcanic systems exist within the United States, including the Long Valley-Mono Craters area, California; Newberry Craters, Oregon; Mt. St. Helens, Washington; the Soccoro magma body of the Rio Grande Rift, New Mexico; and the

Yellowstone caldera, Wyoming. It is recommended that at le at one such site be targeted for a major unified seismic experiment, with the aim of establishing the detailed geometry of the volcanic and associated hydrothermal system.

Relationship of Lithospheric and Asthenospheric Motions

Even if relative motion between surficial parts of the lithosphere can be reconstructed from the geology of continents, it is not safe to infer that the same relations can be found at depth. Within many deformed belts, thrust faults resulting from plate convergence commonly cut only the upper 10 to 15 km of continental crust. Efficient shallow decoupling within crust is indicated by thrust displacement of more than 100 km along shallow dipping faults. Such displacements are seen in the Alpine-Himalayan, Appalachian, or Caledonian mountain systems.

Oppenheimer and Herkenhoff (1981) used teleseismic P-wave to determine the three-dimensional structure underlying the Geysers-Clear Lake volcanic field of the northern California Coast Ranges, and found that a pronounced low-velocity column extends to a depth of more than 45 km beneath the field. The column is inclined rather than upright, for the center of the low-velocity area migrates NNE TO SSW with increasing depth. Heat flow data from this field within the San Andreas fault system suggest a subhorizontal decoupling layer at depth of 15 to 30 km (Lachenbruch and Sass, 1980). The observed migration of the low-velocity column is consistent with the hypothesis that the substratum is decoupled from the brittle crust of the North American plate (see Figure 2.9).

Three-dimensional velocity anomalies have also been determined on a much larger scale for the lithosphere and underlying asthenosphere of the entire San Andreas fault system by Cockerham and Ellsworth (1980) and Raikes (1980). Strong lateral velocity heterogeneities, with scale lengths of 200 to 300 km and with peak contrasts in excess of 6 percent, persist to a depth of over 200 km. Within the depth range from about 100 to 200 km, presumably within the asthenosphere, Raikes (1980) found a high-velocity ridge straddling the San Andreas fault. A similar but shallower feature in the 50- to 100-km-depth range had been proposed earlier by Hadley and Kanamori (1977). A recent, independent study by Walck and Minster (1982) confirms the deeper depth location. This ridge could indicate the double continental subduction zone proposed by Bird (1980) as a means of carrying the transform motion of the San Andreas system across the "big bend" in the fault.

Within the depth interval of 100 to 200 km, Cockerham and Ellsworth (1980) discovered an inclined low-velocity zone dipping eastward from the San Andreas fault. They proposed that this zone coincides with the "window" in the subducted Farallon plate proposed by Dickinson and Snyder (1979) that forms as the Mendocino Triple junction migrates to the northwest.

Seismological measurements of velocity anisotropy within the lithosphere may also aid in the understanding of deeper lithospheric motions. Laboratory petrofabric studies of mantle rocks have shown

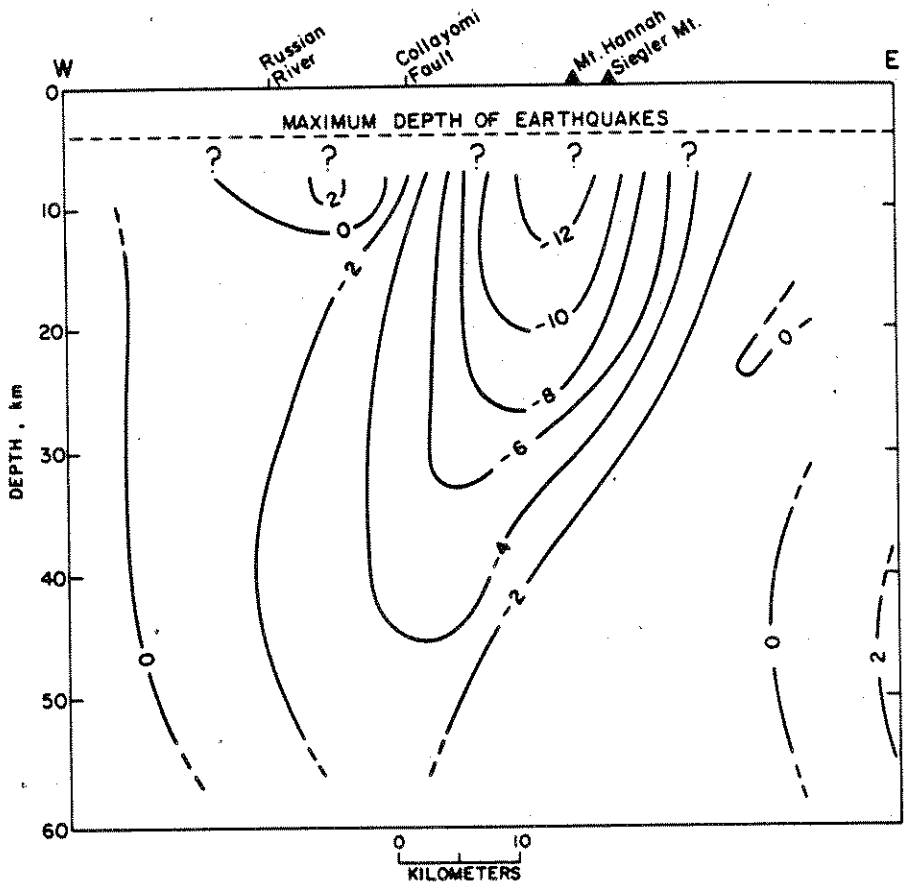


FIGURE 2.9 East-west cross section of Geysers-Clear Lake volcanic field showing low-velocity column; contours in percent of velocity difference. From Oppenheimer and Herkenhoff (1981). © 1981 by the American Geophysical Union.

that variations in seismic velocity with direction originates from the crystallographic orientation of highly anisotropic minerals in rocks produced during ductile flow. It is well known that upper mantle seismic velocity is anisotropic near oceanic divergent margins. Seismic velocities are up to 10 percent higher for paths parallel to the flow lines. Similar, but admittedly more complicated, seismic studies in crustal and mantle rocks in collisional convergent systems might yield critical data demonstrating the presence of thick zones of rocks with well-developed fabric that mark decoupling layers within the lithosphere.

Extensive decoupling has far-reaching consequences for lithospheric structure and evolution. Rocks in the upper crust may have formed and been modified above a deep lithosphere that has been replaced. For example, the COCORP Appalachian data have suggested that the entire inner Piedmont region of this orogenic belt is in one or several subhorizontal thrust sheets. This means that the shallow crust is now underlain by different lithosphere than that which underlay it during the igneous, metamorphic, and deformational events represented in the rocks. It is clear that we must know the extent of lithospheric decoupling before we can relate upper crustal geology to the deeper lithosphere.

Most of the seismological experiments suggested as examples in this chapter stressed the need for improved spatial resolution of lithospheric structure, particularly for those features in the upper 10 to 20 km of the crust. However, as one attempts to look deeper, experimental techniques that rely upon surface energy sources inevitably return increasingly degraded information because of the loss of signal strength. By contrast, while the three-dimensional methods that rely upon teleseismic sources have intrinsically poorer spatial resolution than have surface methods, they retain it to great depths in the earth (100 km or more). Thus, they are our most powerful and effective tool for studying the lower lithosphere and underlying asthenosphere.

> As an example of how deep-penetration seismological approaches may be effectively employed, we suggest a program using teleseismic travel-time and surface-wave phase velocity measurements to map lithospheric and asthenospheric structure along a transverse from the west coast to the Colorado Plateau. This transect, which crosses key geologic provinces such as the Coast ranges, Great Valley, Sierra Nevada, Basin and Range, and Colorado Plateau, is already targeted for new deep reflection surveys, and has been probed by several refraction surveys. Information from these high-resolution techniques would allow effects of the shallow lithosphere to be "stripped" away from the teleseismic observations, providing a clearer view of the deep lithosphere. Together, the shallow- and deep-source programs could provide information on a number of important and still-controversial topics, including the following: What and where is the crust-mantle transition? What is the nature of the San Andreas fault below the brittle upper crust? What uplifted the Colorado Plateau? What drives the extension of

the Basin and Range? These and other problems may not be fully resolved using relatively shallow-sensing high-resolution data alone, but will require the deeper-sensing imagery provided by teleseismic data.

CONCLUSIONS

The tasks ahead seem clear: (1) to develop a three-dimensional understanding of plate boundary systems and to recognize those geological and geophysical features that are unrelated to plate interaction, (2) to use this understanding to reconstruct the extent and evolution of ancient systems that form the major elements of continental crust, (3) to determine the dynamics and evolution of systems that have no modern analogs, and (4) to better understand the deeper lithosphere and asthenosphere and their relation to upper lithosphere kinematics and dynamics. In all these tasks seismology will play a leading role.

The understanding of the earth's history must be focused on the continents, where resides the only evidence for 95 percent of earth history. The continents are the part of the earth on which we live, and are the terranes from which we will continue to derive the bulk of our natural resources. We are subject to natural hazards that are both the direct result of modern plate motions, such as earthquakes and volcanic activity, and the indirect result of processes far from modern active boundaries, such as earthquake activity that is apparently unrelated to plate motion and for which we have no process on which to base prediction theory, or the sinking of continental margins long after they cease to be a part of an active system.

The study of continents and their evolution must be interdisciplinary and international. We are on the threshold of advances in our understanding of the continents that may rival those in the understanding of earth motions that have come from study of the structure and evolution of oceanic lithosphere.

3

CAPABILITIES OF SEISMOLOGY IN LITHOSPHERIC EXPLORATION

The preceding discussions demonstrate not only that major problems of lithospheric geology remain unresolved, but that seismology has played and must continue to play a leading role in the search for answers. Seismology offers the least ambiguity and the highest resolution of all techniques for subsurface exploration short of drilling. However, there must be a new national commitment to image the continental lithosphere seismically and to provide a new generation of instrumentation.

A coordinated effort bringing together information on the physical properties of the earth from seismology, petrology, and laboratory investigations is also essential to our goal of understanding the nature of the continental lithosphere. Not only will knowledge of the evolution of the continental crust provide a new understanding of great scientific importance, but more detailed knowledge of the distribution of physical properties with depth will directly address problems of societal and technological concern such as energy, mineral resources, earthquake risk, and waste disposal.

We stress the point that the various seismic techniques (most of which are already developed) are mutually supportive and can often be employed concurrently with a unified interpretation. We will show that this objective requires spatially unaliased sampling of the seismic wavefield with instrument arrays of 100s to 1,000s of recording locations. For the purpose of this discussion, however, we find it useful first to describe the current capabilities of the various seismic techniques separately. Seven broad categories will be discussed: (1) refraction/wide-angle reflection, (2) narrow-angle reflection, (3) diffraction, (4) natural sources, (5) surface waves, (6) relevant rock physics and petrology, and (7) seismic modeling and interpretation.

In addition to outlining the potential of these various techniques (Table 3.1), we present generic experiments to illustrate especially timely or promising applications of these methods toward solving important geological problems.

TABLE 3.1 Primary Seismic Methodologies

Seismic Method	What Is Measured	Strengths	Weaknesses	Laboratory Impact	Instrumentation Required
Refraction/ wide-angle reflection	Seismic energy is returned to surface by reflection and critical refraction. Travel-time amplitude data provide measure of velocity and Q layering with depth.	Provides average velocity estimates. Independent measure of depth to velocity interfaces. Evaluation of large lithospheric volumes are efficient.	Reduced velocity resolution because of large source-receiver offsets. Requires large energy sources. Current number of instruments is insufficient and produces spatial aliasing. Insensitive to low-velocity layers.	Velocities and transmission properties are closest to duplicating seismic parameters in lab.	Sources: Vibrators to 50 km. Explosives to 100s of km. Earthquakes provide excellent source. Receivers: Three-component 0.5 to 50 Hz. Linear and two-dimensional arrays: 100 to 1,000 instruments. Recorders: FM or digital with wide dynamic range Triggered, programmable, and remote controlled. Small-scale computer adequate for processing.
Reflection, near-vertical incidence	Reflections (primarily P-wave) from impedance boundaries. At angles of incidence >15°, RMS velocities provide estimates of V_P and V_S. Differential frequency absorption related to scattering.	High resolution of laterally inhomogeneous layered boundaries. Statistical methods improve signal-to-noise ratio. Adaptable to three dimensions. Continuity of reflector can infer stratigraphy.	Insensitive to continuous velocity variations. Nonunique interpretation for many layers. Sensitive to noise. Velocity resolution decreases with depth.	Integration of V_P and V_S and reflection strengths leads to prediction of composition and physical properties measured in lab.	Sources: Vibrators: vertical and horizontal. Explosives Receivers: One- and three-component geophones, 5 to 250 Hz. Digital, wide-dynamic-range recorder. Large-scale computers needed for processing.

TABLE 3.1 (continued)

Seismic Method	What Is Measured	Strengths	Weaknesses	Laboratory Impact	Instrumentation Required
Earthquake seismology	Direct and critically refracted P- and S-waves. Measurements require vertical and horizontal seismometers. Travel-time and amplitude variation can be inverted for laterally inhomogeneous structure.	Gives P- and S-wave information. Local earthquakes, rich in high frequencies, give high resolution. Gives three-dimensional structure. Good horizontal and vertical resolution with sufficient ray paths. Teleseisms recorded everywhere; these can be used in areas of no local earthquakes. Possibility of converted phase mapping. Can give stress information. Can be intergrated with refraction and reflection information.	Most current arrays are too sparse for effective use. Limited forward and inverse computational algorithm.	This technique can provide needed velocity-compositions and stress-state information with laboratory correlations.	Digital records optimum. Data are by-product of earthquake arrays. Requires close station spacing for 3-D surveys, $\Delta X < 1/2$ km.
Surface waves	Shear-wave velocities averaged over vertical intervals. Shear anisotropy. Shear Q.	Sources may be distant. Gives average S-wave velocity.	Poor resolution. Little P-wave information. Effects of lateral velocities on surface waves are poorly determined.	Small.	Arrays of instruments 3 to 6 minimum.

REFRACTION AND WIDE-ANGLE SEISMOLOGY

Two-dimensional seismic refraction and wide-angle reflection measurements (together classically referred to as refraction profiling) are among the most important and economical methods for inferring the composition, state, and structure of the lithosphere. As currently practiced, the refraction and wide-angle reflection method involves recording earthquakes and/or explosions along nearly linear profiles or across two-dimensional arrays, generally with single, vertical-component sensors. Explosions are preferred for compressional-wave studies because their time and location of origin are accurately known rather than derived from seismic data, and with a reproducible source, observations can be built up piece by piece. The data consist of seismograms (or event times from seismograms) arranged versus distance from shot (Figure 3.1). As the number of shot points and recorders has increased--from tens to hundreds (in the United States and Europe) to thousands (in the USSR)--the method is showing itself capable of greatly increased resolution. Through multiple profiles or fan-shooting, it lends itself to the rapid isolation of anomalous volumes, essentially the equivalent in the earth of tomography.

Because both refracted and wide-angle reflected arrivals are observed within the same experiment, two separate measures of velocity and depth are, in principle, available: one dependent on Snell's law of refraction, the other on the equality of incident and reflected angles, the law of reflection. The method, while providing about an order of magnitude less resolution of structural details than the normal (narrow-angle) reflection method, is integrative and gives accurate estimates of average velocities of rock bodies. Table 3.2 gives estimated resolution characteristics of various seismic methods. Lateral velocity changes observed in this manner can thus define the subsurface configuration and boundaries between regions with differing histories and compositions.

The Mohorovičić boundary between the crust and mantle--and the details above and to some extent below it, including the Gutenberg low-velocity layer of the upper mantle--has been defined through the observed properties of refracted energy from earthquakes and explosions. Because some discontinuities, especially those that are transitional in nature, are sometimes difficult if not impossible to observe with higher-resolution narrow-angle reflection methods, there is a critical need to integrate the broad spectrum of narrow-to-wide-angle seismic reflections.

Historically, refraction measurements were largely based on the first energy to arrive, which travels via minimum-time Fermat paths. The onset of this energy usually has good signal-to-noise ratios, making for accurate measurement of the arrival time. The travel-time versus range data from these first arrivals can be directly inverted into one-dimensional velocity-depth models, which are good starting models. The data from profiles presented in a record section allow the entire seismogram ensemble to enter into the process of model improvement. Today, synthetic record sections are calculated through complex models and compared with the actual record section, so that the model

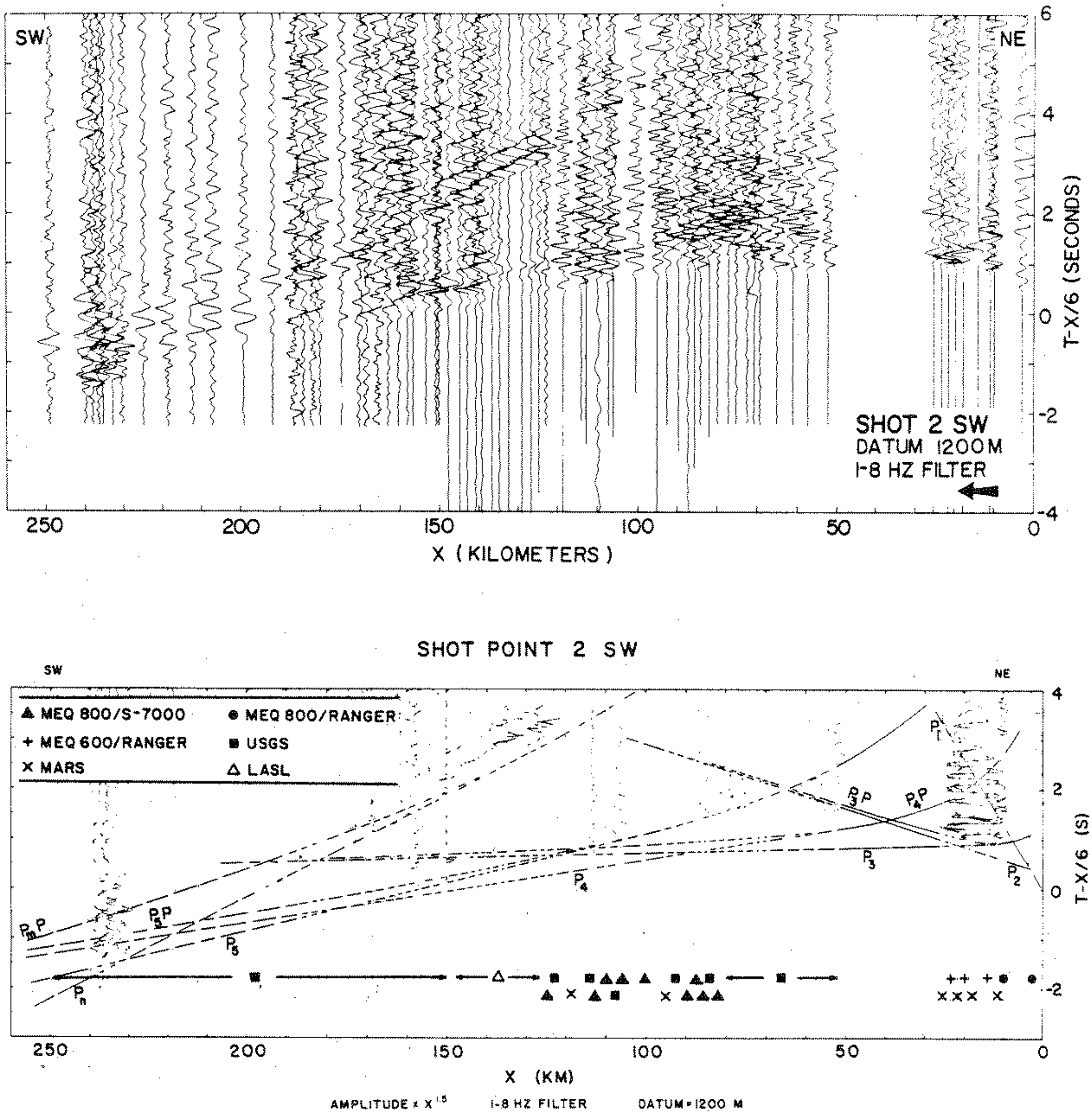


FIGURE 3.1 Record section (top) and interpretation added (bottom), Yellowstone-Snake River Plain seismic refraction experiment. Figures reprinted, with permission, from Baker et al. (1982). © 1982 by the American Geophysical Union.

TABLE 3.2 Resolution Characteristics of Various Seismic Methods

	Vertical Incidence	Wide-Angle	Earthquake Sources	Surface Waves	Laboratory Studies (% accuracy)
Frequency range (Hz)	5-250	1-10	0.5-20.0	0.025-0.5	1-10^6
Differential structures					
P-wave	5 m	500 m	--	--	1%
S-wave	10 m	1,000 m	--	--	1%
Smoothed structure (vertical rays)					
P-wave	100 m	500 m	2 km	--	--
S-wave	100 m	1,000 m	4 km	5 km (V)	--
Smoothed structure (horizontal rays)					
P-wave	1,000 m	2 km	5 km	--	--
S-wave	1,000 m	5 km	5 km	5,000 km (H)	--
Q structure					
P-wave	1,000 m	4 km	3 km	--	25%
S-wave	1,500 m	--	--	20 km (V)	25%
Anisotropy					
P-wave	--	200 km	200 km	--	1%
S-wave	--	--	Undeveloped	100 km (V)	1%

<u>NOTE</u>: V = vertical; H = horizontal.

can be iteratively modified. Furthermore, the ranges and times of the large-amplitude critical reflections are important modeling constraints. Even though they are not first arrivals, they are often the largest arrivals on the seismogram and are easily identified on the record section, since they decay less rapidly beyond the critical point than does the associated refraction. In addition, both time offsets and abrupt amplitude changes within the record section signal lateral structural changes. Through iterations using inhomogeneous ray-tracing procedures, very complex structural models can result. With velocity providing compositional and density bounds, the model can be checked against geologic data as well as against the powerful averaging properties of gravity and seismic surface-wave data.

Two-dimensional array observations, providing a three-dimensional look at the earth, must increasingly replace profiling for research on the more complex problems of continental evolution. As for profiling, the seismograph spacing within an array must be dense enough to sample the entire wavefield appropriate to the problem (especially if earthquake sources are to be employed; see section below on "Natural Sources.")

Historical Summary

Refraction and wide-angle reflection studies of continental structure have been actively pursued in this hemisphere since 1942. Large-scale seismic refraction profiling was pioneered in the United States by the Carnegie Institution of Washington and the University of Wisconsin (Tatel and Tuve, 1955; Steinhart and Meyer, 1961), followed in the 1960s by the U.S. Geological Survey (Pakiser, 1963). The earliest experiments were done with isolated single- or three-component seismographs at spacings of tens of kilometers. The most advanced instruments deployed during this time and into the 1970s were seven-channel FM-recording seismographs with cable-linked individual seismometers that formed linear subarrays; gaps between subarrays were as much as tens of kilometers. Each seismograph typically serviced five vertical seismometers at 1/2-km spacing, and two horizontal seismometers. Profiles were usually hundreds of kilometers long, with repeated explosive sources, often in lakes, at the ends of the profile and less commonly at one or two intermediate points. Repetitions of explosive charges at the same point were required because of the lack of recording equipment. Nuclear test explosions were taken advantage of, especially for profiling at great ranges, but they were a difficult source to employ because of uncertainty and sometimes secrecy of test schedules.

Results of all these early uses of the method showed that although the crust was heterogeneous as shown by scatter of arrivals with range, parameters such as average crustal thickness, upper mantle velocity, and average crustal velocity correlated well with broad-scale tectonic features (tens of kilometers). Correlation with the regional gravity field and in some cases broad-scale magnetic anomaly patterns was excellent, but correlation on a smaller scale (less than 10 km) with geologically mapped structures observed at the surface was not as good. The low correlation and lack of resolution are related directly to the lack of sufficiently closely spaced seismometers and shots as well as to analysis techniques which at that time did not allow modeling of wave paths through laterally inhomogeneous media.

At about the same time, the Soviets were developing the Deep Seismic Sounding (DSS) method for crustal studies (Figure 3.2). Soviet investigations coupled determination of crustal structure with exploration for minerals and petroleum, which involved essentially

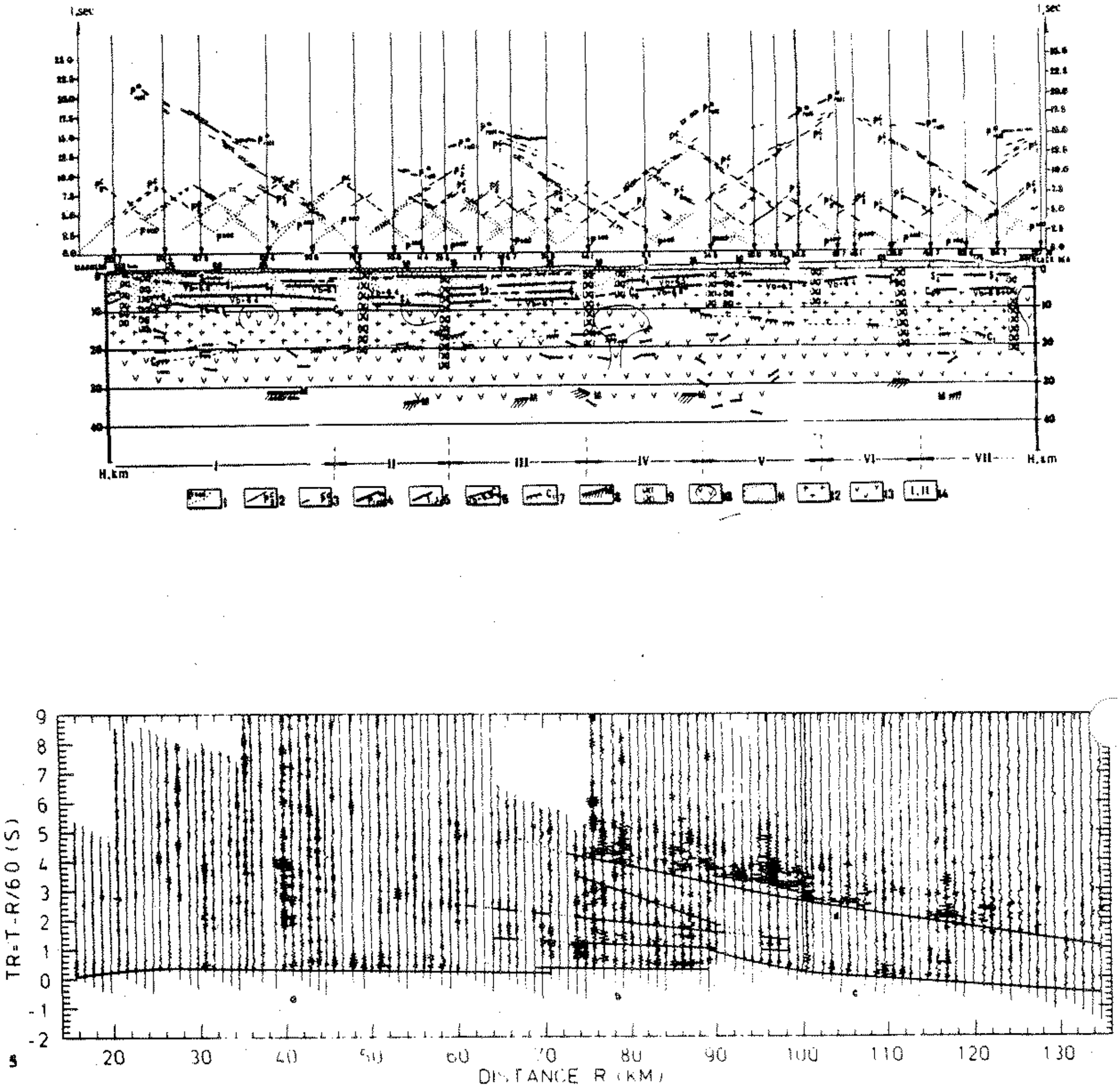


FIGURE 3.2 Soviet Deep Seismic Sounding sections. Top, reprinted, with permission, from Kosminskaya (1971); © 1971 by Plenum Publishing Corporation. Bottom, reprinted, with permission, from Jentsch (1979); © 1979 by Springer-Verlag.

simultaneous study of the underlying crystalline rocks and overlying sediments by a common method that could do both. In the DSS experiments, refraction profiles to distances of up to several hundred kilometers were used. Matched seismographs, with sensors as close as 0.1 km and shot points every 3 to 15 km, provided a densely sampled data set amenable to geologic interpretation, usually down to and including the Mohorovičić discontinuity. Neither U.S. nor European seismologists have achieved such comprehensive coverage.

In the mid-1960s, the European Seismological Commission established a working group that developed a standard FM-recording, programmed turn-on, three-component seismograph, and made long-range plans for coordinated experiments, usually profiles using widely separated explosions. Universities in most European countries each have a number of these instruments, and as many as 125 units can now be deployed simultaneously. About 100 lithospheric profiles have been collected in Europe, including a few that approach DSS in closeness of seismometer spacing.

Programs in the United States benefited from the oil industry's early interest in refraction and from the similarity of equipment needed for refraction and reflection profiling. Although industry interest has largely focused on reflection techniques, the refraction profiling method has continued to be employed in special geologic investigations. In the academic community the modest logistic requirements of at least the smaller-scale refraction experiments have continued to make the method attractive.

Current Practices and Future Plans

Experiments using dense recording arrays are showing the value of increased resolution; the results imply that the least number of sampling points for almost any refraction investigation probably should be increased by about an order of magnitude over the current common practice (typically 12 to 24 seismometers simultaneously observed). If, as we shall consider, seven-channel portable digital seismographs are to be made standard for minimization of cabling and maximization of flexibility, 120 to 240 seismometers and 17 to 35 seismographs will normally be required for refraction experiments if the higher-resolution benefits are to result. Refraction and wide-angle measurements, as with any other seismic measurement, should be made only with sufficient seismographs to avoid spatial aliasing and to record the wavefield simultaneously across the entire area of relevance to the problem if nonrepeatable sources such as earthquakes are to be employed. Full lithospheric investigations using earthquakes, the only practical source for shear-wave investigations, will probably require arrays of greater than 50 km and sensors at less than 1/2-km spacing.

Modern refraction methods serve as a natural partner to normal-incidence higher-resolution reflection methods by providing regional coverage that efficiently separates major changes from minor detail and is capable of providing continuous coverage at crust-mantle depths. Currently, refraction and wide-angle reflection measurements are receiving increasing industry use in regions where volcanic rocks overlie and conceal potentially petroliferous sedimentary basins and narrow-angle reflection methods are unsuccessful. Finally, they are also currently being increasingly used for estimating the extent of magma intrusions underlying crustal rifts, volcanoes, and calderas for the practical purpose of locating geothermal heat sources.

An example of modern seismic refraction techniques is the experiment recently completed in the Yellowstone-Snake River Plain volcanic province of the western United States (Smith et al., 1982). This cooperative seismological experiment involving 11 U.S. and 2 European universities, 2 government laboratories, and 2 oil industry companies brought together 225 single- and three-component seismographs of various types to observe 19 shots; seismometer spacings averaged 3 km. The experiment showed that seismic refraction and wide-angle reflection information can be recorded (Figure 3.3) to delimit features of 4 to 200 km in extent as one should expect from the interval between seismometers.

In a geologic sense, the data showed (1) a thinning of the surface rhyolite-basalt layer toward the Yellowstone volcanic plateau; (2) a thickening of the upper crustal granitic layer toward Yellowstone; (3) an approximately 10-km-thick upper crustal low-velocity layer with a 10 percent reduction compared to the thermally undisturbed rock; (4) a small body with a 30 percent reduction in velocity as discussed in Chapter 2; (5) the presence of an anomalous intermediate crustal layer (6.5 km/s) that appears to be the source of the silicic volcanic rocks; and (6) the presence, at this scale of resolution, of a seismically homogeneous lower crust. Three-dimensional interpretation of the data revealed tectonic features such as batholithic-scale intrusions and crustal low-velocity bodies associated with silicic centers of volcanism at spatial scales of a few kilometers (Figure 3.4).

Another recent example, in this case using matched seismographs, is the USGS experiment in the Imperial Valley. Since 1976 approximately 100 matched, programmable, FM-recording seismographs have been used by the USGS. Their work, usually using vertical seismometers recorded at three gains because of the small dynamic range of FM systems, has been successful in areas where vertical reflections have been difficult or impossible to record. In the Imperial Valley experiment, 40 shots were fired at seven shot points, each shot recorded by 100 portable seismographs--in critical areas at less than 1/2-km spacing along profiles (Figure 3.5). The region crossed by the profiles is laterally heterogeneous, so iterative ray tracing was used to derive two-dimensional models. Resultant three-dimensional views (Figure 3.6) provide both an integrated picture of the structure of the valley and clues to the evolution of the extensional Salton Trough. The sedimentary section in the center of the trough, roughly 5 km in depth, is characterized by a strong velocity gradient due to overburden pressure. A major discovery was that the basement in the trough consists of two distinct types of rocks, metasediments (V_P = 5.65 km/s, density = 2.65 g/cm^3) and granites (V_P = 5.9 km/s, density = 2.75 g/cm^3).

The relationship between the surface geology, including major fault motions, and the crustal structure of the Salton Trough are discussed

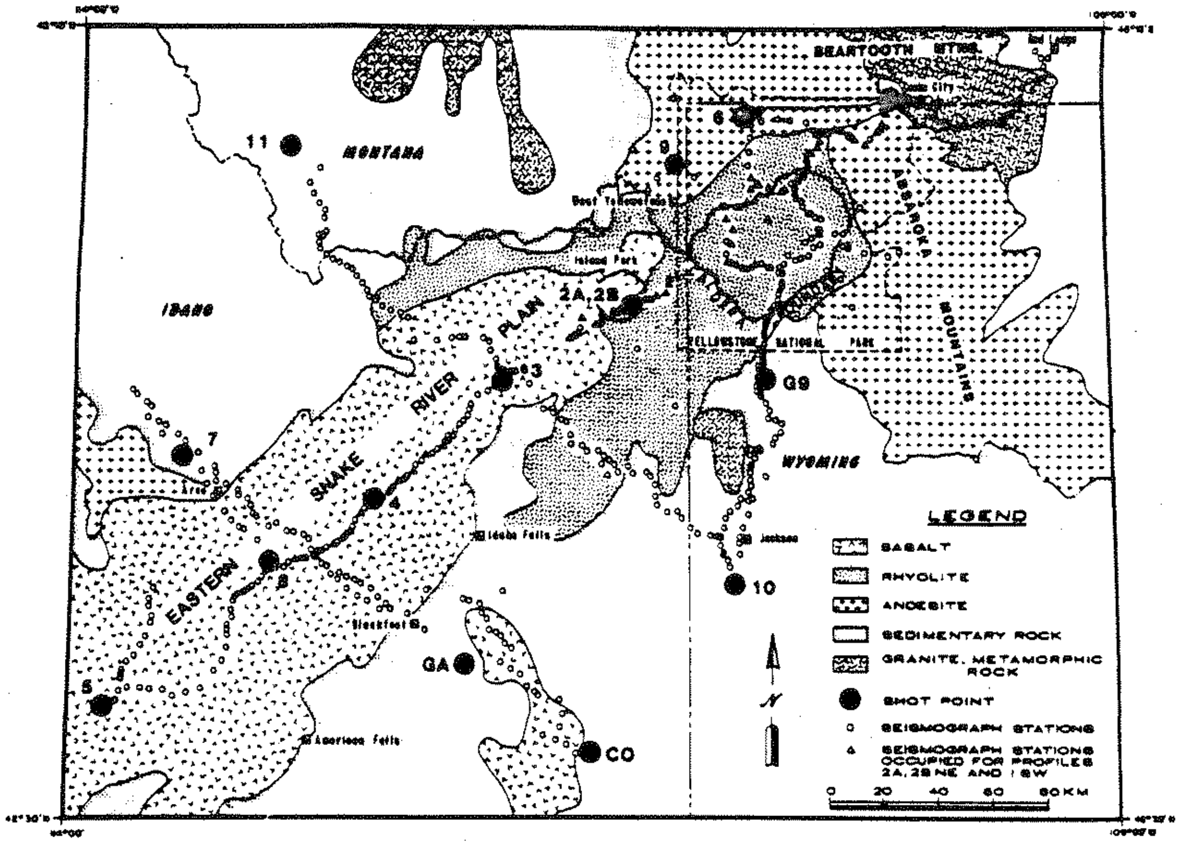


FIGURE 3.3 Index map for 1978 Yellowstone-eastern Snake River Plain seismic experiment. Shot points are indicated by solid circles. Reprinted, with permission, from Smith et al. (1982). © 1982 by the American Geophysical Union.

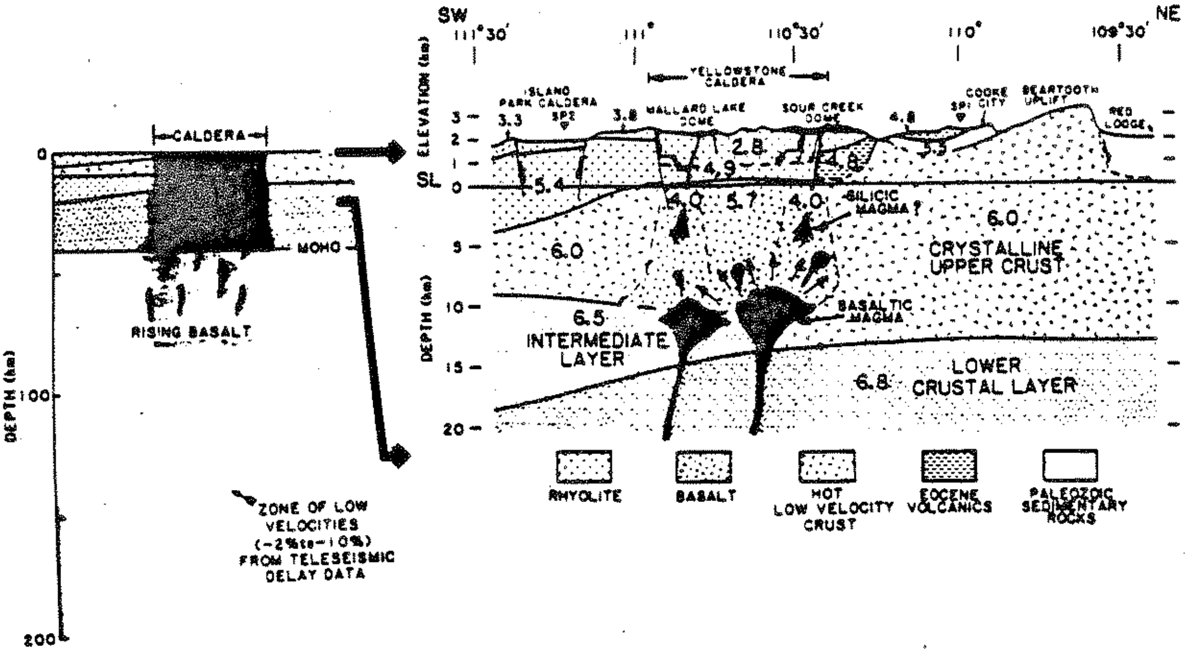


FIGURE 3.4 Idealized NE-SW geologic-seismic velocity model for the crustal structure of the Yellowstone-Island Park-Snake River Plain region. P-wave velocities are in km/s. Reprinted, with permission, from Braile et al. (1982) and Smith et al. (1982). © 1982 by the American Geophysical Union.

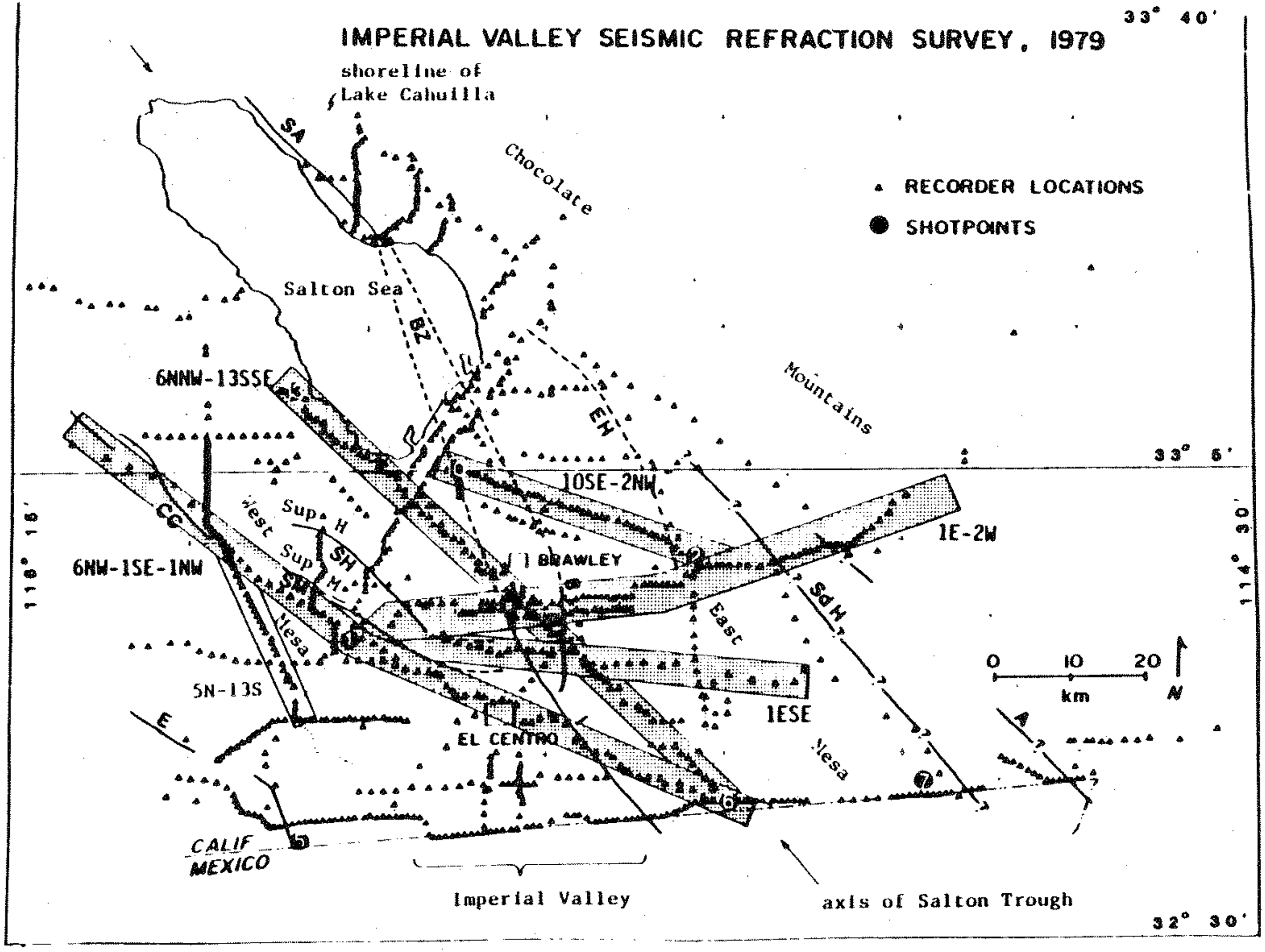


FIGURE 3.5 Location map for Imperial Valley refraction experiment. From Fuis et al. (1983).

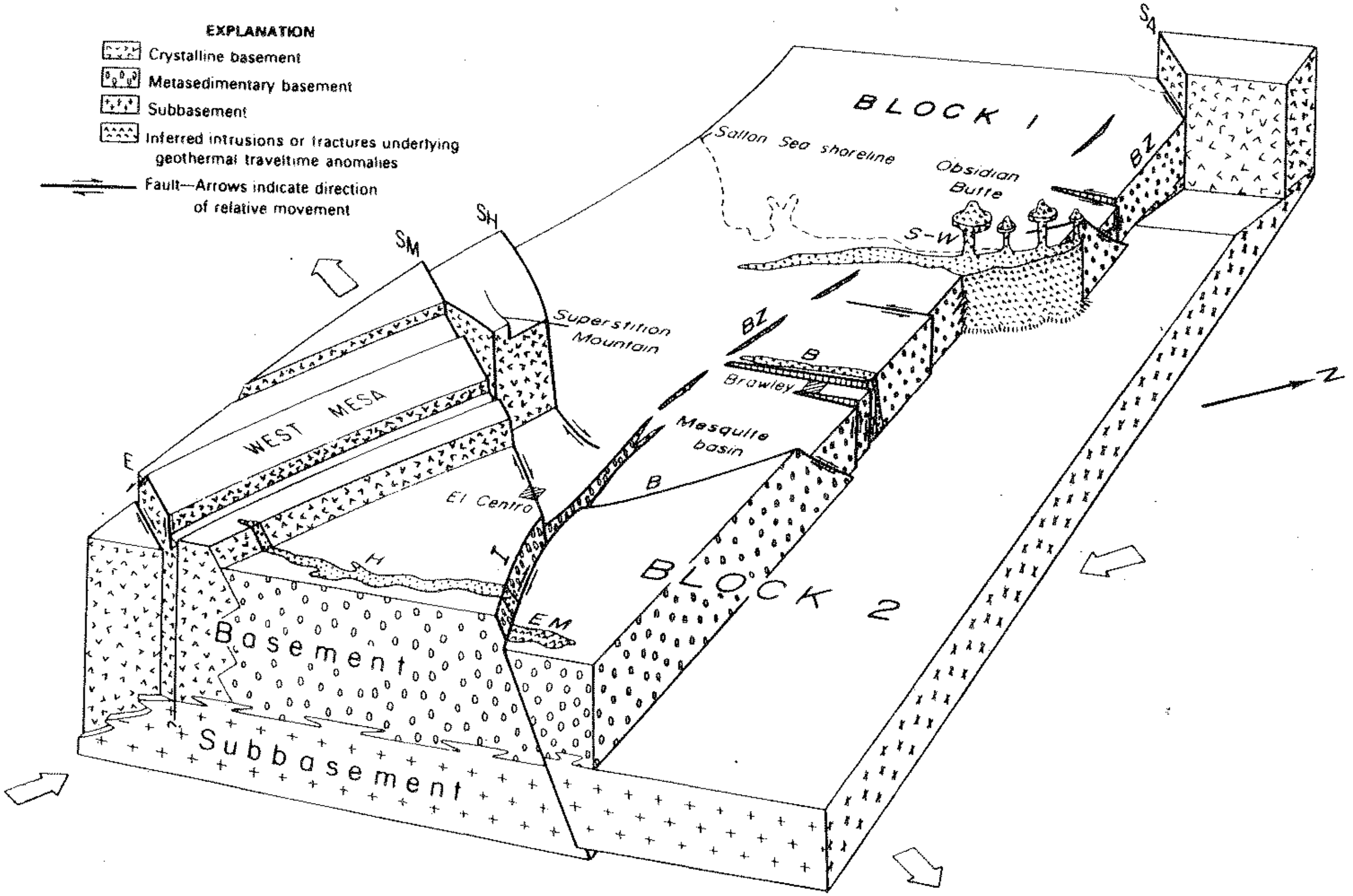


FIGURE 3.6 Three-dimensional interpretation of Imperial Valley structure. From Fuis et al. (1982).

by Fuis et al. (1981). A complex model fitting the seismic refraction data, the gravity, and the geologic and tectonic framework is shown in Figure 3.6 (the sediments have been removed for the model).

REFLECTION SEISMOLOGY

Reflection surveying is essentially an echo-sounding technique (Figure 3.7). Elastic waves generated at the surface propagate downward into the earth, are reflected by discontinuities in the elastic properties of rocks, and then travel back to the surface to be recorded and analyzed. The seismic reflection method, with the highest structural resolution of any geophysical technique, was developed primarily for oil and gas exploration and is the mainstay of that industry. Reflection crews now routinely operate in virtually all marine and land environments.

While all branches of seismology have critical contributions to make to an understanding of the continental lithosphere, the potential of reflection profiling seems particularly exciting for exploration aimed at structural relations. Although the proper interpretation is not always straightforward, seismic sections bear a striking resemblance to geologic cross sections and help to bridge the gap between seismologists and geologists.

Refinements in the seismic reflection method in recent years have led to widespread interest in seismic stratigraphy, a new field of science that merges traditional principles of stratigraphy into the analysis of seismic sections (Figure 3.8). By identifying stratigraphic sequences, bounding unconformities, diagnostic reflection characteristics, and morphologic form from seismic data, the interpreter can deduce much information on the depositional environment and composition of sedimentary rocks. Vail et al. (1977) have used seismic stratigraphic principles and the vast inventory of oil exploration reflection data to deduce an intriguing history of global sea-level change.

Another trend for stratigraphic studies is toward higher resolution in order to define thinner geologic beds (Figure 3.9). By using higher frequencies (although limited by transmission properties in the earth), seismologists can distinguish vertical separations on the order of a few meters. This capability suggests a number of shallow applications, for example, in engineering geology, that have not yet begun to be exploited.

Although the geometrical and stratigraphic aspects obvious on a reflection seismic section are the most commonly used attributes, much more information can often be gleaned. For example, an intrinsic part of analyzing reflection recordings is the determination of seismic velocities. At the present time, sophisticated procedures are commonly used to map variations in the seismic velocity between selected reflecting horizons, and these variations serve as a guide to the intervening lithology. Another example of advanced information extraction is the inversion of the seismic section to obtain an estimate of reflectivity structure. Amplitude and frequency variations of deep reflections can also provide estimates of attenuation within the crust.

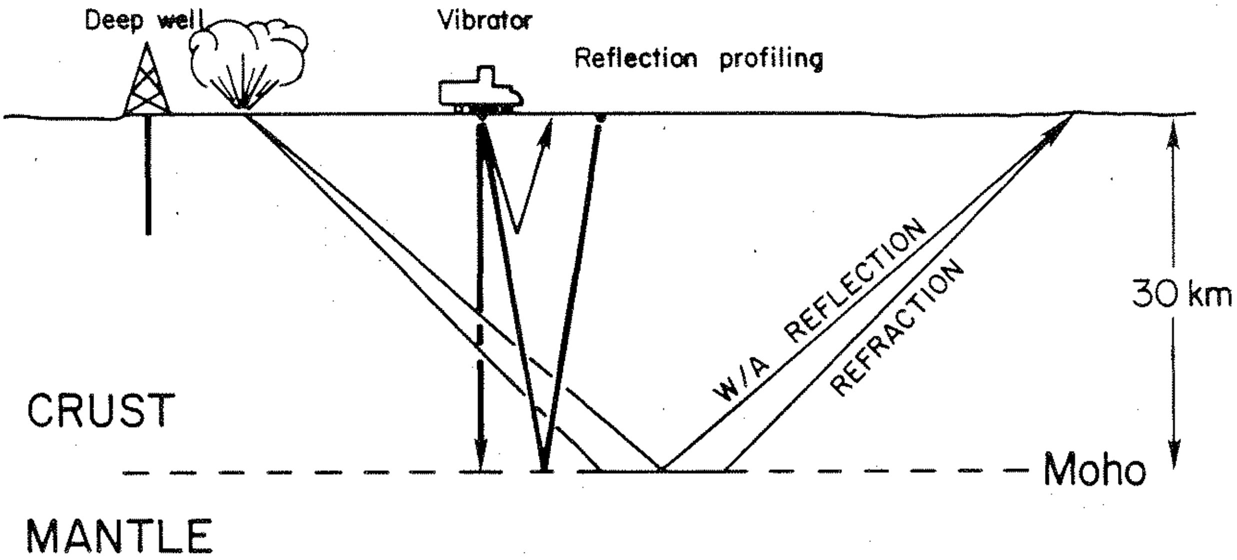


FIGURE 3.7 Schematic diagram of relationship between reflection profiling, wide-angle reflection, and refraction.

Recent years have seen the maturation of shear waves as a new tool to map velocity and attenuation in the crust. Although most reflection work is still done with compressional waves, shear-wave surveys are now considered a practical option, and they yield additional information. For example, shear waves are sensitive in ways different from compressional waves to the anisotropy and fluid content of rocks.

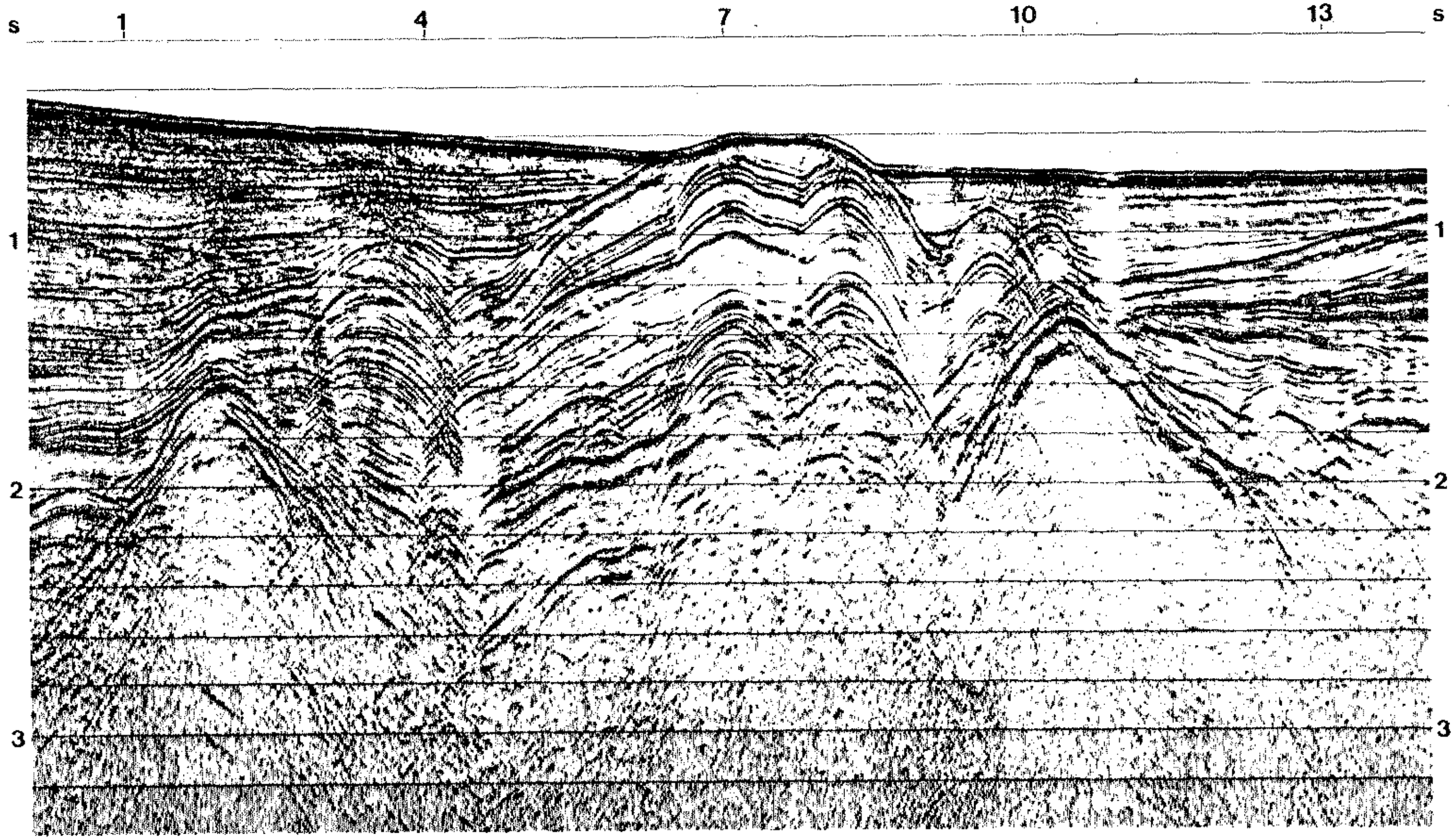
Most reflection data have been acquired by surveying in a linear fashion, e.g., profiling. The result is a two-dimensional image representing a vertical slice through the earth. With the advent of more powerful computers and hardware capable of recording hundreds of channels simultaneously, three-dimensional (3-D) seismic imaging of the subsurface is now practical (Figure 3.10). In spite of the tremendous processing requirements, 3-D reflection imaging will undoubtedly be one of the fastest-growing aspects of seismic exploration.

Much of the success of the reflection method lies in the sophisticated data acquisition systems and computer processing techniques that allow the discrimination of the very weak reflection signals from various types of noise and the display of them in a format readily interpreted in geologic terms. Specialized computers and programs are needed to process the large volumes of data recorded in a reflection survey, and the trends toward 3-D and interactive analysis are pushing the requirements for computer power to new heights. Perhaps the most important advance in improving data quality is the development of the common reflection point (CRP) technique, in which multichannel instrumentation is used to record multiple reflections from the same subsurface point along systematically varying ray paths. When the signals from these ray paths are aligned by appropriate geometric corrections, they can be summed, or "stacked," to improve signal at the expense of noise. The current trend is toward more channels (1,024 are now routinely available) and higher redundancy, or stacking fold. The 3- and 6-fold stacks common in the early 1960s have given way to routine 24- and 48-fold geometrics, with up to 512-fold possible with available equipment.

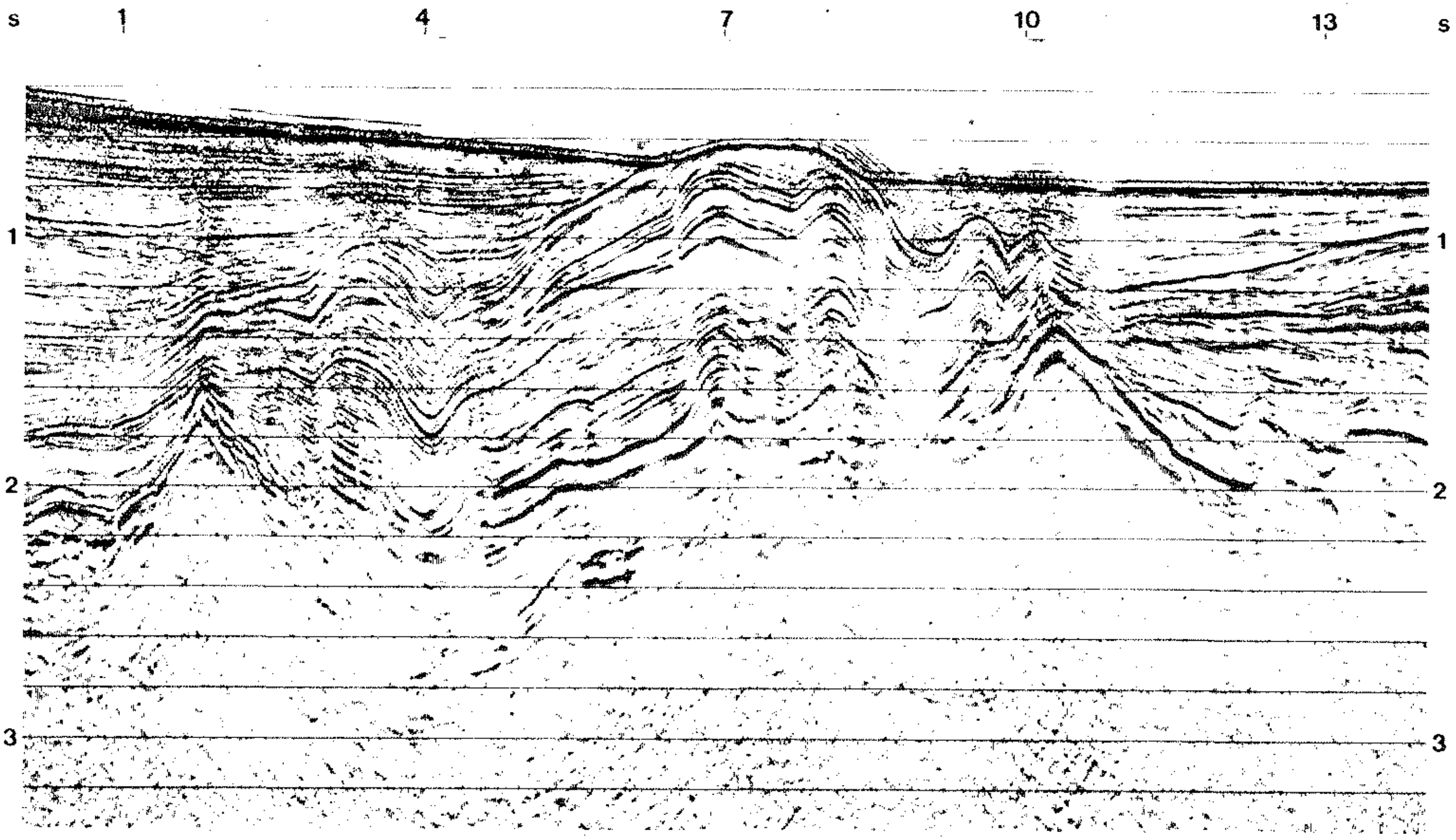
The hardware used in such recording has either inspired or applied the latest digital technology. Analog transmission lines are giving way to digital telemetry, both wire- and radio-linked; one new system has replaced the telemetry wire with fiber optics. Many contractors offer on-site processing capability for the ultimate in data feedback. Dynamite, although still extensively used, has been replaced in many sensitive environments by more flexible and less hazardous sources, such as Vibroseis (TM CONOCO) on land, and air guns in the ocean. Multichannel recording systems range from the massive outfits necessary for 3-D imaging, involving hundreds of recording stations, dozens of men, and a score of support vehicles, to portable systems that can be backpacked into the most rugged terranes.

Several aspects of seismic reflection profiling, as it is currently practiced in the United States, set it apart from complementary seismic methodologies:

1. Reflection technology has been developed and is heavily supported by the oil exploration industry. Thus, state-of-the-art



Stacked time-section of an offshore California profile. Reflector dips do not exceed about 25°. The horizontal scale is in miles.



KIRCHHOFF-SUMMATION migration. The complex of interfering diffractions in the top figure has been resolved into a geologically plausible section showing tight folding and faulting. No muting of traces above the water bottom has been used in these examples so that the higher level of "migration noise" generated by the KIRCHHOFF-SUMMATION method can be seen.

FIGURE 3.8 Example of migration. Reprinted, with permission, from Western Geophysical (1975). © 1975 by Western Geophysical.

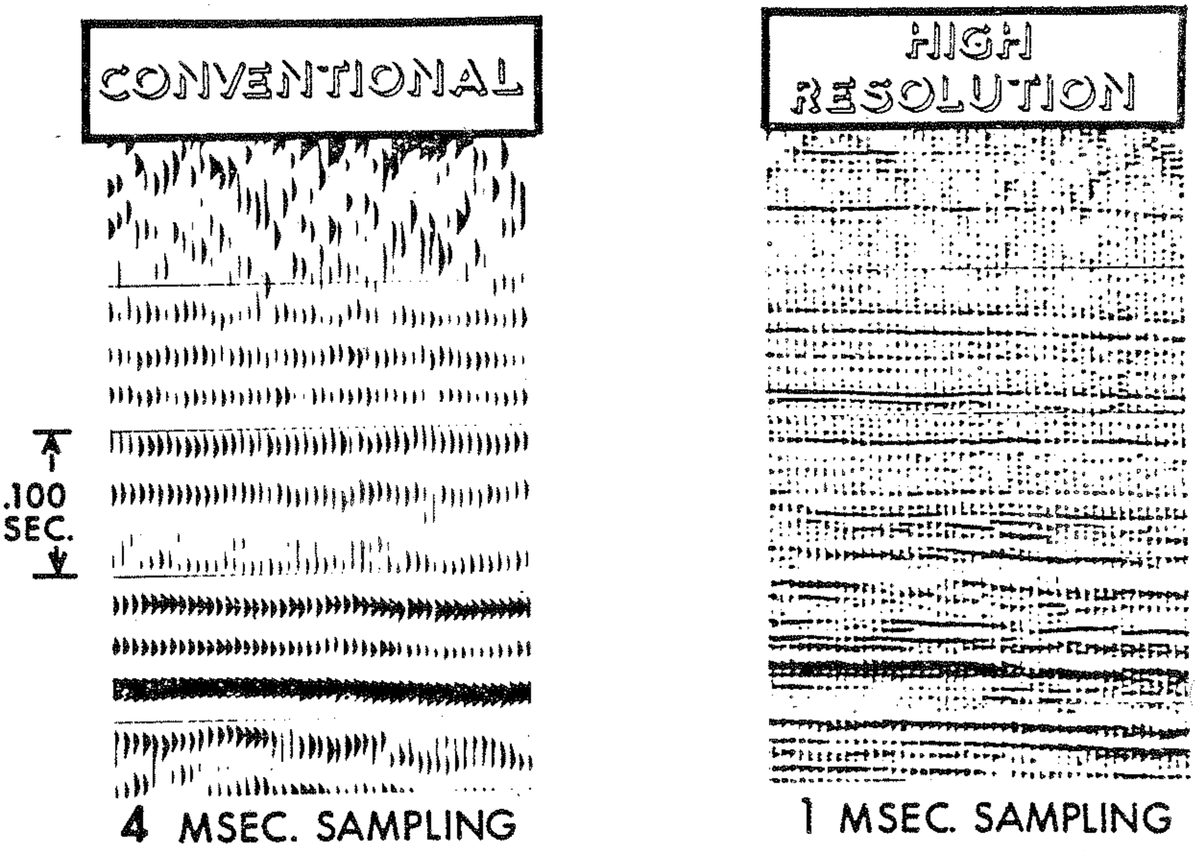


FIGURE 3.9 Comparison of a conventional recording (4-msec sampling) with its high-resolution counterpart sampled at 1 msec. Note the sharp delineation of events so characteristic of the higher and broader frequency content of the high-resolution section. In both displays the ground position and type of receivers were identical. Reprinted, with permission, from Stommel and Graul (1978). © 1978 by John Wiley & Sons, Ltd.

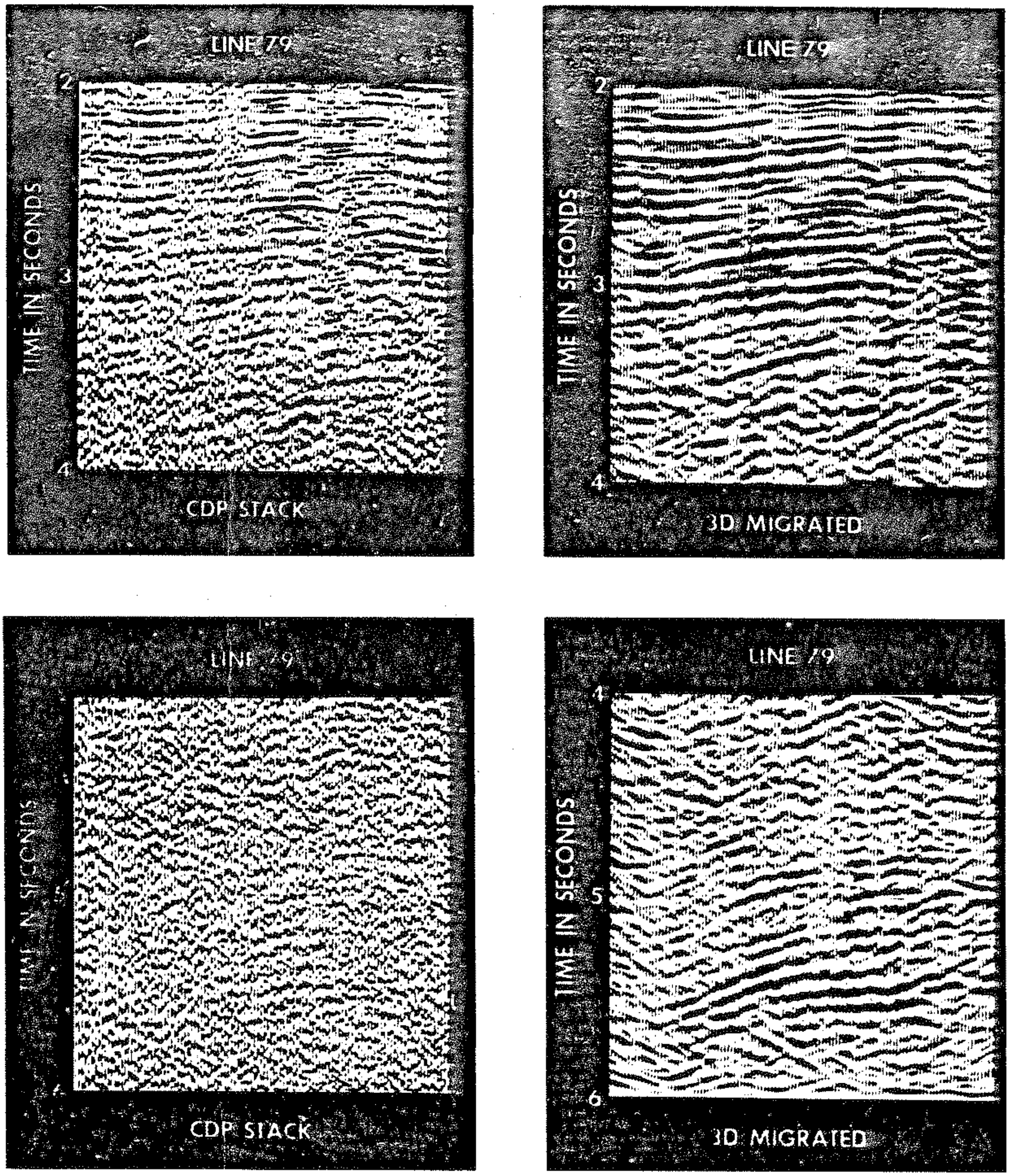


FIGURE 3.10 Improvement of CDP stack display as a result of 3D Migration Stack. The zones most improved are located in the time gate of 4.0 to 6.0 s. Reprinted, with permission, from Bone (1981). © 1981 by Offshore Technology Conference.

field equipment, computers, and programs are available off the shelf. Formats for data exchange and processing are standardized.

2. Results of reflection surveys, whether industrial or academic, are usually presented in a format that is easy for earth scientists in other fields to understand, in that the seismic section is similar in many respects to a geologic cross section.

3. The cost of collecting and processing modern multichannel reflection data on land is usually greater than for other seismic techniques because of the density of recorded data. Capital outlays necessary for modern reflection equipment are high, so that few university research groups can sustain an independent program in reflection seismology.

The reflection method has proven applicable to a wide range of other geological problems apart from locating hydrocarbons in sedimentary basins, and is becoming increasingly important in imaging the crystalline crust. In the United States, for example, reflection surveys carried out on land by the Consortium for Continental Reflection Profiling (COCORP), conducted from Cornell University; U.S. Geological Survey; Virginia Polytech Institute; University of California, Berkeley; University of Kansas; University of Wisconsin, Madison; University of Wyoming; Colorado School of Mines; Princeton University; and various other university groups have provided new insight on a variety of tectonic problems. Several oceanographic institutions, such as Woods Hole Oceanographic Institution, Lamont-Doherty Geological Observatory, Scripps Institution of Oceanography, and the Marine Science Institute at the University of Texas at Galveston, operate major marine reflection programs. Results from land and sea are proving to have far-reaching ramifications for our concepts of lithospheric structure and crustal evolution.

The largest academic application of reflection seismology is the research effort directed by the Consortium for Continental Reflection Profiling. Based at Cornell University, COCORP directs the year-round program to explore major structures in the North American continent using an industrial contract reflection crew with slightly modified recording equipment. COCORP differs from normal oil exploration activities by looking much deeper and in crystalline geologic terranes that have not previously been explored with reflection techniques.

Begun in 1975, COCORP has profiled almost 4,000 km in 15 areas of the United States and has planned a transcontinental network (Figure 3.11). Major scientific results include the following:

1. Revealing the intrinsic heterogeneity of the continental crust with a resolution not previously available, and mapping complex lateral variations.

2. Mapping the deep geometry of major thrust faults in several orogenic systems, thus solving longstanding problems of thrust tectonics. Such surveys have confirmed the compressional origin of key Laramide foreland uplifts (Figure 3.12) and discovered that the crystalline Appalachians are an enormous allochthonous thrust. This latter finding, in particular, has had a profound impact on theories of

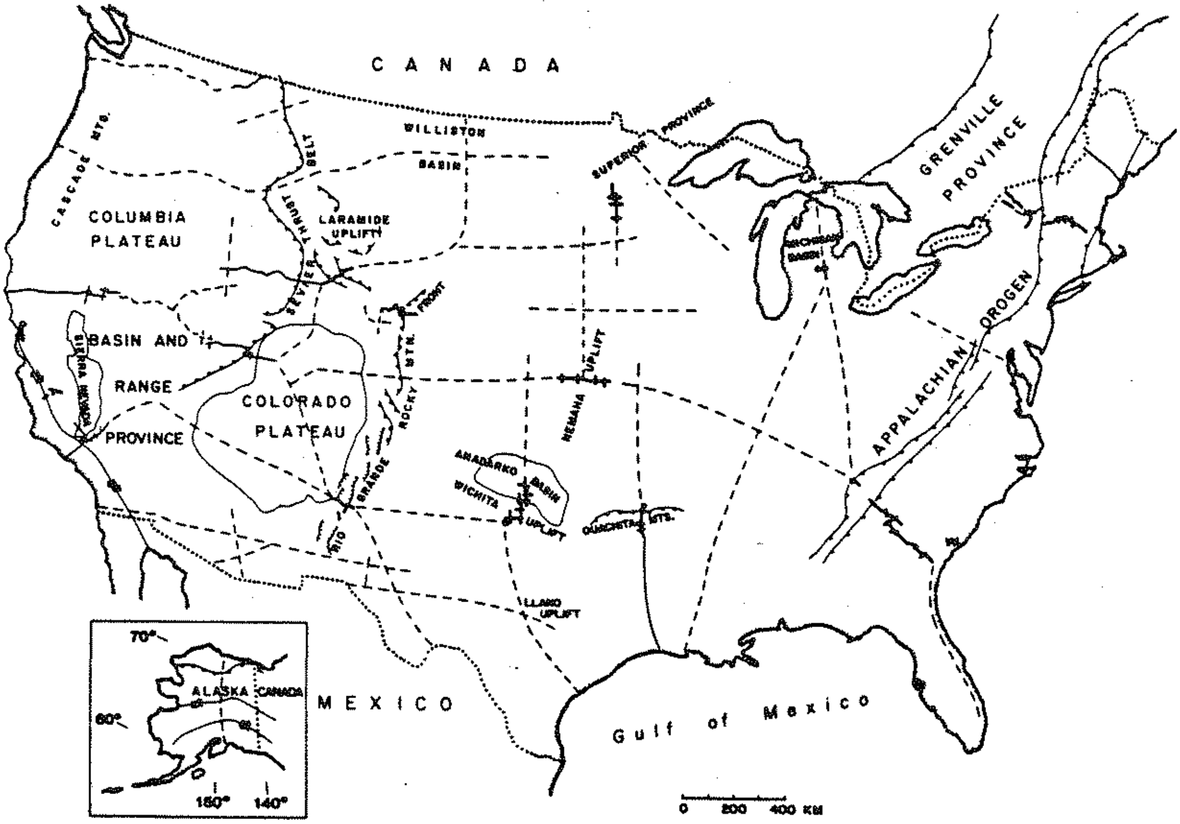
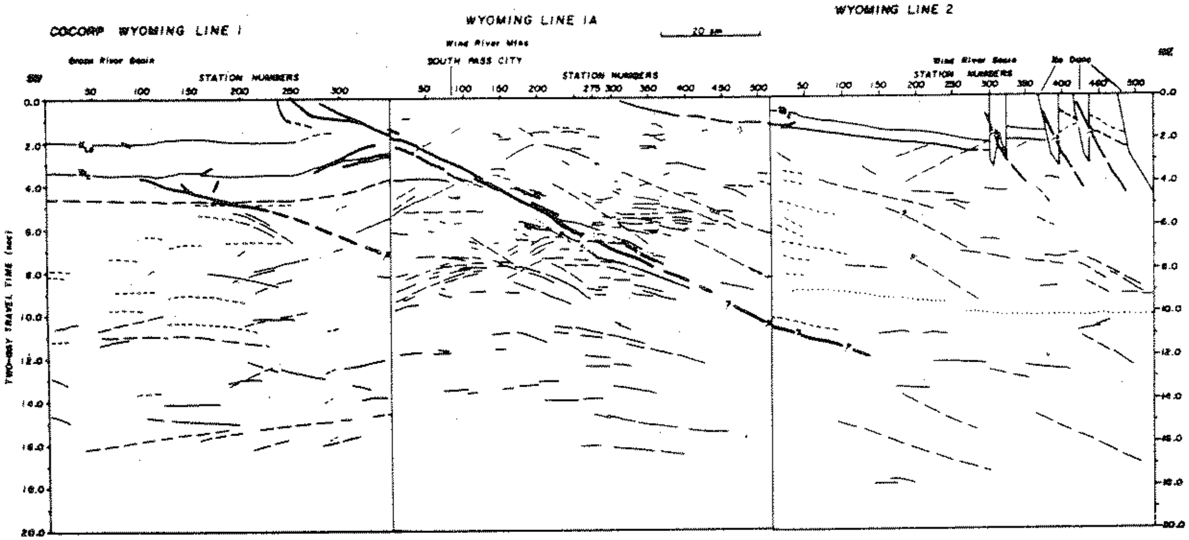


FIGURE 3.11 Map showing COCORP surveys completed (heavy solid lines), planned for near future (light solid lines), and planned schematically for the long term (dashed lines).



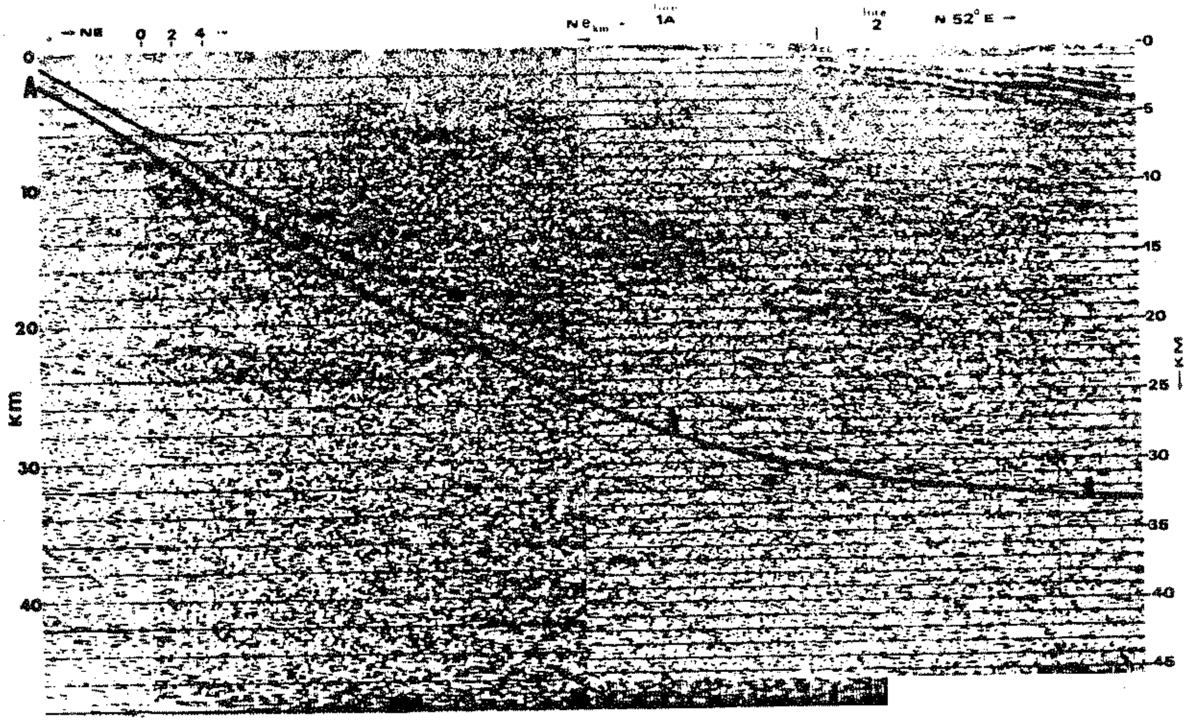


FIGURE 3.12 Top: line drawing of time section taken from Wind River COCORP lines, showing Wind River thrust fault. Reprinted, with permission, from Smithson et al. (1979). © 1979 by the American Geophysical Union. Bottom: migrated depth section of Wind River thrust fault from the same data. Reprinted, with permission, from Lynn et al. (1983). © 1983 by The Geological Society of America.

orogensis and crustal evolution, as it suggests that "thin-skinned"-style overthrusting is an important mode of continental accretion. Implications of such a model include new means of transporting water into the lower crust and a new perspective with which to evaluate the hydrocarbon potential of areas previously "written off." COCORP data have also confirmed that the Wichita Uplift overthrusts the Anadarko Basin, and that the Ouachita Mountains are allochthonous in a manner similar to the Appalachians.

3. Outlining the geometry of continental rifts. COCORP data from the Rio Grande Rift in central New Mexico, across the buried Keweenawan Rift in Kansas and Michigan, across a Triassic graben in the southeastern coastal plain, and most recently across the eastern Basin and Range province of west-central Utah suggest that continental rifting often proceeded along low- to moderate-angle faults, and sometimes involved reactivation of preexisting thrust structures. The Utah data illuminate structures resting upon a master detachment fault tracable over 120 km laterally from the surface to depths of about 20 km. The Rio Grande Rift surveys mapped an active magma chamber at midcrustal depths that had previously been indicated by S-wave data (Sanford et al., 1977).

4. Discovering what is inferred to be an extensive Proterozoic basin buried beneath Paleozoic strata in southern Oklahoma and northern Texas and an unusual layered complex beneath the Adirondack Mountains.

Such a list is not meant to be exhaustive, nor to reflect the debates about interpretation that have arisen in the wake of such important findings, but the list does serve to demonstrate that breadth of the potential contribution that reflection seismology can make to lithospheric exploration.

One aspect of crustal reflection profiling deserves further comment. The most immediate, and therefore dramatic, findings have usually centered on a few key reflections that can be identified by correlation with surface structure or through geological analogs. However, most deep-seismic data are characterized by numerous reflectors that may never be specifically identified in terms of geological formations. Their significance is unlikely to become apparent until a sufficient amount of data, a critical inventory, so to speak, is amassed and the appropriate comparative analyses are made. In this sense, the value of the overall inventory is likely to increase considerably faster than the rate at which new reflection profiles are collected.

The initial steps of a global effort are already underway. The COCORP success has helped to instigate seismic reflection programs in other countries. Major projects emphasizing deep-seismic reflection profiling are in progress or planned in Canada (LITHOPROBE and COCRUST), Great Britain (BIRPS), Germany (DEKOR), France (ECORS), Australia (ACORP), and China. Interest in such work has been expressed by scientists in Saudi Arabia, Israel, Brazil, and Argentina. With adequate support and multinational cooperation, these various projects could establish a global network of deep-seismic reflection surveys. Figure 3.13 represents a hypothetical plan for global reflection

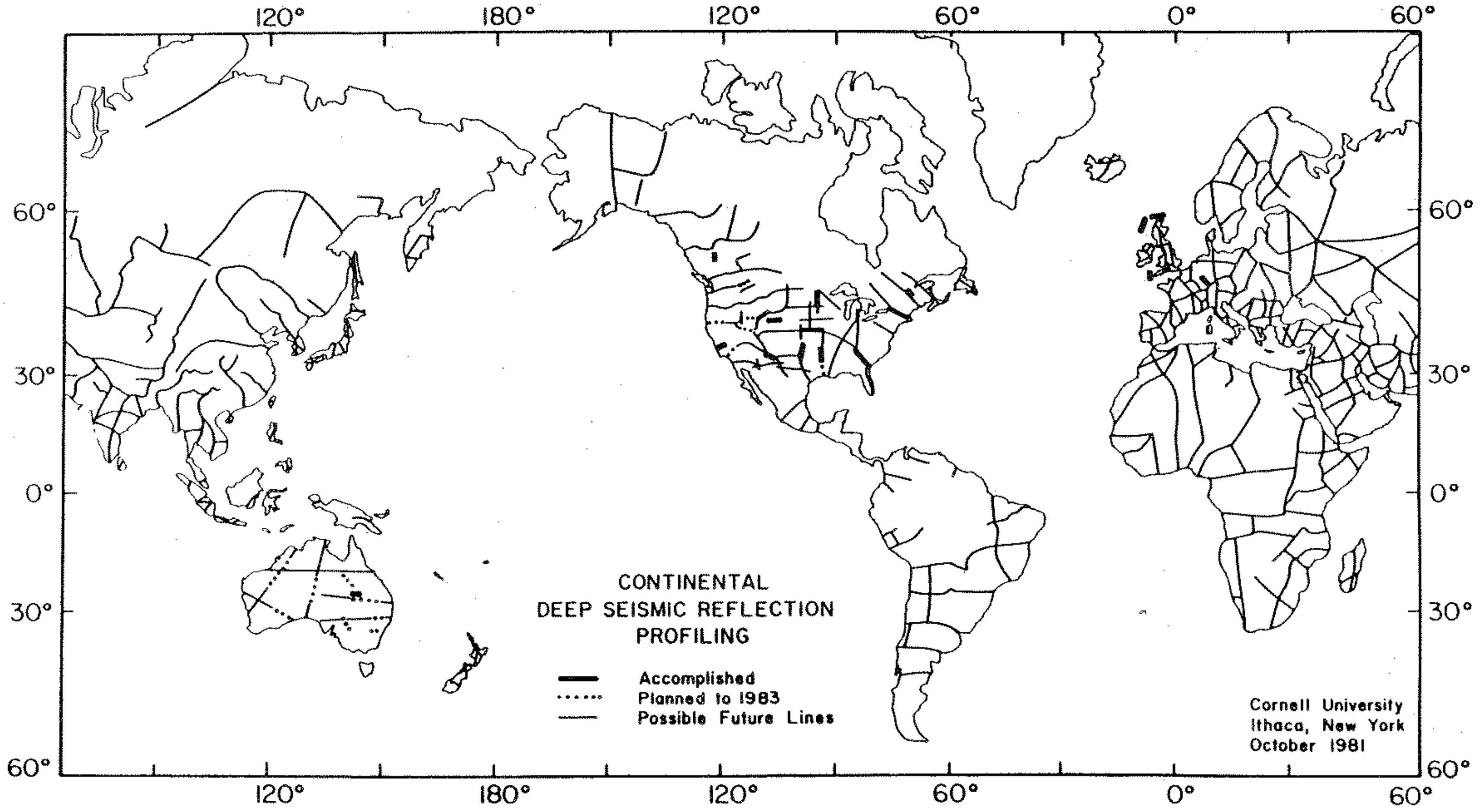


FIGURE 3.13 A hypothetical plan for continental deep-seismic reflection profiling on a global basis. Reprinted, with permission, from Oliver (1982a). © 1982 by the American Geophysical Union.

profiling, prepared to stimulate thought on this subject. It is not an actual plan at this stage. That such a proposal is not completely unrealistic is shown in Figure 3.14, which represents the continental coverage equivalent to the total length of seismic reflection profiles carried out by the petroleum industry on land in 1980.

> In view of the vast tracts of continental lithosphere to be probed by reflection profiling, the demonstrated success of the technique, and the growing international momentum toward a global program of scientific reflection profiling, we recommend that the rate of research reflection surveying by university and government groups be accelerated. We feel that the best way to carry out large-scale reflection field work is through commercial contracting.

DIFFRACTION

The properties of reflected and refracted energy for imagery are well known, but those of diffracted energy, which arises as a consequence of abrupt dislocations in the media, have not been so fully exploited. Diffractions are widely used for the recognition of faults and for velocity analysis. However, most seismic measurements are made with the idea that interfaces are locally planar. Transferring the concept that reflectors are the preferred information source to common daily experience, we would find that observing the reflected rays from a mirror does not give much information about the mirror, but does give information about the source. Indeed, to look for mirrors, we look for reflected images of the source, and in the seismic analogy, an experiment is regarded as a success when time-delayed replicas of the signal transmitted are received.

In personal experience, we perceive the color, texture, and shape of all kinds of surfaces and objects via diffracted light, whether that light comes from a single source or from many. Seldom seen are images of the source in the process. Returning to the seismic problem, reflections are usually regarded as signal, and scattered energy as noise. The questions entertained here are "How much of the subsurface is not mirrorlike?" and "Should energy returned from nonmirrorlike surfaces be regarded as the desired signal?" (Figure 3.15). Side-scanning sonar records, COCORP data, and local earthquake coda all give indications that geologic volumes have many regions with dislocations, and these are exactly the regions where the orderly physical processes of reflection and refraction break down--the no-record areas. We suggest that diffraction is the process of choice for finding and describing these zones. The study of rough interfaces requires a different approach to analysis from that for reflections or refractions. For example, we can observe each diffracting point from an infinite number of perspectives. Unlike a common reflection point, a diffraction point can provide 1,000 different perspectives if observed by a 1,000-element array, for a diffractor acts as an omnidirectional source; there are no critical angles or necessity of equality of incidence and reflection angles.

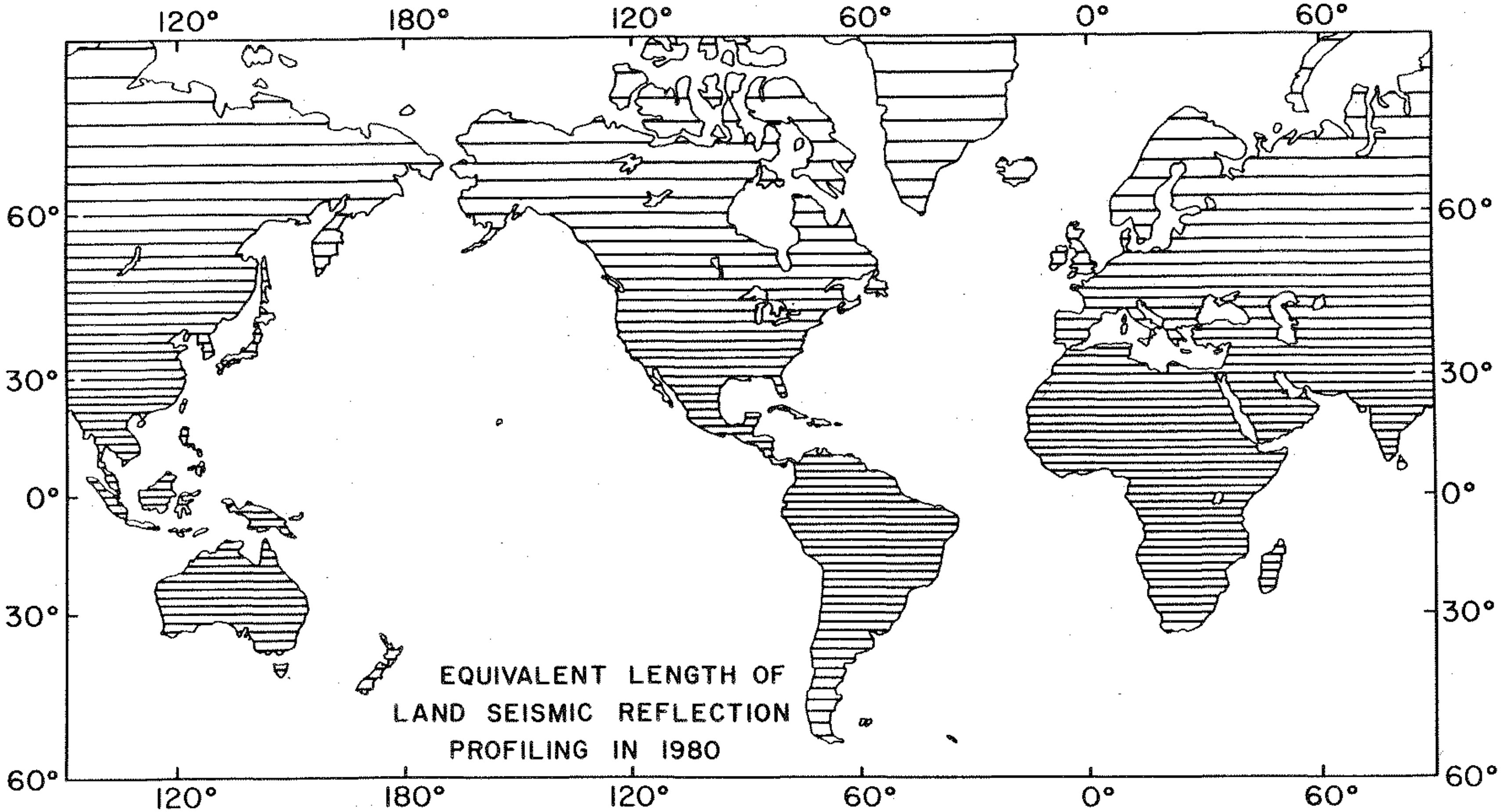


FIGURE 3.14 The lines on the map represent the equivalent continental coverage obtainable from the total length of land seismic reflection profiles carried out by the petroleum industry in 1980. Reprinted, with permission, from Oliver (1983). © 1983 by the National Association of Geology Teachers.

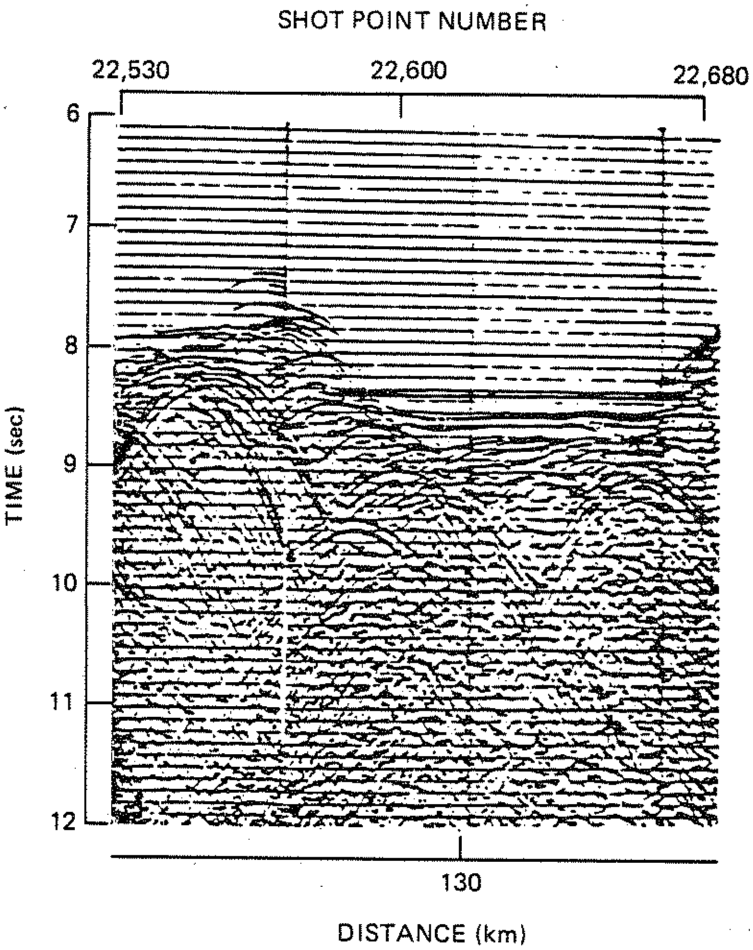


FIGURE 3.15 Smooth, reflecting sedimentary layers overlying rough, diffracting ocean crust, Atlantic Ocean. From NOAA (1980).

Most geophysical exploration experience is from sedimentary basins, and the seismic techniques chosen here emphasize reflection signals for good reason. The structures in other regions, such as shields, are known to be highly contorted and broken, e.g., once-horizontal interfaces are vertical or even overturned. A technique designed for planar interfaces should not be expected to work particularly well in such areas, and we must consider other modes of energy return from depth to provide information about past processes and current configurations.

Fortunately, the techniques required to look for and "focus" on diffracted energy require no change in the field procedures from either the profiles or the two-dimensional recordings that have been recommended for either wide-angle or near-vertical refractions or reflections. It will be necessary to use the array to beam-steer and focus on diffractors within the medium without regard to reflection or refraction rules.

> In view of the likelihood of diffractors in crustal regions containing older metamorphic and igneous rocks, we recommend that in any study of continents using arrays, the search for diffractors and research on their interpretation be considered a desirable and supportable portion of the total seismic effort.

NATURAL SOURCES

Local earthquakes provide both direct and critically refracted compressional- and shear-wave energy at relatively high frequencies and low angles of incidence. Distant earthquakes provide low-frequency direct rays at steeper angles of incidence that penetrate the entire lithosphere. They each provide unique opportunities to study the continental lithosphere.

First, earthquakes provide powerful shear-wave sources, making possible study of the three-dimensional shear-velocity distribution and, through their attenuation, the rheological state of the rocks. Such studies are especially interesting in terms of the location of partial melts (Candres and Ryall, 1983).

Second, earthquakes as impulsive sources at otherwise unobtainable depths allow us to observe critical refractions at lesser ranges than with surface sources. Their varying depths also allow the resolution of more details of the velocity structure. Neither of these two opportunities, powerful shear-waves and impulsive sources at depth, can be duplicated by artificial sources, so the extra uncertainty of determining origin time and location from the seismic data, a calculation that is unnecessary with artificial sources, is tolerable.

Finally, the very existence of earthquakes is helpful in determining what is fracturable, i.e., defining the "brittle" portion of lithosphere. Source properties tell something of the mechanical conditions of the rock fractured.

Seismicity within the continental lithosphere is relatively spatially diffuse in comparison with that of the oceans. Earthquakes under the continents are surprisingly available as energy sources for continental study. With sufficient instruments, very few earthquakes would be needed to characterize an important earth volume. Large parts of the U.S. lithosphere can be efficiently studied using local earthquake sources.

Events of various sizes are distributed in frequency of occurrence in a logarithmic way, as Richter noted: $N = 10(A) 10(-bM)$, where N = the number per unit time of magnitude M or larger events; A is seismicity, a constant related to numbers per unit time per unit area; and b is a constant relating N to M. For the world, A is approximately 8 and b is about 1, meaning 10(8) earthquakes of $M = 0$ or greater occur each year; more importantly, from the same relation there are about 10(5) earthquakes $M = 3$ or greater per year, and these are large enough both in number and size to be useful for regional continental lithospheric investigations, such as are our concern here. Under most noise and attenuation conditions, $M = 3$ events can be seen with good signal-to-noise ratio in ranges in excess of 300 km. Calculation of A and b for areas small enough to relate to tectonic and structural provinces is not regularly undertaken, but if it were, along with estimates of temporal variability of these parameters, experiments using earthquake sources to investigate the continental lithosphere would be reasonably simple to plan in terms of duration of observation and would have a high probability of success.

The use of earthquake-generated waves for velocity inversion was demonstrated by Crosson (1976), who used P-wave arrival times from local earthquakes in the Puget Sound region of Washington to determine a one-dimensional (flat-layered) velocity model. Aki et al. (1977) extended the technique to three-dimensional structures. The three-dimensional inverse technique has since been further developed and applied to volumes under seismograph arrays in California, Hawaii, the central Mississippi Valley (see Chapter 2), and the Yellowstone caldera (Iyer et al., 1981) (Figure 3.16).

These cases show that velocity anomalies exist in the upper and lower lithosphere as well as in the asthenosphere. Thus, the method should be applicable to study shallow features such as batholiths, deeper features including crustal magma bodies, and, with locally generated high-frequency waves and very dense two-dimensional seismograph arrays, such small-scale features as shallow ore deposits.

Today local earthquake hypocenters are generally located based on one-dimensional velocity-depth models, and are always mislocated in areas of lateral velocity variation. Nevertheless, reasonably precise relative locations have allowed delineation of major plate boundaries, and study of source properties along with location has found diagnostic differences in the processes occurring at the three classes of boundaries--spreading, transform, and subducting.

Mislocation leads to poor correlation with inferred geologic structures, incorrect focal depths, and distorted, inconsistent fault-plane solutions. Errors of this sort can have unknown effects on the details of the processes inferred, potentially affecting earthquake prediction and hazard research. Given sufficient observations of body-wave arrivals, there is enough information that lateral velocity and depth

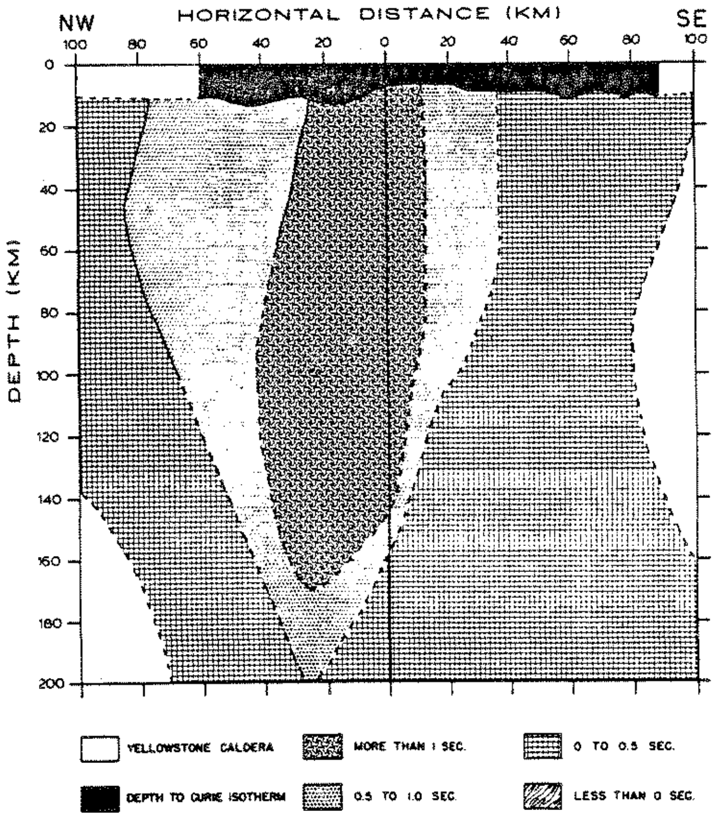


FIGURE 3.16 Projection of relative residuals on southeasterly vertical plane passing through the center of the Yellowstone caldera. Reprinted, with permission, from Iyer et al. (1981). © 1981 by The Geological Society of America.

as well as earthquake location and time can be solved for. In conventional, easy-to-visualize terms, observing an earthquake across an array will provide a large number of two-dimensional observation points (and composite profiles), all of which are amenable to solution for velocity-depth function through iteration, i.e., forward-problem modeling.

More direct, but offering more insight into the physical constraints operating in the process of achieving a satisfactory model, are three-dimensional inverse techniques that can simultaneously relocate the hypocenter and determine laterally varying velocity structure. For example, earthquakes in the northern Wasatch Front, Utah, relocated using this technique (Hawley et al., 1981), were moved by 1 to 3 km in areas characterized by upper crustal lateral velocity variations of 6 to 10 percent. To date, however, data have not been recorded with sufficient density to allow this technique to be applied routinely.

Earthquake data are also needed for study of ongoing dynamic processes, as the earthquake source itself reveals a great deal about the processes operating. For example, as noted earlier, it now seems possible, given observation at sufficiently spaced density and good velocity-depth information, to differentiate between earthquakes arising from shear fractures and those related to dike injection (Kanamori and Given, 1981; Julian and Cockerham, 1983). The spectral properties of the elastic waves radiated allow estimates of stress drop, rupture length and displacement, and apparent stress, all properties of the processes and crucial to understanding them. They are, however, dependent upon spectral properties that are rather unstable, easily modified by conditions between the source and receiver, especially near the latter, and therefore are in need of many averaged observations.

Conventional continuous-recording portable analog seismographs are the only seismographs available today in quantity; they are unsuitable for recording earthquakes where detailed profiling or array studies are needed, because of poor timing accuracy, short recording capacity (one or two days), slow recording speeds, small dynamic range and related poor reading accuracy, and inability to do waveform analysis. Triggered digital seismographs can record thousands of local earthquakes on a single tape without service, maintain precise time, record without distortion within over four or five units of magnitude, and store data in a form suitable to allow the measurement of arrival times to high accuracy and the estimation of spectra. Their recent development opens a new era for use of local earthquakes as sources for deliberate investigations. But full potential of these instrument developments will be realized only if sufficient numbers of matched instruments are available. In fact, array or profile studies of earthquakes everywhere up to now have been seriously flawed by spatial aliasing.

Large numbers of wide-dynamic-range seismographs are required to observe local earthquakes using two-dimensional arrays at sensor spacings close enough to avoid aliasing. Sufficient numbers of such seismographs are recommended to make up a portable network applicable to studies of seismically active volumes. Interestingly, most of the fundamental problem areas of Chapter 2 included seismically active volumes as a portion of the volume to be studied.

We recommend the use of two-dimensional arrays in conjunction with local and teleseismic earthquakes as sources for two- and three-dimensional investigations of the P and S velocity structure of the continental lithosphere.

We recommend accelerating the integration of earthquake and explosion seismology.

Both of these goals benefit by spatially adequate simultaneous recording of sources. The benefits for explosion seismology are efficiency and avoidance of aliasing. The benefits for earthquakes are the same, and are even more important because earthquakes are non-reproducible sources.

SURFACE WAVES

When a disturbance such as an earthquake or explosion occurs within the earth, two classes of seismic waves are generated. One class, the so-called body waves, includes compressional and shear waves, which travel freely through the interior of the earth; such waves are used for all of the other methods discussed in this document. Another class, the surface waves, travel along and are confined to the vicinity of the earth's surface by a wave guide, often involving reflection at the earth's surface and refractions or reflections at depth. Surface waves generally have large amplitudes and are characteristically spread into trains of long duration with varying wave frequency and considerable complexity. They carry a variety of information about the earth, only a part of which has so far been decoded.

Surface waves cover a frequency spectrum ranging from as high as many cycles per second to as low as about 1 cycle per hour. Generally speaking, the lower the frequency (and hence the longer the wavelength) the deeper the region the waves can probe. An important characteristic of surface-wave propagation is that the waves are dispersed, i.e., waves of different frequencies travel at different speeds. Surface waves at the higher end of the frequency spectrum are commonly observed in seismic prospecting; although sometimes used, they are commonly suppressed.

Two basic classes of surface waves can commonly be identified, and representative samples of them, Rayleigh and Love waves (named after their discoverers) are distinguished by their particle motions in vertical and horizontal planes, respectively. Surface waves of different frequencies or periods can be used to explore different parts of the upper portion of the earth. For example, Love and Rayleigh waves of rather long periods, ranging between a few seconds and a minute or so, are useful in providing smooth averages of the velocity-depth function of the crust and upper mantle. Waves at shorter periods, or higher frequencies, correspond to the higher modes of propagation and are sensitive to shallower parts of the earth; waves of the Lg type or the Sn type, commonly both prominent phases, reveal information about specific parts of the crust and uppermost mantle, respectively. These waves are not everywhere present; waves of the Sn and Lg types may propagate well over certain paths and not well at all over others. Such observations can be used to define major features in the crust, while P_L, another trapped wave, may set constraints on the thickness of the lithosphere.

In the period range of about 20 s and shorter, both Love and Rayleigh waves can be used to explore the deep crust and uppermost mantle (Figure 3.17). Indeed, such waves have been the basis for many observations of the so-called mantle high-velocity lid, the Mohorovičić discontinuity and the mantle low-velocity Gutenberg layer. Because of the integrative properties of surface waves and the consequent lack of great resolution at the longer wavelengths, such studies by themselves are somewhat ambiguous, but are of great value for providing average properties.

This report to this point has stressed increased resolution, and, in any information theory sense, the need for unaliased data to avoid error. There is a related aspect to consider: the difference between describing a volume with averaged infrequent samples from a high-resolution measurement and with samples from a low-resolution measurement that inherently averages over the distance between samples. Only the latter provides a valid average description; the former always provides an incorrect aliased description.

Surface-wave observations are both low resolution and averaging. They provide needed general regional properties not available from occasional use of high-resolution methods such as near-vertical reflection, and have a definite place in exploration of the continental lithosphere--the quick, economical determination of average properties. These methods are the ultimate arbiters of general correctness of the regional structure determined, for example, from the high-resolution methods. They perform the same function as requiring that seismically derived models fit observed gravity, but with increased specificity.

The collection of surface-wave data requires sampling at about 5-km spacing if the highest frequency of interest is 0.5 Hz. It would require seismometers (and recorders) having adequate sensitivity down to frequencies of about 0.05 Hz.

The energy in surface waves, although always less than half the total energy of the earthquake, can be quite substantial. Within a limited range of distances from the source, surface waves may in fact be the principal source of observed shaking. Surface waves are also used to determine magnitude and hence the total energy in earthquakes. They also provide information on the attenuation properties of earth materials, although in such studies it is necessary to take into account the effects of topography and geological interfaces so that an unambiguous measure of the earth's energy absorption can be obtained.

> We recognize the importance and contribution of a unified approach to the seismic interpretation and recommend that wherever possible a combination of observational techniques be employed, including body-wave and surface-wave methods, and that a synthesis of all possible geophysical and geological data be used.

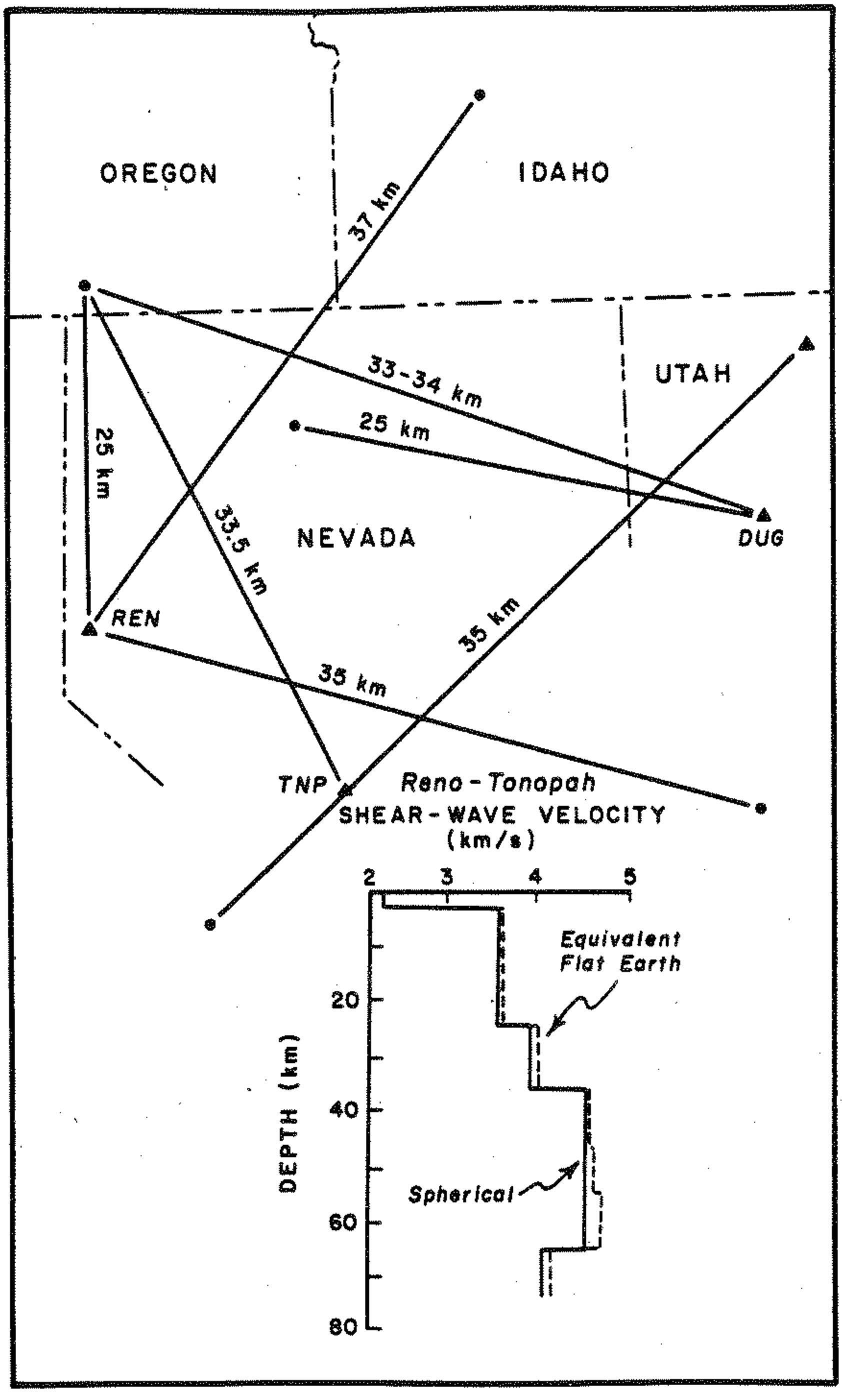


FIGURE 3.17 Summary of second Rayleigh mode dispersion results for average crustal thickness along various paths in the Great Basin. Reprinted, with permission, from Priestley et al. (1980). © 1980 by the American Geophysical Union.

RELEVANT ROCK PHYSICS AND PETROLOGY

The interpretation of subsurface structure determined from field investigations in terms of geologic history, rock types, and physical conditions is critically dependent on one's ability to determine the elastic (and anelastic) properties of earth materials under realistic conditions of temperature and pressure. The technology involved in measurement of the physical properties of rocks is for the most part well developed. Laboratory procedures for velocity measurements are well established and generally rely on the technique or a modification of the technique of Birch (1960). Measurements of P- and S-wave velocities at confining pressures to 10 kilobars have adequate accuracy (±0.01 km/s) and precision (±0.002 km/s) for general applications. Interferometric techniques are also suitable for single-crystal elasticity studies over the pressure-temperature range found in the continental lithosphere. With simple immersion techniques, densities of rock samples can also be measured to an accuracy of 0.005 g/cm^3. Additional research is highly desirable, on the other hand, for improving the accuracy and precision of laboratory investigations of attenuation, pore pressure and its influence on velocity, the dispersion of body waves, and stress-induced anisotropy.

Within the continental lithosphere, there are three depth ranges that require somewhat different approaches for laboratory investigations. The first is the range from 0 to 5 km. In this depth range we are interested in confining pressures of roughly 0 to 2 kilobars and temperatures up to 100°C. Laboratory studies of seismic properties within this depth region are complicated because of the well-known effects of cracks, which lower seismic velocities, and the relatively small sample size (usually cores 1 to 3 cm in diameter and under 9 cm in length). Thus, laboratory velocity measurements do not provide information about the influence on seismic velocities of large-scale features such as fractures, folds, etc., within the upper crust. Furthermore, if the fractured region is water-saturated, as is likely, the influence of pore pressure on velocity is another important variable that is poorly known.

The range of rock types likely to be found in the upper crust is great (Figure 3.18). A wide variety of igneous and metamorphic rocks is exposed on the continental surface, and in many regions they are covered with a sedimentary rock blanket that can reach thicknesses of 10 km or more. Thus, unlike the oceanic regions in which only basalt appears to be abundant in the upper few kilometers, laboratory studies on continental upper crustal composition require measurements on many rock types. Much of this depth region can be reached by continental drilling, which provides valuable samples for laboratory studies, as well as opportunities for unique downhole seismic studies and geophysical well logging.

Within the 5- to 35-km-depth region, pressures required for laboratory studies are from 2 to 10 kilobars, and temperatures are usually in the range of 100°C to 500°C. For the continental lithosphere throughout this depth interval, we are, in general, within the earth's crust, and the most significant laboratory contributions to the

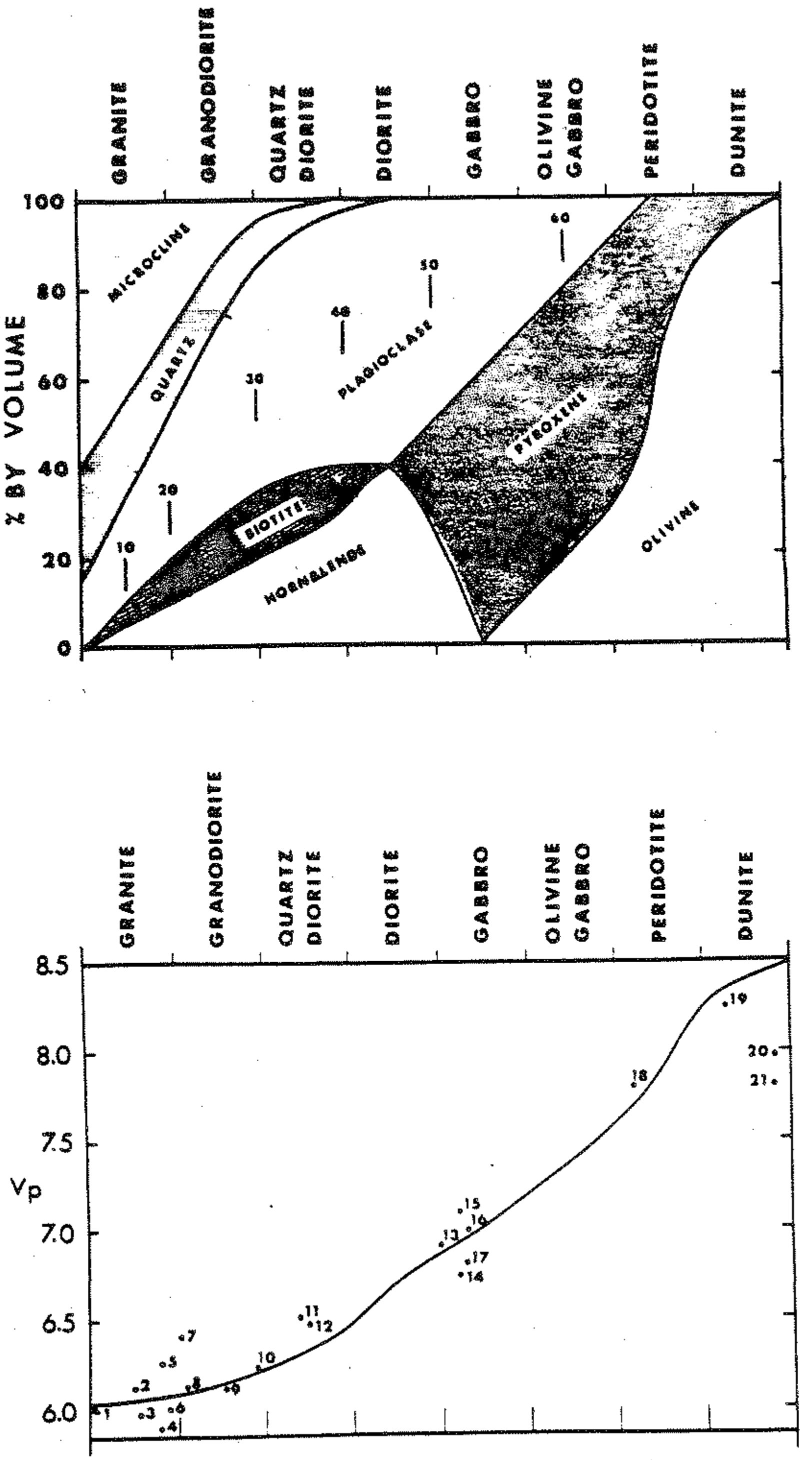


FIGURE 3.18 Top: diagram showing proportions of principal minerals in a series of igneous rocks from granite to dunite. Bottom: diagram showing the variation of calculated velocity with composition for the same sequence of rocks shown at the top. Figures reprinted, with permission, from Christensen (1965). © 1965 by the American Geophysical Union.

interpretation of seismological data include measurements of P- and S-wave velocity changes in igneous and metamorphic rocks as a function of pressure and temperature. Only limited laboratory data are available.

It is within this region that single-crystal elasticity measurements are also important, since most metamorphic rocks have a preferred mineral orientation that produces strong seismic anisotropy. To understand this anisotropy, elastic-wave velocities in common rock-forming minerals as functions of pressure and temperature must be precisely known.

The influence of nonelastic properties at elevated temperatures and increased water contents at upper crustal depths is now becoming apparent (Sibson, 1982). Concommitant velocity decrease and a transition to quasi-plastic creep have been suggested to occur at temperatures as low as 300°C, at depths of 7 to 10 km, and at strain rates of 10^{-15} s^{-1} (Smith, 1981). These findings are particularly important to mechanics of decollement and shallow detachment as well as to limiting the depth of failure of earthquakes. Modeling these processes requires new laboratory determinations on the effect of temperature, pressure, strain, velocity, and material properties for various rock types from experiments that have only recently been developed. These data are particularly important for seismic detection of magma sources and for evaluation of nonelastic deforming layers.

> We thus recommend accelerated research on delineating the location and the physical properties of low-velocity layers.

The pressures within the region from 35- to 100-km depth vary from 10 to 30 kilobars, and temperatures are usually in excess of 500°C. Only a few laboratory velocity measurements have been reported for hydrostatic confining pressures above 10 kilobars. Since temperature at these depths becomes a critical factor in velocities, it is within this pressure-temperature region that the greatest advances in laboratory technology are needed. This is particularly true for studies of partial melting and its influence on seismic velocities, attenuation, electrical and thermal properties. Measurements are further complicated because of the desirability of investigating anisotropy at these high temperatures and pressures.

The resolution of physical properties from surface observations will require a multidisciplinary approach involving measurements of the electrical, gravitational, thermal, and magnetic properties. It will be necessary to obtain rock samples from deep boreholes to establish relationships between the physical properties and the geophysical observations from which it will be possible to infer deep crustal properties.

Such data can be enhanced by knowledge of crustal characteristics in areas where rock sections that are normally deeply buried are exposed by unusual tectonic activity, as in the Jotunheimen area of Norway or the Ivrea zone in the Alps. Diatremes, which bring up samples of the mantle and deep crust, can further contribute to this understanding. Laboratory petrologic studies will provide geopressure and geotemperature data useful for inferring the depth history of various rock layers provided the lithology and its mineral phases can be evaluated from the study of a number of seismic parameters for a given rock unit.

Collisional interactions in the Mediterranean region have brought to the surface an unusual array of rocks believed to represent the lower crust and upper mantle. Berckhemer (1969; see Figure 3.19, top) suggested from petrologic, gravity, and seismic data that the metamorphic terrane of the Ivrea-Verbano zone of northern Italy represents a "crustal chip" that has been upthrust. The geophysical data show a direct connection between the surface exposures and seismic layers of the lower crust and upper mantle. Structural analyses and laboratory velocity measurements in the ultramafic ranks suggest strong anisotropy similar to upper continental mantle anisotropy. Thus, the Ivrea-Verbano zone is believed to represent a cross section through the continental crust (Figure 3.19, bottom).

In addition to the Ivrea-Verbano zone many crystalline terranes throughout the world may represent exposed cross sections of continental crust that have been detached from their origins and brought to the surface by tectonic forces. Examples include the Norwegian Caledonides, the Musgrave Range of Australia, the Vredefort Dome of Africa, and portions of the Nelson Front in Canada. These provide important direct information of the nature of the continental crust and upper mantle.

> We recommend a combination of geochemical, petrologic, and laboratory studies of the seismic properties of rocks from these regions to provide important data for the interpretation of seismic studies of the continental crust and upper mantle.

SEISMIC MODELING AND INTERPRETATION

Comparisons between observed and synthetic seismograms have become an increasingly important part of interpreting seismic refraction and reflection data. The modeling method is now sufficiently developed so that most of the seismogram can be synthesized, leading to greater confidence in the interpretation. For example, the reflectivity method of Fuchs and Muller (1971) is one of the most widely used synthetic seismogram calculations (Figure 3.20). Other computational techniques are possible (e.g. Chapman, 1978; Helmberger, 1968; Cerveny and Psencik, 1979). Modeling two- and three-dimensional media has also become practical, and methods have been extended to calculations of synthetic seismograms of laterally heterogeneous structures (Cerveny and Psencik, 1979; McMechan and Mooney, 1980; Chapman and Drummond, 1982).

Interpretation of multichannel reflection data benefits from modeling. Synthetic seismograms of complex geologic structure can be useful in testing interpretational hypotheses and can illustrate the limitations of the reflection method. A seismic model of the Wind River Uplift (Figure 3.21) shows the distorting effect of the over-

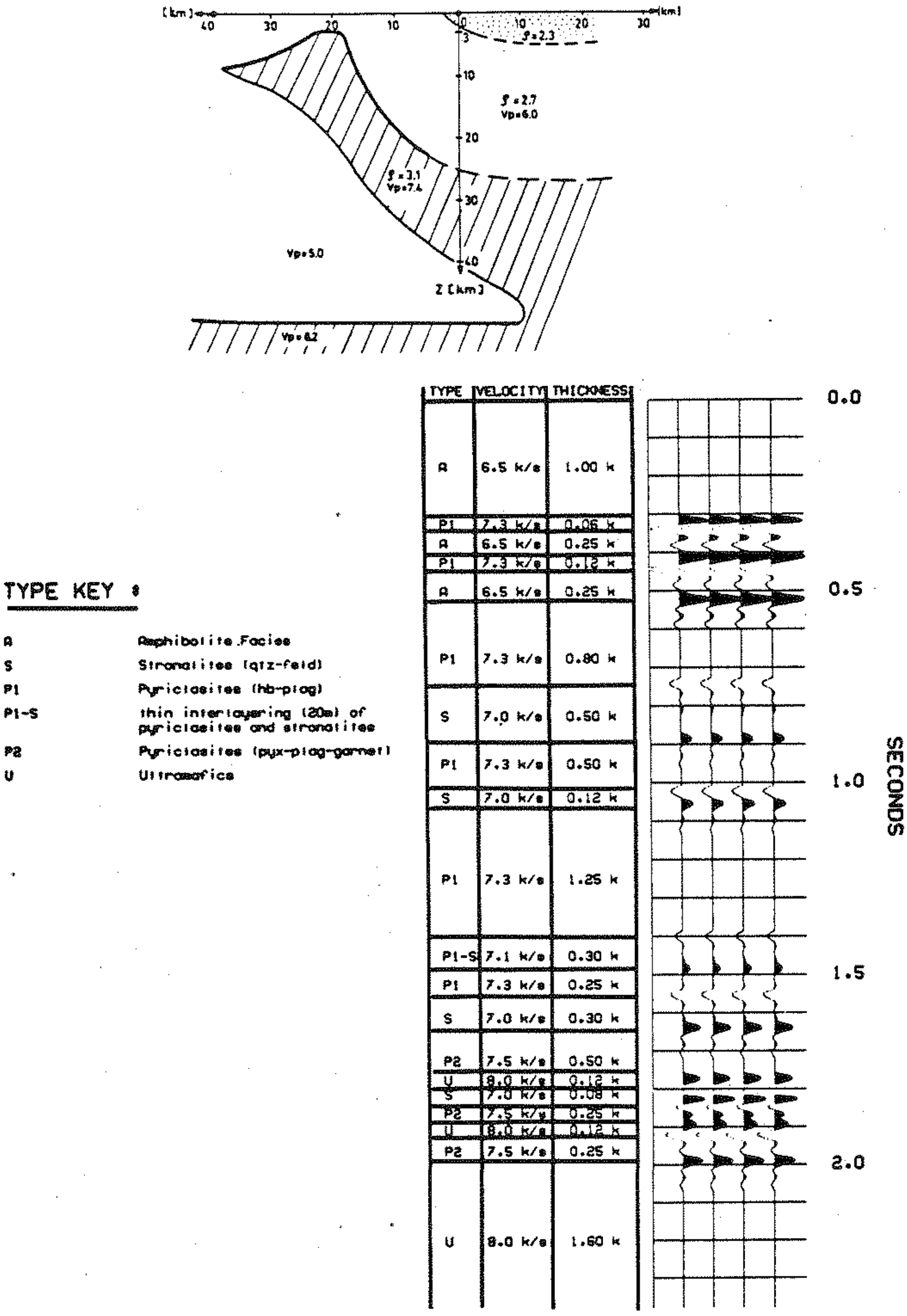


FIGURE 3.19 Top: velocity and density structure of the Ivrea Body from modeling of seismic and gravity data. From Berckhemer (1969). Bottom: one-dimensional synthetic seismogram and input velocity model from Ivrea-Verbano zone. From Hale and Thompson (1982). Top and bottom figures reprinted, with permission, from Hale and Thompson (1982). © 1982 by the American Geophysical Union.

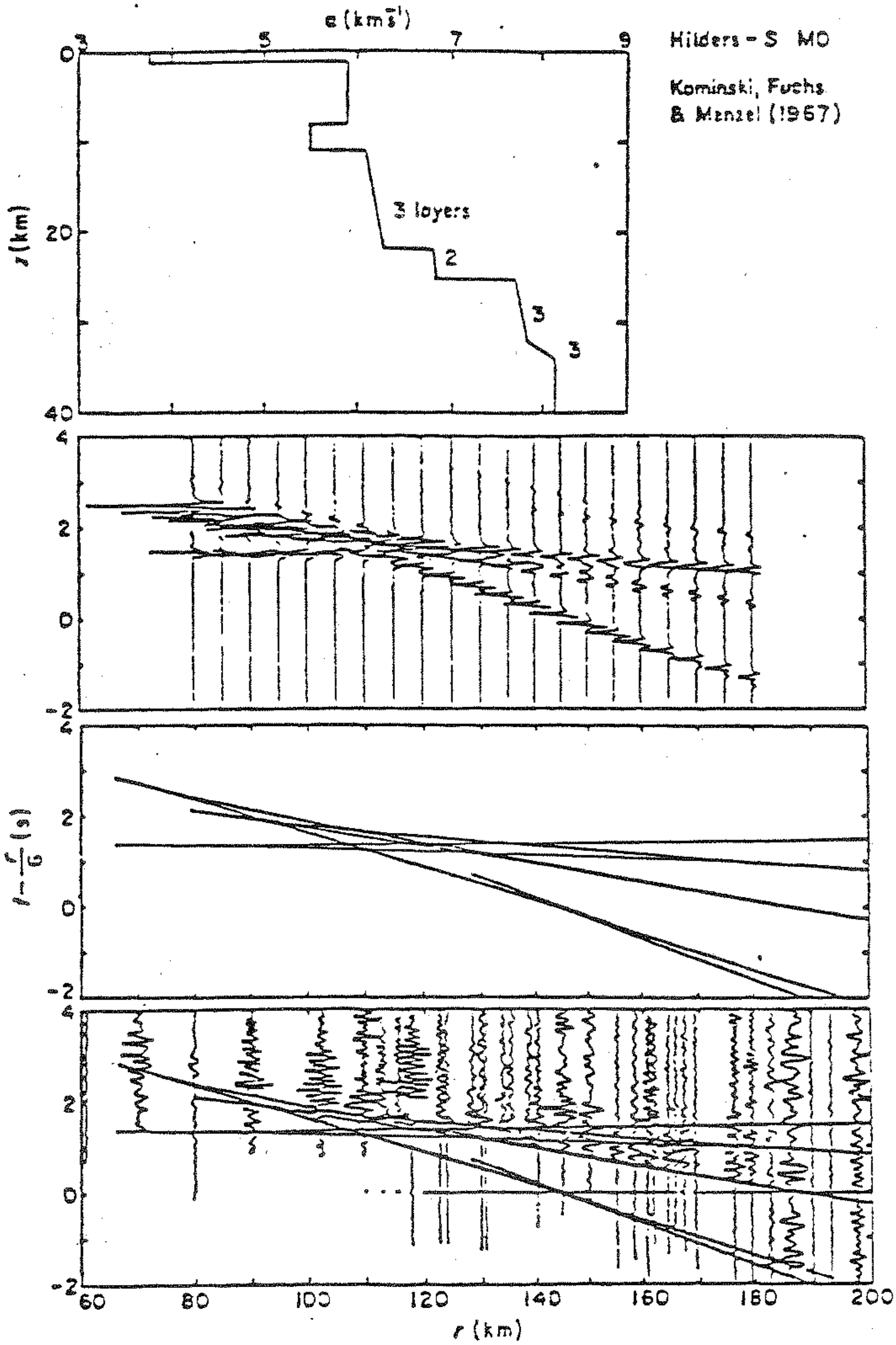


FIGURE 3.20 P velocity-depth function, synthetic seismogram section (vertical displacement), and travel-time curve, compared with the observed record section. Reprinted, with permission, from Fuchs and Muller (1971). © 1971 by Blackwell Scientific Publications Limited.

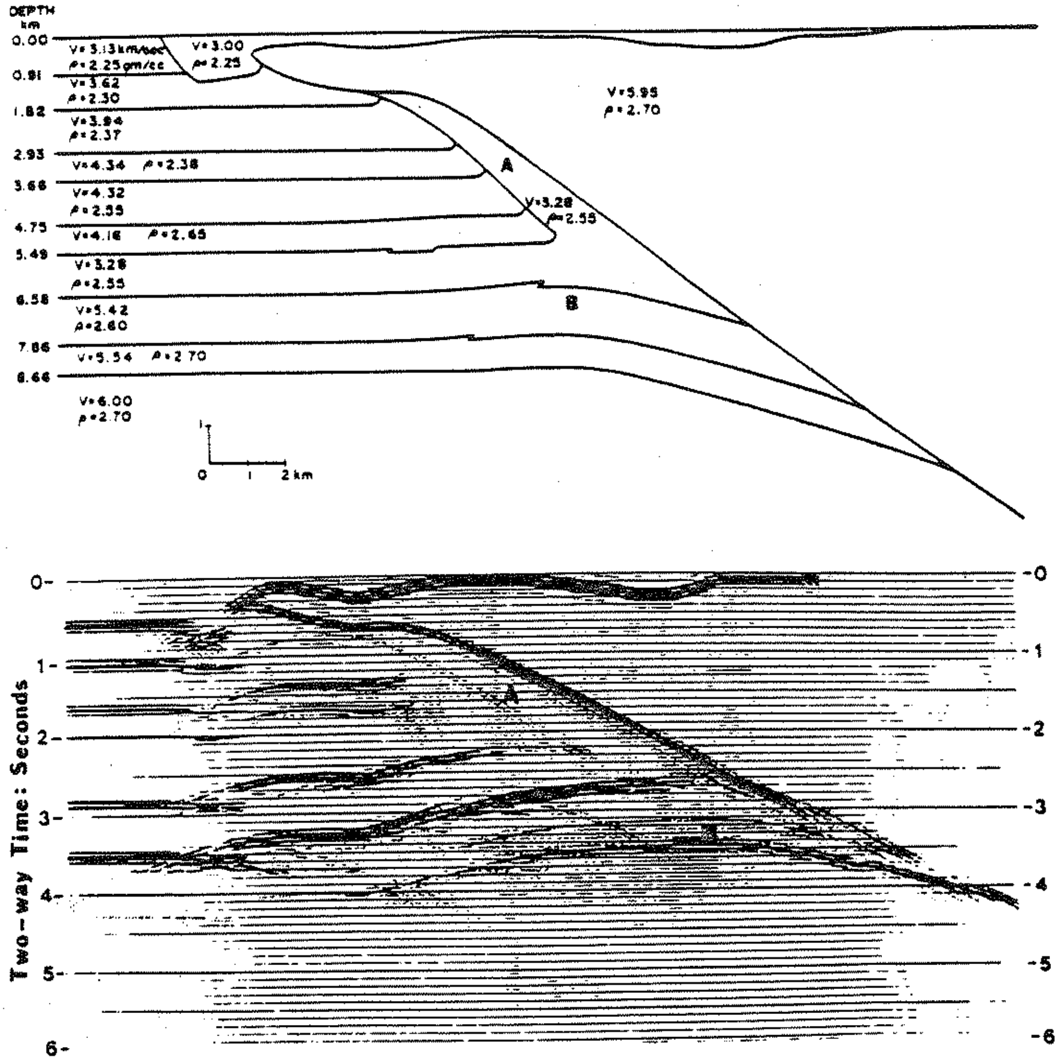


FIGURE 3.21 Two-dimensional model (top) and synthetic seismogram (bottom) for Wind River thrust. Figures reprinted, with permission, from Wong et al. (1982). © 1982 by E. J. Brill.

thrust crystalline block on ray paths that reflect from the underlying sedimentary strata.

The transformation from a seismic (time) section to a geologic (depth) section is not always straightforward (Figure 3.22) as an accurate knowledge of the velocity structure is often not available from the data. Refraction and wide-angle reflection when combined with detailed reflection information can help overcome this limitation. This example shows that simple geologic features produce complex reflection images that are not easily interpretable.

Seismic modeling is also important to the interpretation of refraction and wide-angle reflection data. Fuis et al. (1981) made extensive use of two-dimensional ray-tracing models in their interpretations of a detailed seismic experiment conducted by the USGS in the Imperial Valley, California, a region of strong lateral velocity variation. Forward models were additionally constrained by gravity modeling and geologic data.

McMechan and Mooney (1980) modeled these same data utilizing ray tracing and asymptotic ray theory synthetic seismograms that included the effects of lateral velocity variation (Figure 3.23). Unifying the interpretation with the true-amplitude synthetic seismograms allowed the evaluation of lateral velocity variations where amplitudes were particularly sensitive to discontinuities and velocity gradients.

In spite of modeling's key role in seismic interpretation of all types, relatively few researchers have access to a comprehensive modeling system. Most computer programs that model refraction and wide-angle reflection are ill-equipped to model multichannel reflection geometries. Although good reflection modeling systems are commercially available, computer requirements for all but the simplest models are often prohibitive unless one has a dedicated minicomputer. Furthermore, in order to ease the computer power crunch, most modeling programs incorporate simplifying assumptions that can compromise their accuracy for research problems. Modeling a three-dimensional structure, with its much greater computer requirements, has barely begun, even within the exploration industry.

Thus, there is a general lack of adequate facilities for comprehensive modeling of the full seismic wavefield, from near-vertical reflection to wide-angle refraction, using realistic multichannel recording geometries and targeted for three-dimensional structures. This inadequacy hinders interpretation of seismic data of all types, and its effect will increase as recording systems with 3-D capabilities become more common.

> We recommend an increased effort to develop comprehensive modeling capabilities for seismic arrivals for all offsets from three dimensionally complex structures. This will require research on and development of new software, and the establishment of major new computer facilities, or the upgrading of existing facilities, to execute these programs.

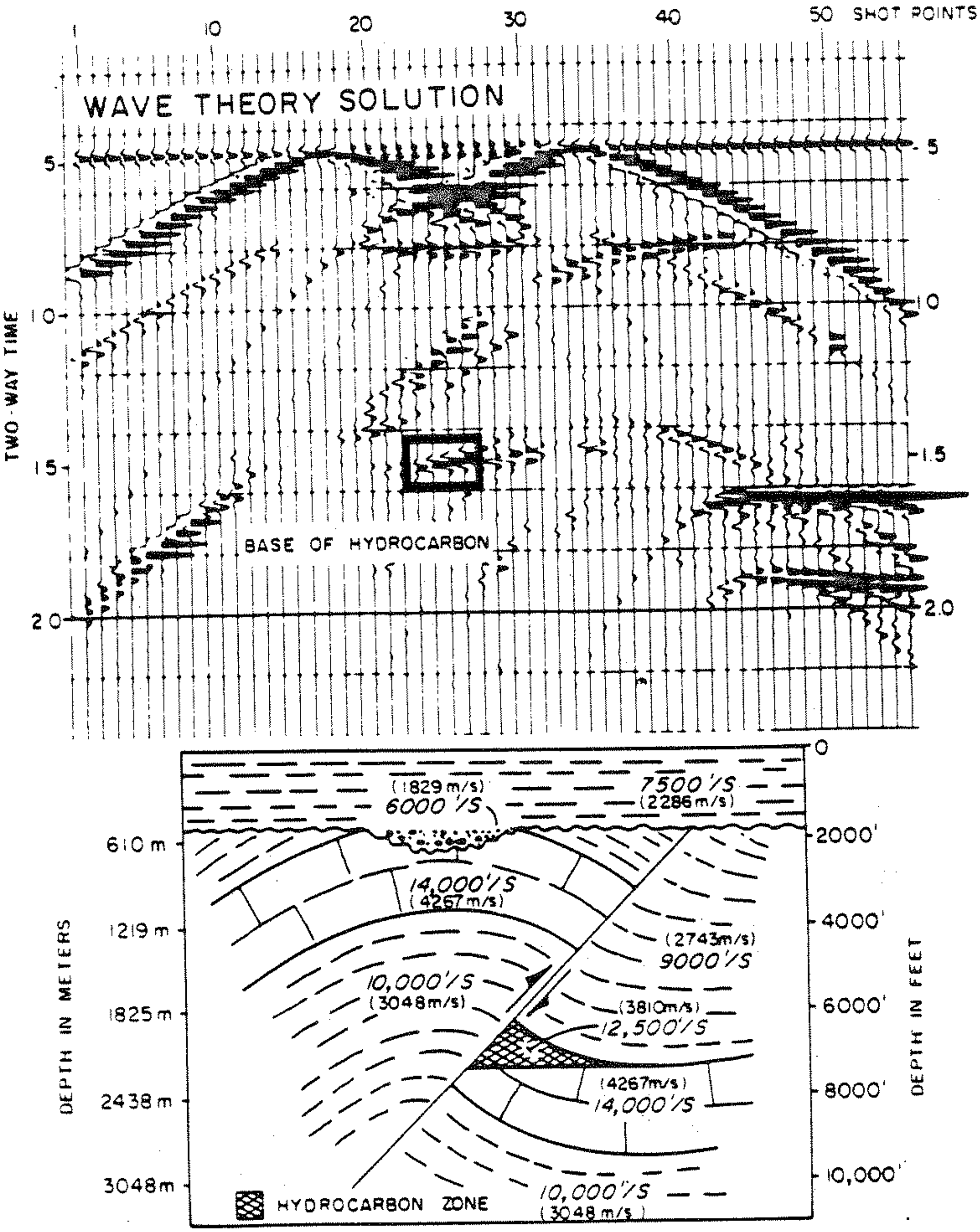


FIGURE 3.22 Computed seismic expression (top) and overthrust-fault model (bottom). Reprinted, with permission, from Neidell and Poggiagliolmi (1977). © 1977 by American Association of Petroleum Geologists.

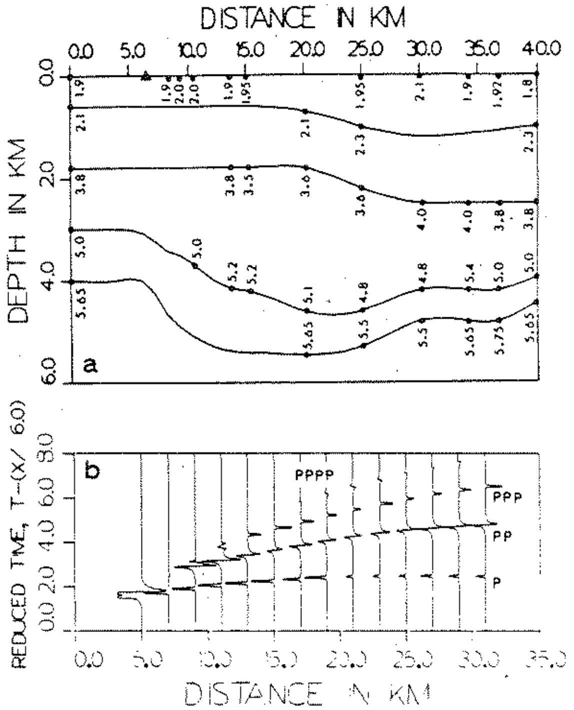


FIGURE 3.23 The response of a model (a) derived from a detailed reversed seismic refraction profile in the Imperial Valley, California, is shown in (b). The model has no first-order discontinuities. The numbers placed along the boundaries in (a) indicate the velocity both above and below the boundary at those points (except for the free-surface boundary). Reprinted, with permission, from McMechan and Mooney (1980). © 1980 by Seismological Society of America.

SUMMARY AND CONCLUSIONS

Although classical techniques of seismology have been critical in the development of current concepts of the crust and lithosphere, these concepts have not led to solutions of a number of fundamental questions about the composition, structure, formation, and evolution of continental crust. A major reason has been the lack of adequate resolution of deeper structure. What is required, then, is vastly improved resolution of deep structure at a scale comparable to the true geological complexity. We have shown that this is achievable by properly planned experiments involving a much greater density of observations than used in the past in this country.

We recognize that the various seismological techniques do not measure the same things and that much can be gained by utilizing two or more of these methods in a coordinated way.

We have seen, for example, that refraction experiments using explosions is the technique that has been widely used to determine the compressional-wave structure of the crust. Earthquakes, on the other hand, are often the only way to determine shear-wave structure. Both are essential to determine Poisson's ratio and to infer other rock properties such as fluid saturation and partial melting. The proper location of local earthquakes requires a knowledge of the velocity structure (often obtained by explosion seismology). Also, earthquakes as seismic sources at otherwise-unobtainable depths allow us to observe critical refractions at lesser ranges than with surface sources, and to examine the fine velocity structure because of their varying depths. We have also seen that narrow-angle reflection methods are able to detect and follow geologic discontinuities and to determine the velocity structure of the earth at shallow depths (upper crust to midcrust), whereas wide-angle or refraction methods are required at greater depths (lower crust and mantle).

> We recommend research devoted to merging narrow-angle (reflection), wide-angle (refraction), and other seismic methods to develop an integrated seismic approach that exploits the full range of seismic recording in a unified manner.

> We recognize that research on seismic theory and laboratory studies of rock properties are important parts of developing a unified treatment of seismic data.

4

INSTRUMENTATION FOR THE 1980s

INTRODUCTION

A growing body of experience, a part of which is reported in the previous chapter, points out that future crustal lithospheric research should employ combined seismological methods. Versatile instruments with large data capacity and both wide dynamic and frequency ranges will be needed to acquire complementary multisource data during a single investigation. We can look forward to this if we take advantage of technology that is widely used in other fields but not yet generally applied in seismology. Microcomputer technology can make versatile seismographs possible and affordable; some new seismographs incorporating microprocessors now change operational characteristics dynamically, based on the incoming signals. Small digital recorders with high capacity, which will allow reasonable service intervals, are evolving rapidly for general computer applications, and microcomputer decision making based on available storage space, projected service interval, and projected occurrence of events at each seismograph should result in optimum use of recording space. Digital seismographs are already capable of undistorted recording across a wide range of amplitudes, approaching that required to record weak artificial-source and powerful earthquake signals.

This chapter discusses the technological requirements in the light of expected applications for this new generation of instruments. Detailed engineering specifications should be formulated by the technical subcommittee of a new working committee to be established to plan and coordinate the new national program (see Chapter 5).

> The Panel recommends that a national workshop, open to all interested parties, be convened under the auspices of the new national working committee to set engineering specifications for "standardized" portable research seismographs in conjunction with the development of guidelines for management and organization of large-scale lithospheric seismology experiments.

Appendix A suggests an agenda for the national workshop that will lead to detailed engineering specifications, prototypes, and finally, manufacture of large numbers of a new class of portable versatile seismographs.

NUMBER OF INSTRUMENTS

One of our foremost concerns is that the data gathered be spatially unaliased, which has not been the case in almost all academic or government research. To achieve this, sensor spacing must be on the order of or less than one-half of the apparent wavelength of the highest-frequency waves being used. In addition, for resolution sufficient to impact geologic problems at the depths of interest, arrays whose apertures are roughly equal to that depth are required.

When typical apertures and sensor spacing are combined with the desirability of two-dimensional arrays for three-dimensional imaging, we find that up to 6,000 sampling points will be required for investigations of problems such as those outlined in the previous chapters. Many other studies could have been included: the Long Valley Caldera of eastern California, presently the site of a hazard notice; Roosevelt Hot Springs, Utah, a region of extensional tectonics and potential geothermal power; the New Madrid region of Missouri and Tennessee, site of large, infrequent earthquakes; the Charleston area of South Carolina, site of a major historical earthquake for which the tectonic causes have not been discerned; and tectonic province boundaries, such as that between the Colorado Plateau and the Basin and Range, where the basic geologic differences at depth are unknown.

The oil exploration industry has already begun using two-dimensional arrays of more than 1,000 sensor groups and data channels, so some problems inherent in the application of these large numbers have been solved. For example, because cabling to a central recorder is impractical for this many data channels, distributed recording has been developed, with each channel recorded at a separate seismograph. The problem of the daily reformatting of more than 1,000 individual cassette tapes into a time-ordered multichannel tape has been solved. The single-channel, radio-controlled seismograph being used today for the shallower targets sought in oil exploration must be considered a candidate for the proposed lithospheric research instrument if additions and modifications to provide for recording unpredictable natural events and for radio control of the larger, 50- to 100-km arrays are added.

The sensor or group spacings commonly used for linear profiling are instructive. Both the sensor spacing chosen for detailed deep refraction experiments such as deep seismic sounding (DSS) and the group spacing used for near-vertical common-depth-point (CDP) reflection profiling are commonly about 100 m. This is not coincidence: the spacing is chosen in both cases to avoid aliasing, as the Nyquist spacing requirement for aliasing avoidance is $D = 2c_{(app)}/f$, where D is the distance between sensors or sensor groups, $c_{(app)}$ is apparent phase velocity across the array, and f is frequency. The typical waves used in DSS experiments have apparent velocities of 5 km/s or greater, and frequencies below 25 Hz; they are unaliased with 100-m spacing. For CDP reflection studies, the apparent velocities are usually higher, and consequently, signals with higher frequencies are also unaliased at 100-m group spacing.

It is also instructive to compare linear profiles with two-dimensional array recording. For example, if 1,000 single-channel seismographs are used, 100-m sensor spacing can be accommodated over a linear profile of 100 km; this is a very adequate instrument density and profile length for high-resolution investigations to depths of 15 to 30 km. But for a three-dimensional investigation at the same spacing, 1,000 sensors can fill a two-dimensional array only 3.3 km on a side, which is adequate for investigations to 2- to 3-km depth. Deeper imaging would be inaccurate because of the small aperture; resolution quickly diminishes with depth, and velocity versus depth cannot be adequately estimated to allow conversion of transit times to depths. We can, however, choose to work only with arrivals that have higher apparent velocities, e.g., 10 km/s. The ray paths used then are more nearly vertical and, if the high-frequency limit is lowered, e.g., 12.5 Hz, an apparent wavelength of 0.8 km results. In this case an array that is 13 km on a side can be populated at 0.4-km sensor spacing to satisfy the alias-avoidance criteria. The data from this array can be used to resolve deep near-normal reflections but not deep wide-angle reflections or refractions. However, if 6,000 data channels are distributed over 4,000 sites (each fourth site being used for a three-component set), an array that is 55 km on a side with 1-km hexagonal geometry can be accommodated. Such an array would be useful for multimethod three-dimensional imaging to 55-km depth, which includes the Moho discontinuity in about 90 percent of North America.

It can be easily seen that 1,000 multichannel instruments can be usefully employed on the basis of the number of institutions interested in continental lithospheric seismological research. There are 30 to 40 of these institutions (see list in this section); some, we estimate, would effectively utilize 30 to 50 multichannel seismographs; others will find that 15 will meet their requirements. We see that 1,000 channels can easily be usefully employed. It is interesting to note that the European seismological community is also planning a new generation of digital instruments and multimethod experiments, and their plans call for up to 30 multichannel instruments per institution.

> The Panel recommends that 400 multichannel portable digital seismographs be procured over the next 5 years, with subsequent additions to provide approximately 1,000 instruments for research by the end of the decade.

It may be argued that adequate coverage of key continental features can be achieved by a considerably smaller number of seismographs used in a roll-along mode. The Panel feels that any economic advantage of such a scheme is not as advantageous as it might appear, and that scientific arguments do not support this contention. For example, explosions powerful enough to achieve total lithospheric critical-angle returns typically require a few thousand kilograms of explosives fired in clusters of deep holes, an expensive and specialized procedure. Repeated shots of smaller size, as are necessary in the stacked roll-along mode, are unnecessary if sufficient seismographs are available.

U.S. Institutions Possibly Interested in Continental Lithospheric Experiments

California Institute of Technology
Carnegie Institution of Washington
Colorado School of Mines
Cornell University
Georgia Institute of Technology
Harvard University
Lamont-Doherty Geological Observatory
Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
New Mexico Institute of Mining and Technology
Pennsylvania State University, University Park
Princeton University
Purdue University
Stanford University
St. Louis University
SUNY at Binghamton
SUNY at Stony Brook
Texas A&M University
University of Alaska
University of Arizona
University of California, Berkeley
University of California, Los Angeles
University of California, San Diego
University of California, Santa Barbara
University of California, Santa Cruz
University of Colorado
University of Hawaii
University of Michigan
University of Minnesota, Minneapolis
University of Montana
University of Nebraska, Lincoln
University of Nevada--Mackay School of Mines
University of Southern California
University of Texas, Austin
University of Texas at Dallas
University of Utah
University of Wisconsin, Madison
University of Wyoming
U.S. Geological Survey
Virginia Polytech Institute and State University
Yale University

Furthermore, such a solution would undermine a vital research objective of the overall program: using earthquakes to estimate shear velocities and rheological-mechanical states throughout the crust. At present such estimates cannot be made because of lack of instruments. The use of earthquakes for precise high-resolution work requires that all observations be made simultaneously at distributed ranges and azimuths. The roll-along mode requires repeated sources at the same locations, which is impossible with earthquakes. Before the time and position of individual earthquakes can be known, velocities and structures within the volume containing the paths between earthquakes and seismographs must be known. Under these conditions, relative location procedures cannot provide enough precision for the higher resolutions we are seeking.

Finally, without adequate instrumentation for training and research at most of the participating institutions, the development of the various array methods envisioned in this work would be seriously slowed and compromised. Each institution needs sufficient instruments to do modern, original work with reasonably complete data sets. At this point, no U.S. academic or governmental institution has anywhere near enough versatile instruments to do multichannel, multimethod work. Indeed, only now with the microcomputer revolution can an instrument of such versatility be built and the analysis power provided to handle the much larger data sets. A number of digital instruments, which are now regarded as prototypes, have been built, so much of the experience necessary has already been gained.

VERSATILITY AND UTILIZATION OF THE NEW INSTRUMENTS

As already indicated, many lithospheric problems can best be attacked through a combination of seismological techniques: recording small explosions and other artificial sources, which can be provided in abundance, have the advantage of known locations and times, and thus, although weak, can provide accurate descriptions from the near surface to considerable depth; recording local earthquakes, which can penetrate deeper into the crust and upper mantle with powerful P-waves and S-waves; and recording distant earthquakes, which allow us to use yet deeper ray paths through the lithosphere. This statement, which briefly summarizes the theme of Chapter 4, leads to the following recommendation:

> The Panel recommends that the new generation of portable digital seismographs be developed to be capable of recording earthquakes, explosions, surface waves, and, if feasible, the signals from weak surface sources such as Vibroseis.

The Panel believes that the best utilization of the large set of new seismographs recommended must be carefully considered. In one sense the recommended instruments can be considered a "national facility" in that they are justified on the basis of existing national and international scientific programs and because they will be operated in part under the direction of a central organization (see Chapter 5). In another sense, however, since these instruments are proposed at an opportune time in the evolution of the technology, a major surge in basic seismological research can be expected because of the greatly improved tools provided to the individual research groups. There is no question that academic lithospheric seismology requires revitalization and modernization. The instruments, then, are not solely a new national facility, but also are vital to the national academic program, for they are the bread-and-butter tools of the seismologist, akin to the microprobe of the geochemist or the x-ray spectrograph of the mineralogist. For approximately $300,000, an institution can be provided with 20 new portable digital seismographs and accessories.

In summary, we see a mix of uses for the instruments, with a balance between large national programs and individual research and associated academic training, and expect that the instruments will be occupied with the latter the majority of the time. The combination provides the health within a discipline that comes from diverse experimental approaches to basic problems.

Finally, we note that several recent National Research Council reports have recommended mobile seismic arrays for earthquake monitoring. The proposed instruments are applicable for this purpose, and will undoubtedly be utilized in this way (NRC, 1977; NRC, 1980c).

STATUS OF CURRENT INSTRUMENTS AND EXPERIMENTS

What is the present inventory of seismographs in the country? Table 4.1 provides a compilation of the number of somewhat modern seismographs currently available for continental lithospheric studies. None of these instruments meets the requirements outlined in this report.

This is not to say that existing instruments have not been used for fairly detailed, cooperative lithospheric studies. A subset of them plus instruments from U.S. industry and European universities were used in the Snake River Plain explosion experiment described in Chapter 3. The problem of using instruments of differing qualities is illustrated in Figure 4.1, which displays the response curves of the instruments used. In this case the data were in fact made compatible, and a single, widely usable data tape resulted, but with an extraordinary outlay of time (more than a man-year) and money. Also, although the experiment was in a seismically active area, earthquakes could not be incorporated into the program because the instruments were not suitable. Unfortunately these and similar nearly incompatible instruments that have only narrow ranges of usefulness will continue to be used in field experiments until they can be phased out.

CAPABILITIES OF SOME PRESENT AND PLANNED INSTRUMENTS

Seismographs incorporating some of the aspects of the advanced design that the Panel is recommending have originated in academia,

TABLE 4.1 Existing Seismic Event Recorders in U.S. Institutions

Recorder	Number
Commercial	
PDR1	Approximately 10
PDR2	20
DR 100	200
MCR 600	20
DCS 302	Approximately 50
Terra Tech	42
Constructed in-house	
USGS portable stations	120
University of Wisconsin digital recording seismographs	15
GEOS	30

industry, and government laboratories. Appendix B presents, for example, specifications for the instruments developed by the U.S. Geological Survey, the University of Wisconsin, Madison, and the University of California, Los Angeles, as well as those for the new instruments being considered for the European Commission for Controlled Source Seismology.

GUIDELINES FOR INSTRUMENTATION DESIGN

An independent, highly relevant meeting sponsored by the National Science Foundation and the University of Utah, "Guidelines for Instrumentation Design in Support of a Proposed Lithospheric Seismology Program," was held in Salt Lake City on May 4 and 5, 1983 (following the meeting of the Seismological Society of America). Fifty-five scientists (including nine Panel and adjunct Panel members) attended, which attests to the importance that research seismologists attach to the problem of lack of portable research seismographs. The discussions clearly supported and amplified the general views of the Panel (see Appendix C, a report of the meeting and list of participants). Time did not permit consideration of engineering specifications, but versions of the following table and figures (Table 4.2, Figures 4.2 and 4.3), which had been prepared by the Panel, provided a basis for discussion. The table (see p. 97) and figures presented here reflect the consensus developed at the meeting.

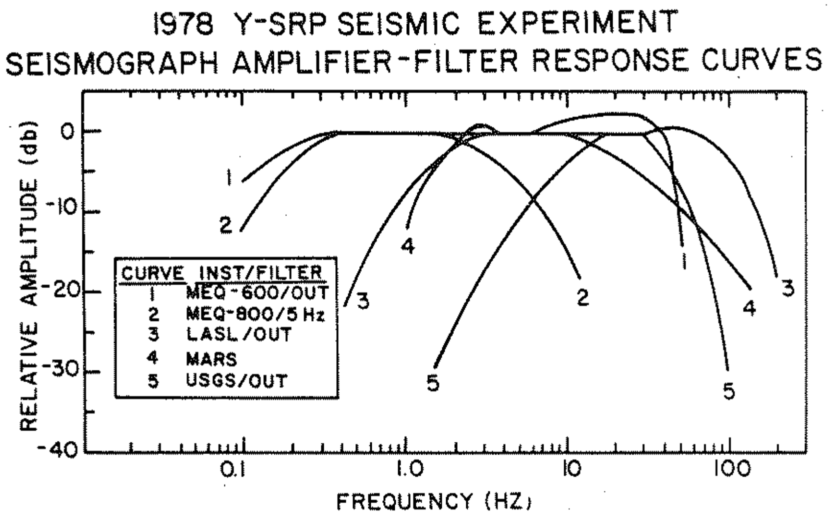


FIGURE 4.1 Response curves of instruments used in the Snake River Plain experiment. Reprinted, with permission, from Braile et al. (1982). © 1982 by the American Geophysical Union.

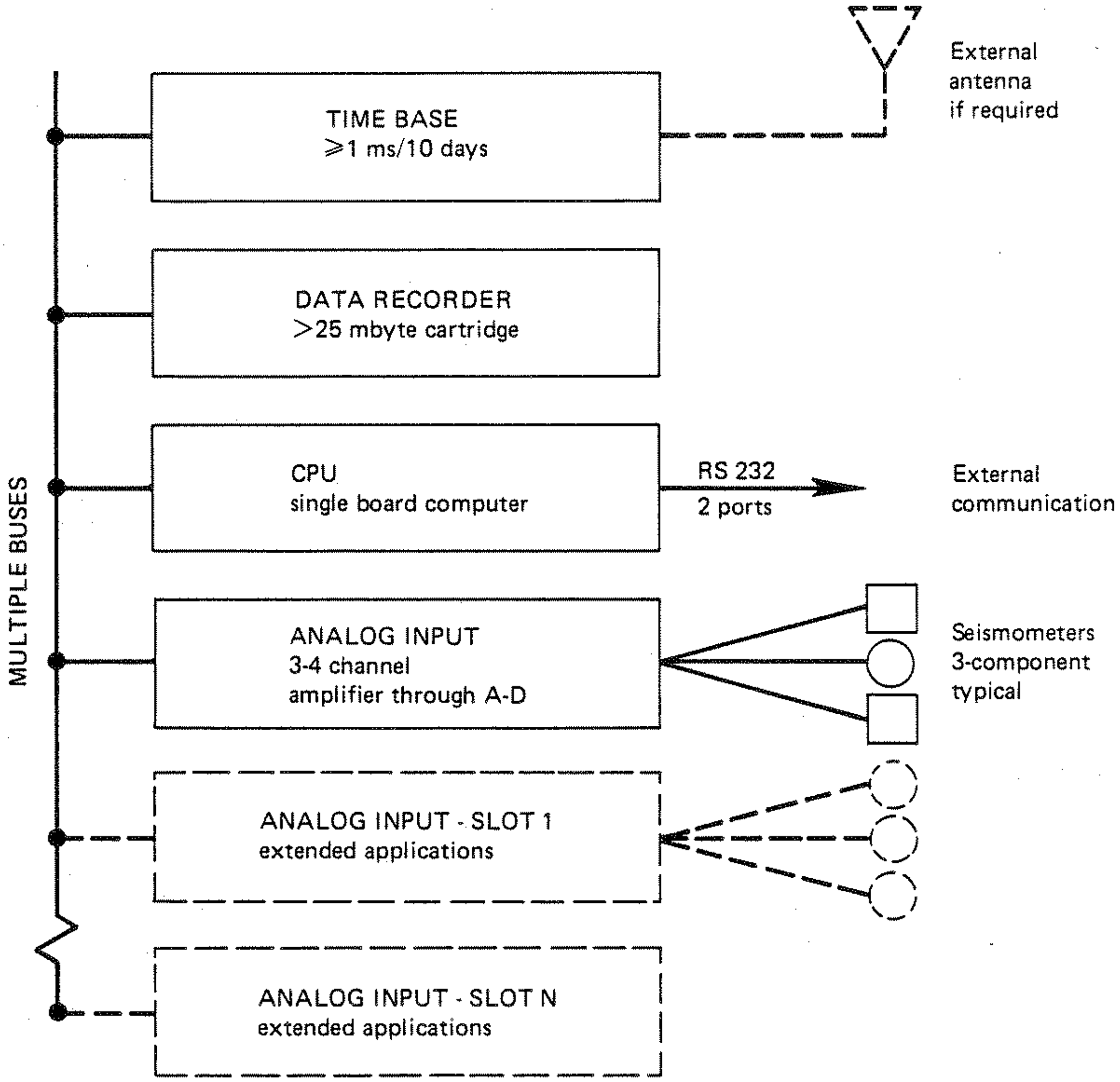


FIGURE 4.2 Typical recording system.

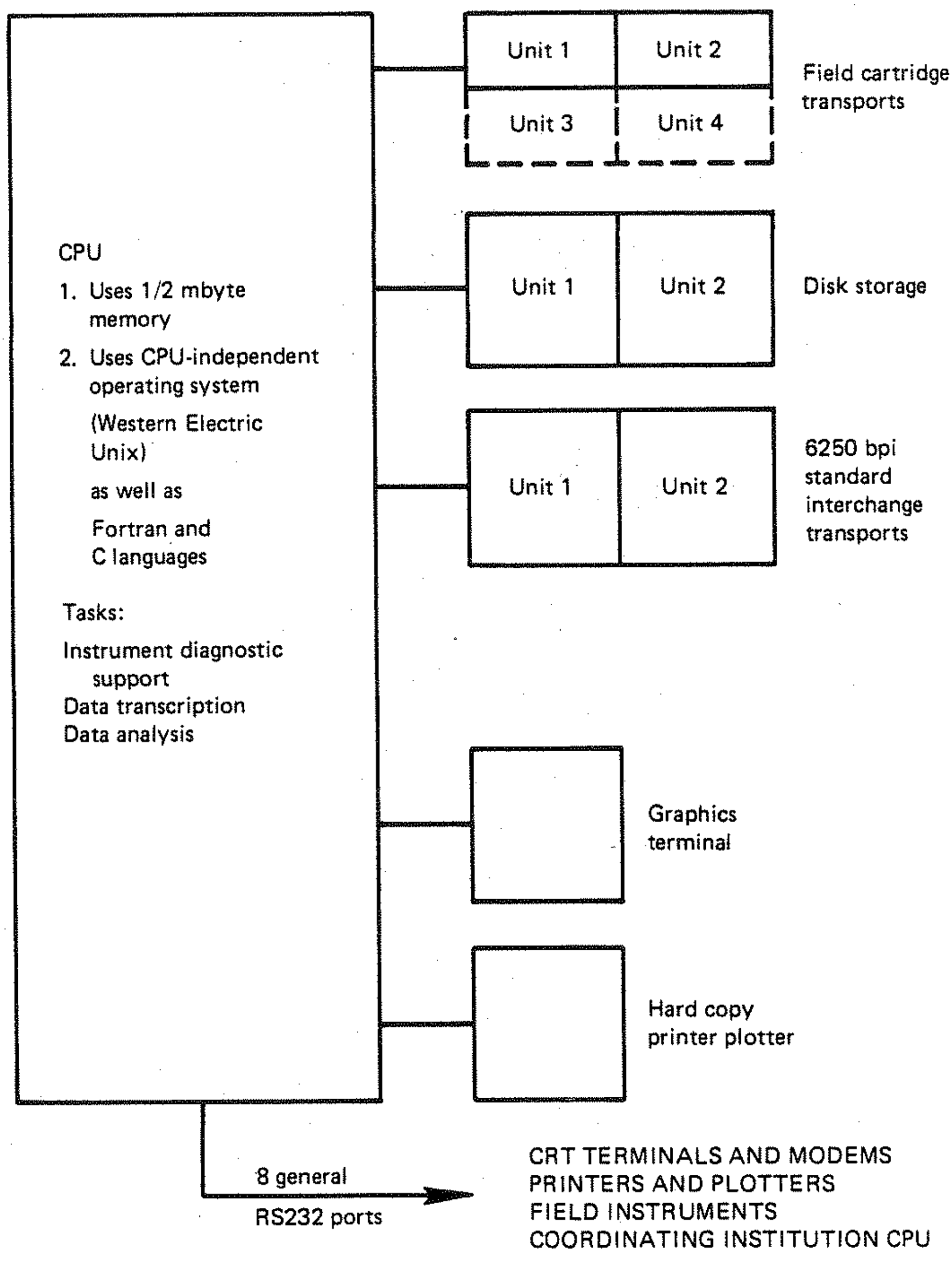


FIGURE 4.3 Field-support computer system.

Portable Seismograph Requirements for Various Applications

The requirements for using the four common seismic sources, which range from very weak to very strong, are shown in Table 4.2, which allows us to explore the possibility that one class of instrument can serve the entire range of applications.

Referring to Table 4.2, we see that the most precise timing is required for recording weak vibrator signals, since they contain relatively high frequencies and must be stacked. Many of the other applications demand operation under logistic extremes, so the general timing requirement may be practically satisfied only through the use of Universal Time (UT) rather than local time. Although unconventional, it is certainly possible to run vibrators and associated seismographs on UT just as well as with conventional synchronization via local radio R(O) signals. If vibrators are to be used at unconventionally large distances from the recording seismographs, as we believe they will be for research, the value of using UT is apparent. (On the other hand, an associated requirement may be that of providing radioed commands to control recording and stacking. Then these radio command signals may also be used for time synchronization.)

There is little difference in the minimum number of channels (1 to 3) for the four classes of experiments: the maximum number per seismograph, 12, reflects practical limits on cabling as well as physical limits on the size of the highly portable seismograph envisioned.

The bandwidth and sample length clearly set broad-band body-wave and surface-wave measurements apart from the other applications. If the sample rate appropriate for 20 Hz is coupled to "several hours" of broad-band recording (20.0 to 0.01 Hz), then the 25 mbytes of storage recommended serves for only four or five recordings, perhaps one-quarter of what could be recorded during a typical 10-day service interval, assuming a reasonable typical teleseismic activity level of two events per day. There is, however, no need to record an entire surface-wave train at high sample rates. If computer "intelligence" selects appropriate sample rates and associated alias filters, the demand for extraordinary recording capacity disappears. However, at the low sample rates unique to this application, both digital and analog filters may be needed. Finally, the 140-dB dynamic range necessary for this broadest-band use further sets this application somewhat apart from the rest.

These problems largely disappear, however, if the requirements for a low-frequency transducer-amplifier and perhaps the analog-to-digital (A-to-D) converter are satisfied in modules separate from and not included in the general, most common instrument configuration. With proper modules and appropriate software, any seismograph should be easily convertible to broad-band use.

The minimum signal dynamic range and the recording resolution needed could be accommodated by gain-ranging and 12-bit A-to-D converters. Gain-ranging digitizers present problems, however; one is that additional time is taken by the gain-ranging process itself, which limits the slew rate and in turn limits the frequency response of the digitizer. To minimize gain-ranging, we recommend 16-bit converters,

TABLE 4.2 Portable Seismograph Requirements for Various Applications

	Artificial Source		Earthquakes	
Requirement	Vibroseis	Explosion	Short-Period Local and Teleseisms	Broad-Band Body and Surface Waves
Time accuracy of any sample	250 μs	1 ms	1 ms	>1 ms
Minimum number of channels (maximum 12)	1	3	3	3
Bandwidth, Hz (exclusive of transducer)	5-200	2-200	500	0.01-20 Hz maximum; 0.1-20 Hz portable
Typical sample rate	4 ms/channel	10 ms/channel	10 ms/channel	40 ms/channel
Event length	20-60 s	1-5 min	10 s - 5 min	30 min to several hours
Dynamic range (exclusive of transducer)	120-140 dB	120-140 dB	120-140 dB	120-140 dB maximum
Minimum resolution (exclusive of transducer)	12 bits	12 bits	12 bits	12 bits
Service interval	10 days (maximum)	10 days (maximum)	10 days (minimum)	10 days (minimum)
Typical number of records per service interval	1,000 sweeps or stacks	100	1,000/day worst case; 20/day typical	10/day or fewer
Special requirements	Radio command to initiate stacking	Programmed turn-on	"Smart" trigger	"Smart" trigger Digital filtering Special seismometers
Master communication	Radio turn-on and sync for T_0	Radio turn-on	--	--
Position	1 m	1 m	10 m	--
Minimum total capacity	10 mbytes	--	25 mbytes	--

which provide 96 dB of dynamic range without gain-ranging, i.e., they are able to resolve 1 part in 65,000. Digitizers with more than 16 bits are not yet practical because sufficiently precise resistor networks are not available. Therefore, since the total range of wide-band or broad-band natural-event seismic signals will be considerably greater than 96 dB, a gain-ranging scheme is still needed. Finally, we note that gain-ranging steps must be as accurate as the least significant bit that can be resolved in the A-to-D converter, and this may also present a problem.

Specific Considerations Relative to a New Seismograph

Fieldworthiness

We start with fieldworthiness because it is easily unappreciated and unplanned for if the designers and builders are not also users. Mechanical shock resistance must be an inherent property, not an add-on. Routine servicing must not compromise the waterproofness and dirtproofness of sensitive elements. Proper instrument operation must be simply and completely verifiable in the field. We note that for the most part these properties are not met in the present generation of commercial instruments. We reemphasize that users and designers must at least in part be common.

Modularity

Figure 4.2 shows a block diagram of a typical recording system for a standard, unspecialized recording application. It illustrates modularity, a concept that the Panel believes is well suited to this instrumentation problem. Existing, well-developed, standard bus and port structures can accommodate both global and application-specific subsystem modules. We view the concept of modularity as a safeguard against obsolescence, as it allows portions of the instruments to be upgraded separately.

Existing microcomputer multiple-bus structures can accommodate microprocessors with 16-bit, 24-bit, and/or 32-bit architecture, and work with low-power CMOS electronics. Hundreds of manufacturers are producing modules that are physically and electronically compatible with various buses that satisfy Institute of Electrical and Electronic Engineers (IEEE) and other bus standards, which testifies to their versatility and to industry interest. Some of these buses, e.g., VME bus, follow internationally agreed-upon standards. This opens the possibility of broadly shared designs and physically compatible subsystem modules designed and built by many manufacturers (Bailey, 1982).

Time Base

The time base requires special thought, for the time of each sample at each recorder across the entire array is to be known to 1 ms or better throughout periods of 10 days or longer. Realistically, low-power, local oscillators cannot provide for this accuracy. Continuous or frequent observation of high-quality radio time signals will be required.

Since these seismographs must work globally, we believe it would be advantageous to avoid national radio time standards, for none of them can be received worldwide, each has different information formats, and each uses a different frequency and thus its own propagation versus time-of-day versus range properties. Timing using geostationary satellite signals, which are available worldwide, is reliable and precise, but requires relatively complex receivers and quite visible and expensive antennas. The low-frequency radio navigation system, Omega, which transmits signals locked to Universal Time, is also available worldwide (except on polar ice), and requires simpler instrumentation and less visible, single-wire antennas. It is recommended for serious consideration and has been used successfully (Schneider et al., 1981). Regardless of the system adopted, the objective is precise timing at each seismograph in an array, so that it will be unnecessary to use a central recorder to achieve accurate inter-data-channel times.

Data Recorders

We believe that data cannot be universally (or, in fact, very often) radioed or wired to a central recording site if versatility, portability, and lowest noise levels are to be maintained. Table 4.2 reflects estimates from experience with existing prototypes with onboard recording, which indicates that for a typical 1- to 2-week service cycle, at least 25 mbytes per channel of storage is required. This is an entirely reasonable expectation with state-of-the-art cartridge tape recorders.

Seismometers to A-to-D Conversion

The seismic amplifier through the A-to-D converter is shown in the "Analog Input" block of Figure 4.2. Amplifiers with internal noise referred to the input of less than 1 microvolt, one-tenth or so of the earth's background noise with typical seismometers, are now readily available if the bandwidth of the signal of interest is limited to five to six octaves. For wider bandwidths, improvements in amplifier design over most that are now available will be needed. Nonetheless, the amplifiers in use today probably have a greater dynamic range (the range between the smallest and the largest signals that can be handled without addition of noise or distortion) than the linear ranges of most low-natural-frequency seismic transducers. Extending the recording range into the high-amplitude, strong-motion region, as when recording close to earthquakes, will require still greater dynamic range than most, if not all, commonly available velocity transducers-seismometers have. Using accelerometers in addition to seismometers is a viable option for solving two problems: extending the dynamic range so as to accommodate and record the signals of strong motions, and detecting and recording signals of lower frequency than those available from practical portable velocity transducers. In summary, combining high dynamic range and wide-frequency response will require new thought in terms of the analog elements to be employed.

RS 232 Ports

The RS 232 ports shown in Figure 4.2 are to satisfy communication requirements. The most important are the five following:

1. Downloading seismometer position and elevation information onto the data storage media (see below).
2. Spot field playback of data from the data cartridge to an external output device such as a strip-chart recorder.
3. Verifying the total system operation, including the seismometer, through an installation-site terminal.
4. Setting the time and verifying correctness.
5. Downloading uniform instructions as to operating parameters into the seismograph from a digital instruction set used by all participants (see below).

Seismometers

All seismometers consist of a mass supported by a spring, which together have a natural resonant frequency. For earth frequencies less than the natural resonant frequency, the motion of the mass in relation to the earth is proportional to acceleration. For earth frequencies above the natural resonant frequency, the mass motion is proportional to earth motion.

In mechanical systems in which the supported mass cuts a magnetic field that is moving with the earth, the induced electromagnetic force is proportional to velocity and is thus larger for frequencies above the natural resonant frequency than for those below it. This higher output-velocity-proportioned response defines the frequency band that is generally used. Very seldom discussed are the other "natural" frequencies associated with the mechanical system, at which spurious resonances occur. These are generally neither accounted for nor designed for, are somewhat random in their frequency of occurrence, and intrude on the linearity of motion of the suspended mass. Thus, it is not only the natural frequency of the transducer that limits its usefulness, but also usually poorly controlled spurious resonance frequencies that govern the useful high-frequency response, and hence the range of the earth motion spectrum that can be sensed. The problems of spurious resonances can be decreased by using many sensors on the same channel, as is done in the exploration industry.

Mechanical systems with a natural resonant frequency below 1 Hz are generally delicate devices, and practical portable seismometers for frequencies below 1 Hz essentially do not exist. As the restoring force required to achieve a low natural resonant frequency in a mechanical system is, by definition, small, their field ability and ruggedness are roughly inversely proportional to their natural resonant frequency. In addition, the off-level sensitivity increases as resonant frequency decreases, so that considerable attention to ground tilting is required where especially stable long-period seismometers are desired.

There have been, of course, other attempts to make other types of transducers with angstrom-range sensitivity, which might be useful for seismology. Stiff-suspension seismometers (accelerometers) integrate the output below the natural resonant frequency. These typically consist of a crystal stack whose natural resonant frequency is much higher than any of the frequencies of interest and, therefore, its output is proportional to acceleration for the frequencies of interest. Its output signal must be accurately doubly integrated to get to ground displacement. This requires integration circuitry incorporated within the seismometers, which requires its own extra external power and adds noise to the signal. So far the units that have been built are delicate and of poor field ability. Such accelerometers, however, have the advantage of being able to operate in any orientation, and are not sensitive to tilt.

The sensitivity of both classes of sensors are also temperature-dependent. Normal, weak-suspension transducers are affected in two ways: (1) the mechanical properties of the springs used for suspension of the moving element are sensitive to temperature, and (2) the strength of the magnets employed today is proportional to temperature. Modern magnetic materials can reduce this problem. Insensitivity to magnetic field strength can also be improved by careful design of the magnetic circuit.

The transducers employed today for virtually all field studies are of the "open-loop" variety, which cannot measure or evaluate their own performance, much less correct for deficiencies. Closed-loop seismometers seem to offer some substantial advantages in shaping the frequency response with a disadvantage of adding system noise to the data. One possible design is the forced-balance seismometer, a transducer in which the moving element is kept at the null position by feedback forces. Unfortunately the system dynamic range of existing portable feedback transducers is limited particularly at lower signal levels by the noise in the feedback amplifier.

Special Considerations Arising from Operation of Large Portable Arrays

Large portable arrays made up of many independent, unattended seismographs will require exceptional reliability as well as efficient installation procedures, including those to verify that the instrument has been properly installed and is operating correctly. The self-checking, calibration, and record-keeping functions must be automated and as independent as possible of the installer. Instructions to the instrument for its operation must be precise and uniform so they will be identical for each instrument, independent of keyed-in instruction through the installer. Finally, the seismographs must be safeguarded as much as possible against electrical, mechanical, and thermal abuse, including such common accidents as reversing the polarity of the battery, dropping the instrument, or leaving it in the sun in an enclosed vehicle.

The tape record itself must contain much more than the record of time and seismic waves, again because of the large numbers. This information must include complete information on mode of operation (triggered, programmed, radio-initiated), sampling rate, filter settings, seismometer type and calibration, UT time, and location. A time history of recording activity should be accessible without playback of the entire field cartridge.

Today location information is not generally contained on the data tapes. This oversight is unimportant when only a few instruments are deployed, as field notebooks suffice, but is of major importance when hundreds or thousands of sensors are deployed in movable, tightly spaced arrays. Absolute position information (latitude, longitude, and elevation) is in principle determinable from one or a few passes of a navigation satellite to any seismologically required precision. Small, low-weight satellite positioning equipment is available and reliable, although costly.

Relative rather than absolute positions between array points are usually sufficient in seismology. New developments in relative positioning appear imminent through simultaneous observations of the same satellite at separate points. With separations of 60 km, relative positions 10 m are currently achieved (Counselman, 1982; Gourevitch et al., 1983). In another system being developed, two minutes of simultaneous observations of the signals of four or more navigational satellites can apparently produce relative positions to 5 m. It is the only system that does not require decoding the orbit parameters contained in the satellite signals. Data from all satellite positioning systems are in digital form, making them easy in principle to include in the digital field record.

Unfortunately there are presently insufficient numbers of navigational satellites, and waits of hours for suitable passes would be common, especially at low latitudes, making the field costs high.

Continuously available signals from the Omega navigation system potentially can be used for seismograph location as well as timing, but this location method is projected to provide relative intraseismograph positions of no better than ±100 m, sufficient only for some applications.

In summary, the data of the new seismographs should include location, instrument diagnostics, total calibration, and a time-duration inventory of the recording. Only the problem of location does not yet have a ready solution, for even with the advances in satellite technology the cost is high because of the time required to wait for passes, and the accuracy of positions from Omega signals is insufficient for many applications.

FIELD-SUPPORT COMPUTER SYSTEM

Field evaluations of both the technological and scientific health of experiments while they are underway require field-support computer systems. The technological evaluation must include unerring recognition of seismograph malfunctions to assure uniform array operation, and the scientific evaluation must include rapid data processing to a point at which judgments can be made as to the course to be followed during the continuing experiment.

The field-support computer system shown in Figure 4.3 is typical of systems envisioned for instrument checkout and field data analysis. It is configured to serve about 200 channels, which will probably be typical of one scientific group's responsibility for either individual or joint projects. For the latter, each subgroup's field-support computer will be essential for coordinating the 25 to 35 groups that will be involved in the 400- to 1,000-channel national program array experiments. Very standardized, efficient, and automated checkout procedures to verify each field unit's performance, and very automated, uniform, and close to real-time data-handling procedures are required. The cartridges from field recorders must be played back, and edited and demultiplexed into time-ordered (high-density) tapes for prompt transfer to a large fixed computer system at a central data collation and analysis facility (see section on Data Management in Chapter 5).

The field computer system suggested in Figure 4.3 is configured to edit and transcribe about 100 to 200 mbytes of field data per day, i.e., 40 to 100 25-mbyte cassettes per 10-day service interval. The data demultiplexing operation will require 150 mbytes of mass storage if five to six full cassettes are to be loaded onto a disk for reordering to standard computer tapes, which are then transferred to the central facility.

Digital communication among subgroups and between the central data collation and analysis facility and the subgroups should probably be accomplished through modems, which will provide for errorfree transfer of instructions for experiment coordination. For example, telephoned or radioed instructions will allow all field parties to download precisely the same set of programs and parameters into all field instruments. For communication between subgroups, modems allow precise transmission of information on data, software, interim results, and logistic details, including map information. Graphics terminals and hard-copy printer-plotters are essential in the field for the analysis, diagnostics, and communication functions already mentioned. We are recommending an operating system, such as Unix, that allows software interchange to be independent of the particular computer processing units (CPU) used. The CPU RAM capacity shown, 1/2 mbyte, is probably a minimum if a Unix operating system is employed.

Finally, the field computer is the principal resource for transforming the field data to computer formats suitable for analysis, whether for individual or joint experiments. With the ability to edit and demultiplex data tapes in the field, preparation time for data analysis following the experiment can be greatly reduced.

5

TO MEET THE CHALLENGE

ORGANIZATION

A modern seismic field experiment using explosive and earthquake sources is a large and expensive operation that almost always exceeds the capability of any one academic institution in terms of manpower and equipment. It has been pointed out that many experiments could well require the deployment of 500 to 1,000 portable, multicomponent digital seismographs. Thus, it is almost axiomatic that cooperative, multi-institutional projects be planned and conducted that utilize the combined facilities and talents of a number of interested groups. It is instructive to examine how this has been done in the past.

Organization of Early U.S. Experiments

The large U.S. field refraction experiments of the 1960s were multi-institutional projects of this kind involving, primarily, the University of Wisconsin, the University of Texas at Dallas, the Carnegie Institution of Washington, Pennsylvania State University, and Princeton University. The organization was very informal. The lead institution was responsible for the explosives and other general aspects of the overall program. Each participant provided its own instruments and obtained its own support. The program lacked a long-term planning aspect and suffered from lack of uniform instrumentation.

Organization of the German (and European) Program

In the early 1960s a priority program of explosion studies of the lithosphere was established; it was entitled "Geophysical Exploration of the Deep Structure in Central Europe." The inauguration and success of the program depended on the existence of a unique organization--the Forschungskollegium "Physik des Erdkorpers"--which was a legally established organization of directors of university institutes engaged in studies of the physics of the earth. This group approached the German Research Society (DFG) with a proposal for cooperative experiments in which they assumed responsibility for the operation of a national program. On the basis of the existence of this program the Volkswagen Foundation provided support for the initial set of 40 standardized seismic refraction seismographs. These three-component, FM-recording seismographs, designed by Professor H. Berckhemer and manufactured by a small company outside of Frankfurt, were a major factor in the success of their program. Although owned by the DFG, the instruments were apportioned more or less equally between a dozen or more cooperating institutes. The instruments proved to be very good and quite inexpensive for the precision attained and became very popular throughout Western Europe (France, Norway, Sweden, etc.). Thus, the stage was set for international cooperation. Numerous seismic profiles have been recorded in Europe utilizing up to 125 of these standardized seismographs. European participants get together each year at meetings of the European Seismological Commission to agree on plans for coordinated field experiments for the following 3 to 4 years. Individual investigators propose specific scientific experiments and obtain support for the field program, explosives, interpretation, etc. Instruments are then brought together from the various institutions to provide the number needed for the experiment. After the field recording, data are principally interpreted by the lead group but are available to all users.

The COCORP Organization

COCORP activities are planned in consultation with committees set up to evaluate geological targets and technical implementations. Members of these committees are selected from the general geological and geophysical community. Sites may be suggested by any interested individual or group. Once collected, processed, and analyzed, COCORP results (seismic sections and computer tapes) are openly distributed for the cost of reproduction. COCORP contracts field work out to a professional seismic exploration firm, thus avoiding problems associated with maintaining the complex recording and vibrating equipment. Data are processed on the COCORP Megaseis computer facility at Cornell University. Field work is carried out year round on a continuous basis resulting in considerable economic savings and operational efficiency. These operations are supervised by faculty, students, and staff in the Department of Geological Sciences at Cornell.

Organization for the Yellowstone-Snake River Plain Experiment

The successful 1978 Yellowstone-Snake River Plain experiment (see Chapter 3) was planned and coordinated by the University of Utah and Purdue University, who took the lead and proposed the research to the National Science Foundation and the U.S. Geological Survey. Upon approval of the research, open invitations to participate in the experiment were extended to any interested organization. The lead universities were responsible for seismograph-station deployment plans, shot point plans, and data dissemination. Discussions were held with the various participants in the project at all stages. At completion of the experiment, each respective organization reduced its own data; data were then sent to the University of Utah for integration and development of a basic data set that was released to the public at the same time as it was released to all the participants via an announcement in EOS. Results of the experiment were presented at a special American Geophysical Union symposium and in a special volume of the Journal of Geophysical Research.

GENERAL GUIDELINES FOR ORGANIZATION OF THE NEW PROGRAM

The Panel agreed on the following general guidelines: (1) the program must be open to all groups interested in participating in large-scale cooperative seismic field programs; (2) allowance must be made for input from the general earth sciences community (geologists, geochemists, geophysicists) in the planning and interpretation stages; (3) cooperation with industry is highly desirable; (4) the instrumentation should be well utilized by the university community for particular regional studies when not required for large-scale cooperative experiments; and (5) a standing organization must be established to assure that the above aims are carried out.

> The Panel recommends the immediate establishment of a permanent working committee composed of members from academia, industry, and government. The role of the working committee is fourfold: (1) to plan and coordinate large-scale field programs; (2) to recommend guidelines and standards for state-of-the-art instrumentation, and for data acquisition and handling, including compatible formats for ease of data exchange; (3) to organize scientific symposia in the area of continental seismology; and (4) to coordinate activities with other national and international programs.
>
> To assure that the overall earth sciences community has access to the program, the Panel recommends that the working committee establish two standing subcommittees: (1) an experiment selection committee with the role of receiving, screening, and recommending specific field experiments to the parent committee, and (2) a technical subcommittee to recommend guidelines and standards for state-of-the-art instrumentation, data acquisition and handling.

Each of the above subcommittees will be chaired by a member of the working committee, and its meetings will be open to all interested participants. The working committee will coordinate their proposed field programs with the plans of the ongoing seismic reflection and refraction programs of the U.S. Geological Survey and the deep-seismic reflection program of COCORP. Proper coordination will take place if these groups are represented on the working committee. It is estimated that meetings of the working committee will consist of approximately 25 members. Meetings of the subcommittees, however, since they involve a larger clientele, could well be somewhat larger from time to time.

Funding

We anticipate that funding for the new portable array of up to 1,000 instruments will be requested under the normal research grant programs of the National Science Foundation, U.S. Geological Survey, Department of Defense, etc. We trust that additional funds will be made available to these granting organizations on the basis of the implementation of the organization proposed in this document and in response to the national and international programs of continental lithospheric studies now underway. We can even hope that industry may see fit to underwrite a portion of the proposed instrumentation. We perceive, then, that the instruments would reside in and be the property of the institution receiving the grant. Thus, we recommend that proposals submitted as a part of this program must justify the number of instruments requested on the basis of the number of staff members, students, and technical staff available to use and maintain them as well as, of course, the university research to be undertaken. The proposal should also include a guarantee that the institution will appoint a member to the working group, and will participate in the annual large-scale cooperative field experiments. We can anticipate that, when not in use, these instruments will be made available on request to other seismologists. We can anticipate that such requests will of course be subject to existing university policies, and with proper guarantees of security and correct handling.

We anticipate that the USGS will acquire their cadre of needed instruments through their own funding channels, justified on operational needs. We trust that they will assume a very active role in the planning and conducting of the cooperative programs recommended in this document.

The acquisition of 400 new portable digital instruments over the first 5 years of the program is considered vital. Acquisition of the 600 additional instruments required for some large-scale experiments in the second 5 years of the program will depend on the success of the program to that date. It is not known at this time how many universities will participate in the program. Standardization of these instruments could be maintained under a contract with the manufacturer of the instruments. However, the problem need not be resolved at this time. This topic could well be a major item on the agenda of the proposed national workshop, recommended in Chapter 4.

COOPERATION WITH INDUSTRY

Since seismological methods are the mainstay of oil exploration, industry R&D is basic to any lithospheric exploration programs that use these techniques. This access to the benefits of an aggressive industrial technology should be a major resource for lithospheric reflection profiling. The increasing use of the reflection method by university and governmental research programs will undoubtedly increase technical (hardware and software) feedback to industry. Common technological interest in electronic hardware and computer software should also benefit programs for refraction exploration.

Industry is primarily interested in the shallow portion of the lithosphere where resources can be economically recovered. However, proper understanding of the geological evolution of a particular resource reservoir requires broader knowledge of regional tectonic relations, knowledge that is intimately related to deeper structure. Although seismic exploration efforts are usually associated with the search for oil within the sedimentary section, the increasing use of detailed seismic methodology in igneous and metamorphic terranes by academic research groups may very well lead to a better understanding of ore formation and should draw interest from mineral exploration interests.

The oil industry is a major employer of university-trained seismologists and geologists. University teaching programs are greatly enhanced by research programs that use state-of-the-art seismic methods and equipment. Thus, a spin-off of such a program is a better-trained and larger pool of earth scientists fluent in modern techniques. Likewise, vigorous programs of seismic exploration in universities should attract valuable industry experience back to academic research. The balance of highly trained personnel between industry and academe is an increasingly important issue.

Since industry is a major potential beneficiary, often in very direct ways, of these kinds of lithospheric exploration programs, it should be willing as a matter of prudent investment to underwrite at least some of these efforts. Academic-industry research consortiums may be a viable means of stretching research dollars from both funding sources in mutually rewarding ways. Efforts to encourage and sustain industry funding for seismological research in university environments should be facilitated.

Proprietary seismic reflection data held in industry are a major source of existing information on the structure of the lithosphere. In many cases some of these data may be eligible for release to, and interpretation by, nonindustry researchers. There are numerous examples of industry drawing upon academic expertise in the analysis of these vast data reserves. Efforts should be made to encourage publication of these seismic data relevant to the important problems of lithospheric structure and evolution.

All of the above areas represent important avenues of mutual industry-academic interest and potential cooperation. Such cooperation should flourish in new and continuing lithospheric exploration programs, and should be aggressively sought by both parties. In fact, the potential for such cooperation and mutual assistance is a major strength of academic seismology.

> The Panel recognizes that the advice, cooperation, and support of industry is vital to attaining the goals of this program. To this end, we recommend that the working committee

include one or more petroleum industry members, and that it meet annually in conjunction with meetings of the Society of Exploration Geophysicists (SEG).

The Panel feels that the working committee could be set up under the auspices of the SEG and that such a possibility should be examined. Another suggestion was that the working committee be set up as a standing subcommittee of the Committee on Seismology of the NAS/NRC. It could still hold meetings in conjunction with the SEG.

INTERACTION WITH MAJOR EXISTING PROGRAMS

The single most important program to explore the continents using reflection profiling is that directed by the Consortium for Continental Reflection Profiling (COCORP). It is a prime example of very successful industry-academic cooperation. Since its first field work in 1975, COCORP has collected more than 3,000 miles of multichannel seismic reflection data in areas of particular geological interest: Wind River Uplift, Rio Grande Rift, Hardeman County, the southern Appalachians, the Sierra Nevada, Kansas, the Mojave Desert, Utah, the Adirondacks, etc. Results from some areas are spectacular, and all have had an impact on our understanding of various aspects of continental evolution. Results from several of their field programs are included as examples in Chapters 2 and 3 of this report.

A facet of the COCORP effort of direct interest to the new committee is the passive piggyback experiment in which research groups use the COCORP vibrators as sources for three-dimensional and wide-angle seismic measurements. Such experiments should continue to be planned and conducted. Gravity, magnetic, and even drilling programs have followed along COCORP survey routes using the accurately surveyed stations and, of course, the COCORP results, in their own studies. The economic efficiency and scientific desirability of such auxiliary activities are obvious.

Based on the success to date of the COCORP program, this and/or other deep-seismic reflection work should be accelerated. Since one land crew can cover only about 800 km/year on a full-time basis, it will take many years to acquire a necessary basic catalog of deep crustal information. The Panel recognizes that much work remains to be done, and thus included in Chapter 3 the recommendation that U.S. efforts to explore continental structure by reflection profiling should be accelerated. We further note that, when possible, such work should incorporate two-dimensional profiling with narrow-to-wide offsets, three-dimensional areal surveys, and application of new instrumentation, synthetic seismograms, and inverse procedures.

The recommendations of this report are primarily aimed at the academic community with a major intent to revitalize and modernize important areas of lithospheric seismology. At the same time, we applaud the resurgence of the USGS in the areas of refraction and reflection experiments of the continental crust. A major refraction survey was run for about 600 km across Saudi Arabia by the USGS in

1978. To make this study possible, a new set of 100 seismic recording instruments was designed and assembled. These instruments have been busy ever since, running profiles in many areas of the United States (e.g., Imperial Valley and Mojave Desert) to define shallow and sometimes deep crustal structure under the aegis of the National Earthquake Hazard Reduction Program. Under the same program and others, seismic reflection profiling has been utilized in various areas--i.e., the southern and central Appalachians (1979-1981), the New Madrid region (1979-1980), and the Charleston area (1980-1981). The USGS has implemented a formal program of Deep Crustal Studies, under which existing crustal reflection data are being purchased and new data obtained in support of interdisciplinary programs. The first new survey under this program was a 112-km line in central California in 1983. In 1984 a line is planned in Maine connecting with the SOQUIP lines in Quebec, and it will perhaps include a marine extension. It is planned that each year one additional site will be profiled.

> While the Panel recognizes that the USGS programs are operational programs designed to fulfill specific objectives, we trust that, whenever possible, the USGS will take an active part in the planning and carrying out of the field programs recommended in this report.

CURRENT UNIVERSITY FIELD WORK IN REFLECTION SEISMOLOGY

From the preceding discussion we see that reflection profiling is a very important technique in studies of the continental lithosphere. A recent development has been the acquisition of seismic reflection equipment at universities. Vibrator equipment has been acquired by Cornell University (aside from the COCORP project), the Universities of California, Berkeley; Kansas; Texas at Dallas; Wisconsin, Madison; and Wyoming; the Colorado School of Mines, and perhaps others. Computational facilities devoted to reflection seismology on the continents are operated at Cornell, Princeton, Stanford, and the Universities of Texas, Utah, Wisconsin, and Wyoming. Although these developments are excellent from the standpoint of education, problems arise if expensive field surveys on a large scale are contemplated. Although obsolescent field equipment is often obtained at little or no cost from the petroleum industry, maintenance and operational costs are far from insignificant.

One role for university-operated reflection equipment is to apply it to specific scientific problems of limited scope that have educational value for participating students. On the other hand, exploration of the lithosphere on a larger scale can be carried out by commercially available crews. One major advantage of commercial contracting is the continuous upgrading and maintenance of instruments that is largely funded by the petroleum industry.

DATA MANAGEMENT

A general problem that needs to be addressed includes: (1) the quick interchange of data among institutions participating in an experiment, (2) the specification of data formats, (3) the exchange of software, and (4) the rapid release of the data for distribution to all interested scientists. By the time a full complement of instruments is available for large experiments, perhaps 150 standard tapes would be generated in 10 days of recording. From these the data pertaining to events of interest (or time windows) would need to be sorted out and assembled. The lead institution in a large experiment would normally take responsibility for initial data handling, either in its own processing facility or by using some other facility, and would be responsible for distribution to participants. This plan assumes some progress in technology and improvements in computing capabilities at educational institutions before large numbers of instruments become available.

The details of data management are a proper subject for study by the technical subcommittee of the permanent working committee. It is important to note that in early cooperative experiments when smaller numbers of instruments are involved, enough computing power will probably be available to handle the data, but this computing capacity may exist in only a few institutions. From early experience, we should learn the best way to proceed with larger experiments.

To release the data and make it widely available to all interested scientists rapidly and efficiently, and to preserve its availability for years to come, we suggest that the data might best be distributed at cost through a commercial distribution center.

The problems of digital data dissemination to the community have been addressed by the Panel on Data Problems in Seismology of the Committee on Seismology. In its report entitled Effective Use of Earthquake Data, the Panel concluded that "establishing a national seismological data base at a National Center for Seismological Studies is both desirable and feasible at this time" (NRC, 1983, p. 2). The Panel's principal recommendations were that the National Center for Seismological Studies (NCSS) be established to ensure the effective use, via a well-organized data base, of current and future digital seismic data.

Thus, another option for dissemination of the digital data acquired during this program to the broader community is to place the data set from each experiment in the data base at the proposed NCSS (after a suitable period of time to allow analysis of the data by the participants in the experiment). The data sets would then be available to any user of the NCSS for further analysis or other disposition. Use of the proposed NCSS would ensure the rapid and cost-effective distribution of the data to all interested scientists.

REFERENCES

Aki, K. (1981) 3-D inhomogeneities in the upper mantle, Tectonophysics 75, 31-40.

Aki, K., A. Christofferson, and E. S. Husebye (1977) Determination of the three-dimensional seismic structure of the lithosphere, J. Geophys. Res. 82, 277-296.

Allen, C. R. (1981) The modern San Andreas fault, in W. G. Ernst, ed., The Geotectonic Development of California. Englewood Cliffs, N.J., Prentice-Hall, pp. 551-534.

Arabasz, W. J., and R. B. Smith (1981) Earthquake prediction in the intermountain seismic belt--an intraplate extensional regime, in D. W. Simpson and P. G. Richards, eds., Earthquake Prediction--An International Review, Maurice Ewing Series 4. Washington, D.C., Am. Geophys. Union, pp. 238-258.

Bailey, Chris (1982) Bus standards enrich microcomputer board variety, Electron. Des. (Apr. 15), 77-85.

Baker, M. R., L. W. Braile, and R. B. Smith (1982) Amplitude and phase normalization of seismograms from multiple seismograph recording systems for the Yellowstone-Snake River Plain seismic refraction experiment, J. Geophys. Res. 87, 2611-2619.

Berckhemer, H. (1969) Direct evidence for the composition of the lower crust and the Moho, Tectonophysics 8, 97-105.

Birch, F. (1960) The velocity of compressional waves in rocks to 10 kilobars, Part 1, J. Geophys. Res. 65, 1083-1103.

Bird, P. (1978) Initiation of intracontinental subduction in the Himalaya, J. Geophys. Res. 83, 4975-4987.

Bird, P. (1980) Fault slip rates microplate velocities and mantle flow in southern California (abs.), EOS, Trans. Am. Geophys. Union 61, 1125-1126.

Bone, Marion R. (1981) A Case History of 3D Seismic Application in the Gulf of Mexico. Geophysical Service Inc.

Bott, M. H. P. (1980) Mechanism of subsidence at passive continental margins, dynamics of plate interiors, Geodynamics Series 1. Washington, D.C., Am. Geophys. Union, pp. 27-35.

Braile, L. W., R. B. Smith, J. Ansorge, M. R. Baker, M. A. Sparlin, C. Prodehl, M. M. Schilly, J. H. Healy, S. T. Mueller, and K. H. Olsen (1982) The Yellowstone-Snake River Plain seismic profiling experimerustal structure of the eastern Snake River Plain. J. Geophys. 87, 2597-2609.

Brown, L. D... Krumhansl, C. E. Chapin, A. R. Sanford, F. A. Cook, S. Kaufm. E. Oliver, and F. S. Schilt (1979) COCORP seismic reflectidies of the Rio Grande Rift, in R. E. Riecker, ed., Rio Grant: Tectonics and Magmatism. Washington, D.C., Am. Geophys., pp. 169-184.

Brown, L. D.. Chaplin, A. R. Sanford, S. Kaufman, and J. Oliver (1980) Dcructure of the Rio Grande Rift from seismic reflectifiling, J. Geophys. Res. 85, 4773-4800.

Brown, L. D.,ensen, J. Oliver, S. Kaufman, and D. Steiner (1982) Rift stri beneath the Michigan Basin from COCORP profiling, Geology 15-649.

Burchfiel, B.1980) Eastern European Alpine system and the Carpathiacline as an example of collision tectonics, Tectonopt 63, 31-61.

Candres, C. Cd F. Ryall (1983) Geometry of magma bodies beneath Long Vallalifornia, determined from anomalous earthquake signals, ys. Res. Lett. 10(8), 690-692.

Cape, C. D., Geary, and G. A. Thompson (1983) Cenozoic normal faulting he shallow structure of the Rio Grande Rift near Socorro, exico, Geol. Soc. Am. Bull. 94, 3-14.

Carter, J. D.G. Audley-Charles, and A. J. Barber (1976) Stratigral analysis of island arc-continental margin collision in easternesia, Geol. Soc. Lond. J. 132, 179-198.

Cerveny, V., Psencik (1979) Ray amplitudes of seismic waves in laterallynogeneous media, Geophys. J. R. Astron. Soc. 57, 91-106.

Cerveny, J., ager, and I. Psencik (1974) Computation of geometriceading of seismic body waves in laterally inhomogenmedia with curved interfaces, Geophys. J. R. Astron. Soc. 38, 9

Cerveny, V., Molotokov, and I. Psencik (1977) Ray Method in Seismologyague University, 214 pp.

Chapman, C. H78) A new method for computing synthetic seismograms, Geophys. JAstron. Soc. 54, 481-518.

Chapman, C. H.R. Drummond (1982) Body-wave seismograms in inhomogeneedia using Maslov asymptotic theory, Bull. Seismol. Soc. Am. 777-S318.

Chen, W. P., a Molnar (1981) Constraints on the seismic wave velocity sure beneath the Tibetan Plateau and their tectonic implicatio. Geophys. Res. 86, 5937-5962.

Christensen, N (1965) Compressional wave velocities in metamorphic rocks at Pres to 10 kilobars, J. Geophys. Res. 70, 6147-6164.

Cockerham, R. nd W. L. Ellsworth (1980) Remnants of the subduction process in mantle beneath central California (abs.), Earthquake Notes 50, 5

Cook, F. A., a E. Oliver (1981) The late Precambrian-early Paleozoic nental edge in the Appalachian orogen, Am. J. Sci. 281, 993-10

Cook, F. A., L. D. Brown, and J. E. Oliver (1980) The southern Appalachians and the growth of continents, *Sci. Am. 243*(4), 156-168.

Coney, P. J. (1980) Cordilleran metamorphic core complexes: an overview, *Geol. Soc. Am. Memoir 153*, 7-31.

Coney, P. J., D. L. Jones, and J. W. H. Monger (1980) Cordilleran suspect terranes, *Nature 28*, 329-333.

Counselman, C. C. (1982) The Macrometer (TM) Interferometric Surveyor, *in Proceedings*, International Symposium on Land Information at the Local Level, University of Maine at Orono, August 9-12, pp. 233-241.

Crosson, R. (1976) Crustal structure modeling of earthquake data. 1. Simultaneous least squares estimation of hypocenter and velocity parameters, *J. Geophys. Res 81*, 3036-3046.

Davis, G. A., J. W. H. Monger, and B. C. Burchfiel (1978) Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, *in Pacific Coast Paleostratigraphy*, Symposium 2, Pacific Section, *Soc. Econ. Paleontol. Mineral.*, 1-32.

Dewey, J. F. (1980) Episodicity, sequence, and style at convergent plate boundaries, *Geol. Assoc. Can. Spec. Pap. 2020*, 553-573.

Dickinson, W. R., and W. S. Snyder (1979) Geometry of subducted slabs related to San Andreas transform, *J. Geol. 87*, 609-627.

Duffield, W. A., C. R. Bacon, and G. B. Dalrymple (1980) Late Cenozoic volcanism, geochronology, and structure of the Coso Range, Inyo County, California, *J. Geophys. Res. 85*, 2381-2404.

Ervin, C. P., and L. D. McGinnis (1975) Reelfoot Rift: reactivated precursor to the Mississippi Embayment, *Geol. Soc. Am. Bull. 86*, 1287-1295.

Fuchs, K., and G. Muller (1971) Computation of synthetic seismograms with the reflectivity method and comparison with observations, *Geophys. J. R. Astron. Soc. 23*, 417-433.

Fuis, G. S., W. D. Mooney, J. H. Healy, G. A. McMechan, and W. J. Lutter (1981) Seismic refraction studies of the Imperial Valley region: profile models, a travel-time contour map, and a gravity model. USGS Open-file Report No. 81-270.

Fuis, G. S., W. D. Mooney, J. H. Healy, G. A. McMechan, and W. J. Lutter (1982) Crustal structure of the Imperial Valley region, *U.S. Geol. Surv. Prof. Pap. 1254*, 25-49.

Fuis, G. S., W. D. Mooney, J. H. Healy, G. A. McMechan, and W. J. Lutter (1983) A seismic refraction survey of the Imperial Valley region, California, *J. Geophys. Res.* (in press).

Gee, D. G. (1975) A tectonic model for the central part of the Scandanavian Caledonides, *Am. J. Sci. 275A*, 468-515.

Gourevitch, S. A., R. I. Abbot, C. C. Counselman, R. W. King, A. R. Paradis, and I. I. Shapiro (1983) Portable Interferometer Terminals for Geodynamics: Status and Plans (abs.), NASA Geodynamics Program Review, January.

Hadley, D., and H. Kanamori (1977) Seismic structure of the Transverse Ranges, California, *Geol. Soc. Am. Bull. 88*, 1469-1478.

Hale, L. D., and G. A. Thompson (1982) The seismic reflection character of the continental Mohorovičić discontinuity, *J. Geophys. Res. 87*, 4625-4635.

Hamilton, W. (1979) Tectonics of the Indonesian region, U.S. Geol. Surv. Prof. Pap. 1078, 345 pp.

Harris, L. D., and R. C. Milici (1977) Characteristics of thin-skinned style of deformation in the southern Appalachians, and potential for hydrocarbon traps, U.S. Geol. Surv. Prof. Pap. 1018, 40 pp.

Hawley, B. W., G. Zandt, and R. B. Smith (1981) Simultaneous inversion for hypocenters and lateral velocity variations: an iterative solution with a layered model, J. Geophys. Res 86, 7073-7086.

Haxby, W. F., D. L. Turcotte, and J. M. Bird (1976) Thermal and mechanical evolution of the Michigan Basin, Tectonophysics 36, 57-75.

Helmberger, D. V. (1968) A travel time and amplitude interpretation of a marine refracton profile: primary waves, J. Geophys. Res. 74, 483-494.

Hinze, W. J., J. W. Bradley, and A. R. Brown (1978) Gravimeter surveying in the Michican Basin deep borehole, J. Geophys. Res. 83, 5864-5868.

Inter-Union Commission on the Lithosphere (1981) Dynamics and Evolution of the Lithosphere: The Framework for Earth Resources and the Reduction of Hazards, ICL Report No. 1. Karlsruhe, Federal Republic of Germany.

Isachsen, T. W. (1975) Possible evidence for contemporary doming of the Adirondack Mountains, New York, and suggested implications for regional tectonics and seismicity, Tectonophysics 29, 169-181.

Isacks, B., J. Oliver, and L. R. Sykes (1968) Seismology and the new global tectonics, J. Geophys. Res. 73, 5855-5899.

Iyer, H. M., and R. M. Stewart (1977) Teleseismic technique to locate magma in the crust and upper mantle, Bull. 96, Oreg., Dep. Geol. Miner. Ind.

Iyer, H. M., J. R. Evans, G. Zandt, R. M. Stewart, J. M. Coakley, and J. N. Roloff (1981) A deep low-velocity body under the Yellowstone caldera, Wyoming: delineation using teleseismic P-wave residuals and tectonic interpretation: summary, Geol. Soc. Am. Bull. 92, 792-798.

Jentsch, M. (1979) Reinterpretation of a deep seismic-sounding profile on the Ukranian Shield, J. Geophys. 45, 355-372.

Jones, D. L., A. Cox, P. Coney, and M. Beck (1982) The growth of western North America, Sci. Am. 247, 70-84.

Julian, B., and R. S. Cockerham (1983) Mechanisms of the May 1980 earthquakes near Long Valley caldera, California: evidence for dike injection, Earthquake Notes 54, 88-89.

Kanamori, H., and J. W. Given (1981) Use of long period surface waves for fast determination of earthquake source parameters, Phys. Earth Planet. Int. 11, 312-337.

Keller, G. R., L. W. Braile, and J. W. Schlue (1979) Regional crustal structure of the Rio Grande Rift from surface wave dispersion measurements, *in* R. E. Riecker, ed., Rio Grande Rift: Tectonics and Magnetism. Washington, D.C., Am. Geophys. Union, pp. 115-126.

Kosminskaya, I. P. (1971) Deep Seismic Sounding of the Earth's Crust and Upper Mantle. New York, Plenum Publishing, 184 pp.

Lachenbruch, A. H., and J. H. Sass (1980) Heat flow and the energetics of the San Andreas fault zone, J. Geophys. Res. 85, 6185-6222.

Lynn, H. B., L. D. Hale, and G. A. Thompson (1981) Seismic reflections from the basal contacts of batholiths, J. Geophys. Res. 86, 10633-10638.

Lynn, H. B., S. Quam, and G. A. Thompson (1983) Depth migration and interpretation of the COCORP Wind River, Wyoming, seismic reflection, Geology 11, 462-469.

McKenzie, D. P. (1972) Active tectonics of the Mediterranean region, Geophys J. R. Astron. Soc. 8, 1-32.

McKenzie, D. (1978) Some remarks on the development of sedimentary basins, Earth Planet. Sci. Lett. 40, 25-32.

McMechan, G. A., and W. Mooney (1980) Asymptotic ray theory and synthetic seismograms for laterally varying structures: theory and application to the Imperial Valley, California, Bull. Seismol. Soc. Am. 70, 2021-2035.

Molnar, P., and D. Gray (1979) Subduction of continental lithosphere: some constraints and uncertainties, Geology 7, 58-62.

Molnar, P., and P. Tapponnier (1975) Cenozoic tectonics of Asia: effects of a continental collision, Science 189, 419-426.

Montadert, L. D., D. Roberts, J. C. Sibuet, and H. Gairaud (1980) Rift structure and continent ocean transition along the NE Atlantic passive continental margins (abs.), Int. Geol. Congr., Resumes 3, 1347.

Mooney, W. D. (1983) Crustal and upper mantle velocity structure of the central Yunnan Province, southwest China, using earthquake sources, submitted to J. Seis. Res. Yunnan, P.R.C.

National Oceanic and Atmospheric Administration (1980) Cental North Atlantic Ocean Basin and Continental Margins: Geology, Geophysics, Geochemistry, and Resources Including the Transatlantic Traverse. NOAA Atlas 3. Washington, D.C., U.S. Government Printing Office.

National Research Council (1977) Global Earthquake Monitoring: Its Uses, Potentials, and Support Requirements. Panel on Seismograph Networks, Committee on Seismology, Assembly of Mathematical and Physical Sciences. Washington, D.C., National Academy of Sciences.

National Research Council (1980a) Continental Tectonics. Studies in Geophysics. Geophysics Study Committee, Geophysics Research Board, Assembly of Mathematical and Physical Sciences. Washington, D.C., National Academy of Sciences.

National Research Council (1980b) Geodynamics in the 1980's. U.S. Geodynamics Committee, Geophysical Research Board, Assembly of Mathematical and Physical Sciences. Washington, D.C., National Academy of Sciences.

National Research Council (1980c) U.S. Earthquake Observatories: Recommendations for a New National Network. Panel on National, Regional, and Local Seismograph Networks; Committee on Seismology; Assembly of Mathematical and Physical Sciences. Washington, D.C., National Academy of Sciences.

National Research Council (1983) Effective Use of Earthquake Data. Panel on Data Problems in Seismology; Committee on Seismology; Board on Earth Sciences; Commission on Physical Sciences, Mathematics, and Resources. Washington, D.C., National Academy of Sciences.

National Research Council (1984) Explosive Volcanism: Inception, Evolution, and Hazards. Studies in Geophysics. Geophysics Study Committee; Geophysics Research Forum; Commission on Physical Sciences, Mathematics, and Resources. Washington, D.C., National Academy Press.

Neidell, N. S., and E. Poggiagliolmi (1977) Stratigraphic modeling and interpretation-geophysical principles, AAPG Memoir 26, 389-416.

Oliver, Jack (1982a) Exploration of the continental basement the world over by seismic reflection profiling: a goal for the solid earth sciences, EOS 63 (no. 7).

Oliver, Jack (1982b) Probing the structure of the deep continental crust, Science 216, 689-695.

Oliver, Jack (1983) Exploring the geologic structure of the continental crust, J. Geol. Educ. 31, 277-294.

Olson, K. H, G. R. Keller, and J. N. Stewart (1979) Crustal structure along the Rio Grande Rift from seismic refraction profiles, in R. E. Riecker, ed., Rio Grande Rift: Tectonics and Magmatism. Washington, D.C., Am. Geophys. Union, pp. 127-143.

Oppenheimer, D. H., and K. E. Herkenhoff (1981) Velocity-density properties of the lithosphere from three-dimensional modeling at the Geysers-Clear Lake, California, J. Geophys. Res. 86, 6057-6065.

Pakiser, L. C. (1963) Structure of the crust and upper mantle in the western United States, J. Geophys. Res. 68, 5747-5756.

Perez, O., and K. H. Jacob (1980) Tectonic model and seismic potential of the eastern gulf of Alaska and Yakataga seismic gap, J. Geophys. Res. 85, 7132-7150.

Priestley, K., J. Orcutt, and J. N. Brune (1980) Higher-mode surface waves and structure of the Great Basin of Nevada and western Utah, J. Geophys. Res. 85, 7166-7174.

Raikes, S. A. (1980) Regional variations in upper mantle structure beneath southern California, Geophys. J. R. Astron. Soc. 63, 187-216.

Reasenberg, P., W. Ellsworth, and A. Walter (1980) Teleseismic evidence for a low-velocity body under the Coso geothermal area. J. Geophys. Res. 85, 2471-2483.

Riecker, R. E., ed. (1979) Rio Grande Rift: Tectonics and Magmatism. Washington, D.C., Am. Geophys. Union, 438 pp.

Rinehart, E. J., A. R. Sanford, and R. M. Ward (1979) Geographic extent and shape of an extensive magma body at midcrustal depths in the Rio Grande Rift near Socorro, New Mexico, in R. E. Riecker, ed., Rio Grande Rift: Tectonics and Magmatism. Washington, D.C., Am. Geophys. Union, pp. 237-251.

Sanford, A. L., R. P. Mott, Jr., P. J. Shuleski, E. J. Rinehart, F. J. Caravella, R. M. Ward, and T. C. Wallace (1977) Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico, in J. G. Heacock, ed., The Earth's Crust, Geophys. Monogr. 20, Washington, D.C., Am. Geophys. Union, pp. 385-403.

Schneider, J. F., R. P. Meyer, and L. A. Powell (1981) Timing and positioning of seismographs from Omega navigation signals, in Proceedings of the Sixth Annual Meeting of the International Omega Association, Montreal, pp. 11-1 to 11-8.

Seeber, L., and J. Armbruster (1981) Great detachment earthquakes along the Himalayan Arc and long-term forecasting, in D. W. Simpson and P. G. Richards, eds., Earthquake Prediction: An International Review, Maurice Ewing Series 4. Washington, D.C., Am. Geophys. Union, pp. 259-277.

Sibson, R. H. (1982) Fault zone models, heat flow, and the depth distribution of earthquakes in the continental crust of the United States, Bull. Seis. Soc. Am. 72, 151-163.

Sleep, N. H., and L. L. Sloss (1978) A deep borehole in the Michigan Basin, J. Geophys. Res. 83, 5815-5819.

Smith, R. B. (1981) Listric faults and earthquakes, What evidence? EOS, Trans. Am. Geophys. Union 62, 961.

Smith, R. B., and L. W. Braile (1984) Crustal structure and evolution of an explosive silicic volcanic system at Yellowstone National Park, in National Research Council, Explosive Volcanism. Washington, D.C., National Academy Press.

Smith, R. B., M. M. Schilly, L. W. Braile, J. Ansorge, J. L. Lehman, M. R. Baker, C. Prodehl, J. H. Healy, S. Mueller, and R. W. Greensfelder (1982) The 1978 Yellowstone-Eastern Snake River Plain seismic profiling experiment: crustal structure of the Yellowstone region and experiment design, J. Geophys. Res. 87, 2583-2596.

Smithson, S. B., J. A. Brewer, S. Kaufman, J. E. Oliver, and C. A. Hurich (1979) Structure of the Laramide Wind River uplift, Wyoming, from COCORP deep reflection data and from gravity data, J. Geophys. Res. 84, 5955-5972.

Stauber, D. A. (1982) Two-dimensional compressional wave velocity structure under San Francisco volcanic field, Arizona, from teleseismic P residual measurements, J. Geophys. Res. 87, b7, 5451.

Steinhart, J. S., and D. P. Meyer (1961) Explosion studies of continental structure, Carnegie Inst. Washington Publ. 627, 409 pp.

Stommel, H. E., and J. M. Graul (1978) Current trends in geophysics, Arabian J. Sci. Eng., Special Issue.

Tatel, H. E. , and M. A. Tuve (1955) Seismic exploration of a continental crust, in Poldervart, ed., Crust of the Earth, Geol. Soc. Am. Spec. Pap. 62, 35-50.

Thompson, G. A., and M. L. Zoback (1979) Regional geophysics of the Colorado Plateau, Tectonophysics 61, 149-181.

Tucholke, B. E., and G. S. Mountain (1979) Seismic stratigrahy, lithostratigraphy and paleosedimentation patterns in the North American Basin, in M. Talwani, ed., Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment, Maurice Ewing Series 3. Washington, D.C., Am. Geophys. Union, pp. 58-86.

Vail, P. R., R. M. Mitchum, Jr., R. G. Todd, J. M. Widmer, S. Thompson, III, J. B. Sangree, J. N. Bubb, and W. G. Hatlelid (1977) Seismic stratigraphy and global changes of sea level, in Seismic Stratigraphy, AAPG Memoir 26, 49-212.

Walck, M. C., and B. J. Minster (1982) Relative array analysis of upper mantle lateral velocity variations in southern California, J. Geophys. Res. 87, 1757-1772.

Walcott, R. I. (1978) Present tectonics and late Cenozoic evolution of New Zealand, Geophys. J. R. Astron. Soc. 52, 137-164.

Western Geophysical (1975) Wave Equation Migration: Two Approaches. Houston, Tex.

Wong, Y. K., S. B. Smithson, and R. L. Zawislak (1982) The role of seismic modeling in deep crustal reflection interpretation, Part I, Contrib. Terti. Quat. Geol. 20, 91-109.

Zandt, G. (1981) Seismic images of the deep structure of the San Andreas fault system central Coast Ranges, California, J. Geophys. Res. 86, 5039-5052.

Zoback, M. D., R. M. Hamilton, A. J. Crane, D. P. Russ, F. A McKeowan, and S. R. Brockman (1980) Recurrent intraplate tectonism in the New Madrid seismic zone, Science 209, 971-976.

APPENDIX A

POSSIBLE AGENDA FOR NATIONAL WORKSHOP ON INSTRUMENT DEVELOPMENT

PHASE 1--DESIGN

Announcements and invitations to industry, academia, and government for National Workshop on Instrument Development to be held as soon as possible after acceptance of this report (sponsored by Committee on Seismology in association with national meeting, e.g., SEG).

NATIONAL WORKSHOP ON INSTRUMENT DEVELOPMENT to present and prioritize specific scientific and technological requirements.

Tentative Agenda:

1. Technical presentations of existing systems and subsystems.
2. Presentations and critique of paper designs, for example:
    a. Single-channel with integral seismometer, tape recorder, battery, Omega receiver for time, and/or radio receiver for local time and commands.

    b. Three-channel system with attributes as above.

    c. Six-channel system to provide for three-component velocity transducer and three-component accelerometer. The latter satisfies both strong-motion and long-period transducer needs.

    d. Greater-than-six-channel system with provisions for digital telemetry or long wires from remote transducers, radio command, and consensus triggering.

    e. Central event-detector array to control recording in the individual instruments. Radio commands include turn-on, sampling speed, record duration.
3. Recommendations for basic instrument design from discussion generated by presentations of existing and paper designs.

4. Appointment of a committee to study and implement the selected design. The following seven specialties should be considered for inclusion:

    a. analog hardware
    b. digital hardware
    c. software
    d. packaging
    e. diagnostics
    f. playback hardware
    g. playback software

5. Selection of an institution to seek support for the activities of the Design Team for a one-year period.

DESIGN TEAM

Meeting #1 (during Workshop)

1. Formulate rough specifications and block diagrams.

2. Choose bus standards, if required.

3. Formulate and adopt standard transducer specifications.

4. Formulate or adopt existing tape-recording formats and standards for field recording and data interchange.

5. Adopt operating system and language standards.

After meeting #1:

1. Design Team members formulate detailed specifications and block diagrams in specialty areas.

2. Permanent working committee distributes designs to all interested parties with requests for mail reviews by both potential manufacturers and users.

Meeting #2 (six months after National Workshop):

1. Revise specifications according to mail reviews. Assemble and publish detailed designs and specifications.

2. Devise plans to carry through the prototype stage.

APPENDIX B

CAPABILITIES OF SOME PRESENT AND PLANNED INSTRUMENTS

Seismographs incorporating some of the aspects of the advanced design we are recommending have originated in academia, industry, and government laboratories. In this appendix we present, as examples, specifications for the instruments developed by the U.S. Geological Survey; the University of Wisconsin, Madison; the University of California, Los Angeles; and those for the new instruments being considered for the European Commission for Controlled Source Seismology. They are as follows:

Exhibit B-1	Specifications for USGS Digital Event Recorder, GEOS
Exhibit B-2	General Specifications, University of Wisconsin Digital Recording Seismograph
Exhibit B-3	Specifications for UCLA Eight-Channel Seismograph
Exhibit B-4	Specifications for New European Consortium-Designed Portable Digital Seismograph

EXHIBIT B-1 Specifications for USGS Digital Event Recorder, GEOS

Sensor Inputs

Input channels: 6 balanced differential inputs.
Input impedance: 940-K-ohm differential, 470 K ohms to ground. May be shunted for lower impedance.
Input voltage for full-scale input: ±10 mV to ±10 V programmable in 6-dB steps, 60-dB to 0-dB gain.
Preamplifier dynamic range: greater than 100 dB at 0-dB gain.
System noise: less than 3 μV peak to peak in the bandpass 1 Hz to 50 Hz; less than 5 μV peak to peak in the bandpass 1 Hz to 500 Hz.
Option: noise can be reduced to 1 μV peak to peak in the bandpass 1 Hz to 50 Hz with low-noise Op Amps, power will be increased by 70 mW per channel.
Filters: low pass Butterworth, 42 dB per octave; 17 Hz, 33 Hz, 50 Hz, and 100 Hz. High pass: 6 dB per octave at 1 Hz.
Calibration: internal, automatic with or without sensors.
Transient protection: inputs protected with transient protectors at ±15 V.
Input connectors: waterproof, multipin, 3-channel each.

A/D Converter and Multiplexer

Resolution: 16 bits (1 part in 65,536).
Stability and linearity: ±1 count no missing codes over full temperature range of -20°C to +60°C.
Conversion rate (total samples per second for all active channels): 1,200 samples per second maximum, .29 samples per second minimum. Programmable as 1,200/N were N is 1 through 4,096.
Crossfeed isolation: greater than 100 dB.

Data Memory

Size: 4,096 words, 16 bits per word.
Access: data are read into the memory via a cycle steal DMA from the A/D converter. Data are written from the memory via a simultaneous DMA to the magnetic tape formatter.
Pretrigger memory: five 512-word blocks minimum at 1,200 samples per second (2.14 seconds). Six 512-word blocks at 300 samples per second (10.24 seconds).

Program Memory

Executable memory: 4 K 12-bit word CMOS RAM.
Program storage: 8 K 12-bit word CMOS PROM.
Alternate program storage: programs may be stored on magnetic tape for loading directly into program RAM.

Power Requirements

Voltage, current: +24 VDC nominal ±15%, 40 mA nominal in operating mode with display off; 300 mA nominal with display on; 600 mA with display on and recording.

Internal batteries: +24 V, 5 AH Gates type, will operate about 3 days on internal batteries. Connector provided for internal battery charging or external battery operation.

Recording Modes

Self-triggering:

Near-field: short-term average (STA), long-term average (LTA) ratio.

Teleseismic: comparative ratios for two selected frequency bands.

Preset time: will record at selectable times and intervals.

Both: will operate in both preset time and self-triggering modes.

Manual: will record under keyboard control for start-stop functions.

Recording Media

Cartridge: 3M type DC300 with up to 450 ft of digital tape.

Recording density: 1,600 bpi.

Number of tracks: 4, recorded in serpentine fashion, records on one track at a time.

Record block length: 512 words (5.12 in.), interrecord gap, 0.75 in.

Tape capacity: 3,680 512-word blocks (1.88 million samples) typical for 450-ft tape. Twenty-six minutes continuous record time at the maximum sample rate.

Tape speed: 30 ips, write or read.

Display and Keyboard

Display type: LED with optical filters, 32 characters, alphanumeric, 18 segment, character height .15 in.

Keyboard type: mechanical switch with dust cover and water seal. Twenty-button keyboard with numeric and function entry.

Status

Time, battery voltage, number of events, percentage of tape used, up-time (elapsed time since power on).

Internal Time Base

Frequency: 3 MHz

Temperature stability: ±1 x 10^{-6}, -20°C to +70°C.

Aging rate: less than 5 x 10^{-7} per year.

Communications Interface

I/O port: RS-232 compatible, Baud rate programmable to standard rates.

Time Synchronization

WWVB receiver: internal receiver designed to be used with active, ferrite antenna. Will automatically synchronize internal clock to WWVB under program command.

External time: will start internal clock with external pulse and will compare and note time difference between external time tick and internal clock after start-up.

Manual start: time can be entered through keyboard and started by key manually.

Physical and Environmental Characteristics

Case type: waterproof aluminum case, 20 1/2 in. long, 9 7/8 in. wide, 13 3/4 in. high.

Weight: 47 lb with internal batteries.

Operating temperature range: -20°C to +60°C, 15% to 95% relative humidity.

EXHIBIT B-2 General Specifications, University of Wisconsin Digital Recording Seismograph (Three-component system)

Recorder:	5-in. reel-to-reel, 1/4-in. tape.
Tape:	1,800 ft (audio grade).
Tape format:	4 tracks digital: 1 component/track; 1 track error correction. System status, time, and Omega phase distributed with the data.
Capacity:	6 hours recording (e.g., 360 3-component 60-s events at 100 samples/s/track).
Delay:	512 samples/track.
Dynamic range:	106 dB. Input noise = 0.25 μV_{pp}. Clipped = 0.05 μV_{pp} input.
Modes:	Programmed and/or triggered.
Configuration programming:	Sample rate; amplifier gain; trigger parameters.
Schedule programming:	Time (in whole minutes), day, function (e.g., turn-on, trigger arm and disarm). Up to 24 entries.
Display:	12-digit LED.
Status review:	Includes time, configuration, current use time, number of events recorded, times of last 100 events.
Internal timing:	TCXO clock to 99 days.
External timing:	N x 10 s from phase pattern of Omega radio navigation signal.
Positioning:	Differential Omega relative positioning between recording stations.
Power:	12.5 V DC ±20%. 25 mA quiescent current; 400 mA recording.
Dimensions:	56 x 33 x 40 cm.
Weight:	22 kg.
Temperature:	0°C to 50°C normal operating range. -20°C to 70°C at reduced specifications. -40°C to 80°C storage.

EXHIBIT B-3 Specifications for UCLA Eight-Channel Seismograph

GENERAL

Number of channels:	8
Signal processing:	Microprocessor-controlled 12-bit A/D conversion
Interfaces:	Standard keyboard 2-line 16-character LCD display 2 RS232C serial ports (2 x 16)/(4 x 8) bit bidirectional programmable parallel I/O 1 IEEE-488 port 3 Edge meters with 8-bit precision voltage outputs
Display:	3 Edge meter outputs. Software selects of 3 of 8 input channels for display. Display gain also software-selectable. Data are displayed after digital signal processing is done. Analog voltage outputs paralleling meters are available above each meter for chart recorders, etc. (8-bit resolution).

SIGNAL PROCESSING

6502 Microprocessor-controlled software allows:

Channel selection:	1 to 8
Sample rate:	DC-1000 samples x channels/s
Recursive filter:	DC-40 samples x channels/s; $f(X_1) = 15/16\ f(X_{1-t}) + 1/16\ X_1$; output resolution 16 bits
Other filters:	Optional
Gain:	1, 2, 4, and 8 times input
Input conditioning:	Seismic Amp. appropriate for specific seismometer used. (Specified by user.)
Input protection:	±25 V

TIME BASE

	Long-term stability	±0.2 ppm/yr
	Temperature stability	±0.2 ppm/yr 0°C to 50°C
Optional:	WWV Internal Receiver	
	Absolute accuracy	±2 ms
External synch.:	For accurate time setting from external device	

CARTRIDGE RECORDER

Capacity:	23.6 M bytes formatted (13,700 blocks) x (6904 bytes/block) Cartridge recorder has its own 6502 computer with 2 8-K-byte buffers shared with master processor allowing continuous data sampling concurrent with recording.
Density:	8333 bpi
Throughput:	690 bytes/s maximum
Buffer write time:	6 s nominal
Playback access time:	45 s
Error rate:	Soft: 1 in 10^7 Hard: 1 in 10^9

INTERFACES

64-key standard size ASCII tactile keyboard
2 RS232C serial Baud rate programmable
(300 to 19,200 Baud)
1 IEEE-488 ASCII
1 (2 x 16)/(4 x 8) bidirectional programmable

SYSTEM POWER

	Current:	300 mA
	Voltage:	12 V nominal
Internal battery:		6 AH
	Typical Field Power Consumption	
	20 sample/s one channel	
	7.2 AH/day	3.6 W
External:	Current:	300 mA
	Voltage:	12 V nominal

EXHIBIT B-4 Specifications for New European Consortium-Designed Portable Digital Seismograph

1.0 Technical Requirements

1. Digitizing intervals: Different applications require that the uppermost corner frequency should be selectable in three steps:
   a. 50.0 Hz
   b. 25.0 Hz
   c. 12.5 Hz
   The lower frequency of 0.1 Hz should be internally selectable to DC.
2. Internal noise should be <0.5 μV_{pp} and related to the signals in the band between 0.1 and 50 Hz.
3. Dynamic range: >100 dB with gain-ranging amplifier.
4. Resolution during digitizing: 10 bits.
5. Amplitude errors: <1% after correction for the filter amplitude.
6. Number of channels: variable, one to four.
7. Timing: quartz clock accurate to $<\pm 5 \times 10^{-7}$ (between -20°C and +60°C) $<\pm 5 \times 10^{-8}$ at constant temperature during a 24-hour period.
   a. It should be possible to synchronize using an external time source.
   b. Time code: Fast code and Slow code following the Claustahler recommendation.
8. Event-trigger windows in pre-event recorder mode:
   a. >5 s for an upper frequency of 50 Hz.
   b. >10 s for an upper frequency of 25 Hz.
   c. >20 s for an upper frequency of 12 Hz.
9. Clock with programmable time windows capable of turning on and off at >50-min window lengths.

2.0 Operating Requirements

1. Operating temperature range: -20°C to +60°C.
2. Power supply: external 9 to 15 V; internal monocell.
3. Power requirement (without the data recorder):
   a. In the event trigger mode: <50 mA
   b. The data recorder should also have lower power requirements.
4. Dimensions: 50 x 80 x 20 cm (height, width, depth) in a suitcase or shockproof casing including the data recorder.
5. Maximum weight: 15 kg.
6. Housing: should be dustproof and waterproof.
7. Mechanical stability: can be dropped from 1 m.
8. Uncomplicated operation.
9. The control of the function of the instrument, calibration pulses, the setting of the clock at the on and off times should be located in a terminal that can be attached to it (there should be no switches or places that need to be serviced within the housing).
10. Price: less than about U.S. $5,000.

APPENDIX C

SUMMARY OF PROCEEDINGS OF A WORKSHOP ON GUIDELINES FOR INSTRUMENTATION DESIGN IN SUPPORT OF A PROPOSED LITHOSPHERIC SEISMOLOGY PROGRAM

May 4-5, 1983
Salt Lake City, Utah

This meeting was convened under the auspices of and with support from the National Science Foundation, Division of Earth Sciences. It was convened by Robert B. Smith and Walter J. Arabasz of the Department of Geology and Geophysics, University of Utah. This appendix includes the following:

Exhibit C-1	Introduction and Summary of Proceedings
Exhibit C-2	Conclusions
Exhibit C-3	Workshop Participants

EXHIBIT C-1

INTRODUCTION AND SUMMARY OF PROCEEDINGS

Walter J. Arabasz and Robert B. Smith

Introduction

A workshop on "Guidelines for Instrumentation Design in Support of a Proposed Lithospheric Seismology Program" was held May 4-5, 1983, at the Marriott Hotel, Salt Lake City, Utah. The two-day workshop, organized with support from the National Science Foundation, was hosted by the University of Utah and was convened in conjunction with the 1983 Annual Meeting of the Seismological Society of America (SSA). Its goal was to initiate dialogue among seismologists, engineers, technicians, and manufacturers of seismic instruments regarding new instrumentation for lithospheric seismology. Specifically, the focus was discussion of minimum design criteria for a new generation of portable digital seismographs--applicable for lithospheric exploration during the next decade and beyond.

As national and international advocacy grows for large-scale initiatives in lithospheric seismology, there is a clear need to develop some consensus within the seismological community about the character and design of instrumentation to be developed and used for such studies. In the case of U.S. seismologists, the program alluded to in the workshop title is one being addressed by the Committee on Seismology of the National Academy of Sciences (NAS).

A basic motivation for organizing the workshop was the assessment by us and many of our colleagues in the seismological community that new initiatives in lithospheric seismology will require a much different and more modern type of instrument than is currently available. Several organizations, both industrial and academic, are pursuing diverse instrument designs for different objectives. It was felt that a workshop to address common goals might achieve some minimum standardization and eliminate duplication of effort. Timing of the 1983 SSA meeting in Salt Lake City provided an ideal opportunity for the University of Utah to propose and organize the desired workshop as an adjunct to the SSA meeting.

Organization of the workshop was coordinated with ongoing efforts of a subcommittee on lithospheric seismology reporting to the NAS Committee on Seismology. In particular, community input was needed by that NAS subcommittee to formulate recommendations regarding a national set of instruments for investigations in lithospheric seismology. The Salt Lake City meeting was not intended to preempt a workshop (of much greater scope) likely to be proposed by the NAS subcommittee. Rather, the intent was preliminary discussion of instrument standards. As a practical matter, research initiatives (already made by various institutions) involving instrument development and/or procurement were waiting on some sense from the seismological community regarding preferred future direction.

The workshop was an open meeting. A general announcement and invitation to all interested persons were made as part of the program announcement of the Salt Lake City SSA meeting. Notice was mailed to all SSA members, and special efforts were made to notify research groups actively involved with seismic instrumentation and lithospheric seismology.

Fifty-five individuals, identified in Exhibit C-3, participated in the workshop. The format of the meeting involved a spectrum of topical presentations intended to provide some focus for discussion. Fifteen selected participants had been invited in advance to prepare brief presentations and lead corresponding open discussions. The final session of the workshop consisted of a general discussion, led by Walter D. Mooney, John Orcutt, and Scott B. Smithson, aimed at some formulation of conclusions and consensus.

We next present a synopsis of the workshop proceedings. A separate statement of conclusions and concensus (Exhibit C-2)--written by Mooney, Orcutt, and Smithson--then follows.

Summary of Proceedings

The workshop was organized into four sessions: (I) Introduction, (II) Current Lithospheric Seismology Research, (III) Guidelines for Instrumentation and Data Handling, and (IV) General Discussion. A synopsis of each session is provided. (See "Proceedings"[1] for complete report.)

I. Introduction

The motivation for worrying about multiple, standardized seismic instruments comes from the prospect of large-scale multi-institutional field studies of the continental lithosphere during the 1980s. Perhaps the most concrete sign that support for such studies may be feasible is a soon-to-be-released report of the NAS Committee on Seismology [Seismological Studies of the Continental Lithosphere] discussed above. It is understood that the report will recommend that up to 1,000 versatile new seismographs be made available to the U.S. seismological community. For perspective, geophysical industry now uses more than 1,000 recording channels for individual 3-D seismic reflection surveys, and industry consensus foresees common usage of more than 1,000 recording channels for seismic acquisition operations by 1990 (Hewitt, 1983).

---

[1] Proceedings of a Workshop on Guidelines for Instrumentation Design in Support of a Proposed Lithospheric Seismology Program (rev. September 1983), available from Department of Geology and Geophysics, Seismograph Stations, University of Utah, Salt Lake City, Utah 84112.

Federal funding for multimillion-dollar efforts in lithospheric seismology appears feasible only under the masthead of a national program--with standardized equipment constituting a truly national facility. Analogous national facilities, for example, include nuclear reactors of the physics community, giant telescopes of the astronomy community, and hardware of the oceanography community such as deep-sea drilling vessels and the Alvin submersible. Successful funding for new instrumentation and large-scale cooperative experiments in lithospheric seismology undoubtedly depends upon community consensus, unified and prioritized goals, and well-documented plans for use by government funding agencies. A clear relationship between federal funding probabilities and consensus agreement among scientists about priorities has been emphatically stated by George A. Keyworth, II, President Reagan's Science Advisor and director of the Office of Science and Technology Policy (see EOS, May 10, 1983, p. 371).

Seismic instrumentation for the 1980s was identified as the key topic for the present workshop. Indeed, ideas from the workshop participants--as initial indications of community sentiment--were being solicited as valuable input to the NAS report. Apart from the design of standardized instruments, a number of problems were apparent at the outset that eventually would have to be resolved. How would a very large number of portable instruments be maintained and deployed? (Commercially? By dispersal among academic/federal institutions with commitment to cooperate?) How would massive amounts of digital data be archived, accessed, and managed? Can the complete spectrum of seismic applications from Vibroseis[2] to long-period recording be reconciled with realistic design flexibility for a standard seismograph? High-angle reflection experiments seem to require an order of magnitude more instruments than are needed for most other applications; can inexpensive multicopies be reconciled with deluxe instruments needed for most earthquake applications?

Introductory presentations also touched upon a general comparison of active and passive seismic methods for seismic exploration of the lithosphere, an outline of a host of geological problems amenable to seismic investigation, and perspectives on reflection seismology being carried out by university researchers. Also, the idea was well established that new "facilities" for lithospheric seismology clearly go beyond seismographic instruments. They must include equipment for communication and telemetry, perhaps seismic vibrators, playback/processing facilities, and corresponding technical personnel for maintenance and operation.

Studies of surface waves and of teleseismic and local body waves will undoubtedly continue to play an important role in seismic investigations of continental lithosphere. Instrumental possibilities for enhancing such studies warrant serious consideration. These include improving Global Digital Seismic Network (GDSN) coverage--and perhaps upgrading some subset of 1,600 existing telemetered seismic stations to allow their effective use as broadband, large-dynamic-range

---

[2] Throughout this report, the term Vibroseis refers to the trademark of CONOCO, Inc.

networks with enormous aperture. Such suggestions were raised, but not pursued within the framework of the workshop because of its focus on portable digital seismographs.

II. Current Lithospheric Seismology Research

This section of the workshop provided additional introductory background--an overview of existing suitable instrumentation now in use by university/federal researchers, and "what's happening" in terms of international cooperative programs in crustal seismology. A review of the 1978, 1980 Yellowstone-Snake River Plain seismic experiments illustrated effectively the current state of multi-institutional cooperative experiments in lithospheric seismology. At its peak in 1978, the project involved up to 220 instruments, 40 people, and no less than 7 different types of analog and digital seismographs. Subsequent problems for uniform data processing were monumental.

Current instrumental capabilities of U.S. seismologists for pursuing large-scale lithospheric seismology are, in a word, dismal. The continued lack of any significant number of standardized digital seismographs means multi-institutional investigations with "bastard" equipment--and grossly inefficient data collection and processing.

By way of information, current international cooperative programs include the following: (1) An experiment, still in its planning stage, has been proposed for the East African Rift in Kenya; a preliminary phase during the Northern Hemisphere summer of 1984 will be followed by a major experiment during the summer of 1986. The experiment was conceived by the seismology group at Leicester, England; Randy Keller (University of Texas, El Paso) and Klaus Prodehl (Karlsruhe) are involved in planning. (2) As part of a protocol agreement signed in 1980 by the United States and the People's Republic of China, a large-scale crustal refraction project has been planned for Yunnan Province in China. After initial training of Chinese seismologists in the United States, U.S. seismologists will travel to China, under National Science Foundation auspices, to complement Chinese efforts in completing a 1,200-km-long profile. Instrumentation will include 200 new Chinese-built FM-recording seismographs.

III. Guidelines for Instrumentation and Data Handling

During what turned out to be the longest, and perhaps most critical, session of the workshop, group discussion focused on draft specifications for new portable digital seismographs. Initial discussion--and an earlier introductory presentation--seemed to establish basic, nearly universally held expectations for new portable digital seismographs. These include: (1) versatility for varied active/passive seismic applications; (2) reliability under a variety of field conditions; (3) simple (i.e., "fixable" in the field) modular design; (4) rugged, "bounceable" construction (conceivably involving a case suitable for air-freight without yet another external box); (5)

design features to protect vital electronics from water and dirt; (6) compact, reasonably lightweight packaging; (7) "smart" programmable triggering; and (8) low power consumption. (Elimination of requirement for bipolar voltage would facilitate use of locally available 12-V batteries in foreign countries.) These guidelines obviously reflect common field experience--and lead to insistence that design engineers "go into the field" with new instrumentation during the developmental stage.

A complete outline of design parameters suggested by the workshop participants for new portable digital seismographs is contained in the "Proceedings." The following is a thumbnail sketch.

Time Accuracy of Any Sample: 1 ms absolute accuracy (0.1 μs relative accuracy) for explosion and earthquake recording; 250 μs for Vibroseis. (The need for continuously accurate, as opposed to "correctable," timing is open for community debate. But flexible international use of instruments points toward an Omega system.)

Number of Channels: Minimum of 3, but preferably up to 12. (Grouping into 6 or 12 may be feasible for telemetry.)

Bandwidth: 2 to 200 Hz for explosion recording, 5 to 200 Hz for Vibroseis, 0.1 to 500 Hz for local earthquake recording, and 0.01 to 20 Hz for teleseism/surface-wave recording.

Minimum Capacity: 40 to 120 Mbytes for Vibroseis; unspecified for other applications, but 100 Mbytes probably needed (e.g., 25 Mbytes often inadequate for local earthquake recording).

Sample Rate/Event Length: 1 ms/channel, 1 to 5 min for explosion recording; 1 ms/channel, 20 to 60 s for Vibroseis; 0.5 ms/channel, 10 s to 5 min for local earthquakes; 1 s/channel, up to several hours for teleseisms/surface waves.

Signal Dynamic Range: 90 dB for explosion/Vibroseis recording, 90 to 140 dB for local earthquakes (with gain ranging), and up to 140 dB for teleseisms/surface waves.

Resolution/Linearity: 12-bit minimum resolution with gain ranging; half-step differential linearity. (Undecided: Sequential or simultaneously sampling? A-D for every channel or shared?)

Recording Medium: Cartridges are not perfect, but probably represent consensus choice. Solid-state memory was suggested for consideration in production of any large number of active seismic recorders (if distinct from "all-purpose" recorder).

Special Requirements: (1) capability of operating on internal batteries for at least 10 days (important for earthquake recording under emergency conditions); (2) target weight of 20 kg; (3) programmable turn-on; (4) "smart" (unspecified) trigger; (5) capability of stacking and digital filtering; (6) flexibility to accommodate telemetry as well as improvements and new developments downstream; and, perhaps, (7) intelligent computerized checkout to isolate defective modules.

Designing versatility into a standard instrument leads to consideration of a basic instrument augmented by application-specific ("user-specified") subsystems. There was strong consensus that the instrument recorder box should be modular and should incorporate standardized controller software. A standard bus should be selected, and some application-specific subsystems may simply be cards that can be inserted into that bus. (Regarding consideration of a standard bus, see Bailey, 1982). Further, a standard data format must eventually be specified. Selection of A-D converters should be for the fastest sampling rate ever needed, and acquisition functions such as A-D should be independent, but controlled by a microprocessor. Analyses of power consumption and cost-effectiveness will be necessary before any decision can be made regarding where to lock in A-D converters and alias filters.

The morning session on instrumentation continued with presentations dealing with digital ocean-bottom-seismograph (OBS) applications and "feedback" instruments (i.e., having a response controlled by electronics rather than mechanics) for long-period seismology. The experience of oceanographers is clearly useful and relevant for a lithospheric seismology program. Such experience includes the development and comparative testing of digital OBSs, and the management of successful national facilities such as the Deep Sea Drilling Project, Sea Beam bottom mapping, and the Alvin submersible. Regarding long-period instrument response, it was shown that by careful attention to amplifiers (and selection of high-quality sites), it is possible to use mass-produced velocity transducers for inexpensive, portable, high-performance long-period systems effective to periods of 200 s.

During a luncheon, Michael M. Schilly of Amoco Production Company, Denver, give a slide presentation that provided a superb follow-up to the morning's discussion on new portable digital seismographs. As part of a comparison of industry and academic seismic acquisition techniques, Schilly described a state-of-the-art industry experiment for 3-D seismic reflection imaging that involved the use of up to 1,200 seismic group recorders (SGRs)--portable digital cassette recorders controlled by telemetry. Also, he provided a direct comparison of this type of seismic data acquisition by industry (relating to a 3-D experiment carried out by Amoco in the Porcupine Mountain area of northeastern Utah) contrasted with the 1978 Yellowstone-Snake River Plain (Y-SRP) experiment. The comparison is shown in Table C-1-1. (Obvious differences between the Y-SRP recording of refractions and wide-angle reflections and industry recording of 2-D or 3-D high-angle reflections should be kept in mind.)

European seismologists have also been planning the development of new digital seismographs (up to 300) for cooperative studies in crustal seismology. (See "Proceedings" for complete specifications.) Relevant comments from a European visitor touched upon (1) the inevitable need

TABLE C-1-1 Comparisons of Industry Data Acquisition (Porcupine) Versus University Data Acquisition (Y-SRP 1978)

	Y-SRP 1978	Porcupine
Objectives	MOHO 40 km	Down to 6 km
Time to acquire	1 month	6 months
Profiles	12	332 x 210
Seismograms	1,600	791,040
No. charges	12	1648
Charge size	1,000-8,000 lb	80 lb
Seismometers	Variable	MD-81S
Recorders	Analog and digital	SGR II
Components	X, Y, Z	Z
Recorder spacing	1-5 km	61 x 107 m
Total recorders	170	1,000 (480 live)
Data length	10-30 s	6 s
Sample rate	0.02 samples/s	0.002 samples/s
Surveying	Hand picked, ±.1 km	±1 m
Data reduction	6 months	Concurrent with survey
Data processing	2 months	2 months
Cost/trace	$275	$10

SOURCE: Reprinted, with permission, from M. M. Schilly, Amoco Production Company, Denver.

for compromise between what everyone ideally wanted and what was economically reasonable and realistic, (2) an estimated price tag of U.S. $10,000 to $12,000 per instrument for the currently specified European standard instrument, and (3) the practical observation that "each joint workshop (of European seismologists) delayed progress by half a year." (A committee of five was finally selected to determine specifications that eventually satisfied about two-thirds of the seismologists.)

After long discussion of instrumentation issues, data handling was addressed only briefly. There was basic agreement that a standard data format was necessary--but not achievable during the workshop. Regarding data playback, it remains to be debated and decided whether there should be one large national center or several regional playback facilities. In any case, a lithospheric seismology program will require commitments to both hardware and software, and cooperative software development will have to be pursued to meet the needs of varied users with their varied computer facilities.

IV. General Discussion

The final discussion session of the workshop was chaired by Walter D. Mooney, John Orcutt, and Scott B. Smithson, whose synthesis (Exhibit C-2) follows in the form of "Conclusions." (For a reportorial account of this session, see the "Proceedings.") Discussion points included (1) the need for concessions in specifications for a standard instrument (to preclude undue delay); (2) the need for early agreement on a standard bus structure, instrument case, and other items requiring compatibility; and (3) the idea that encouraging individual expertise might be preferable to fostering general competition in instrument development--perhaps the best respective components should be integrated to achieve the needed standard instrument.

The notion of comparison testing of available digital seismographs generated lively discussion--with due attention to issues that would be sensitive to commercial interests. The idea of a "shoot-out" linked to any national instrumental development program was judged to be premature.

Where do we go from here? The need for future workshops was evident, particularly involving technicians and engineers from both industry and university/government research labs to focus on unresolved problems of instrument development. The workshop ended with the general sense that many basic issues were still unresolved--but a start had been made, the NAS lithospheric seismology report would next be released, and future workshops would then follow to continue momentum for developing new instruments and programs for lithospheric seismology.

REFERENCES

Bailey, C. (1982) Bus standards enrich microcomputer board variety, Electronic Design (April 15), 77-86.

Hewitt, M. R. (1983) Delphi survey, Geophysics: The Leading Edge of Exploration 2(6), 18-31.

EXHIBIT C-2

CONCLUSIONS

Walter D. Mooney, John Orcutt, and Scott B. Smithson

In the final discussion of the meeting the three panel members attempted to summarize the scientific interests that were voiced during the meeting. These include microearthquake studies, local velocity/structural studies (such as short seismic-refraction profiles), teleseismic delay-time studies, major lithospheric explosion profiles, and major combined earthquake-explosion investigations designed to produce a high-resolution image of the lithosphere. There was an air of excitement to the present state of the science and a strong desire to proceed with some of the experiments that new instrumentation will make possible. From the presentations given it was clear that we are not a science in search of an experiment, but experimentalists in need of the proper tools.

Reflecting this widely felt need, a clear majority (about 75 percent) of those present agreed that a substantial portion of their research goals would be met by a standard instrument with the basic capabilities outlined during the technical sessions: portable, digital with variable sample rate, event triggering and programmable, three-component, gain ranging and self-calibrating. The instrument would include standard 1- or 2-Hz geophones. It was generally agreed that the basic specifications could be arrived at from the notes and tables compiled in the earlier discussion and that valuable time and scientific momentum should not be lost in a search for the "ideal" instrument that did all things for all investigators. Rather, purchase or construction of the first complement of 50 is the next order of business.

Authors presided over final workshop session, General Discussion.

EXHIBIT C-3

WORKSHOP PARTICIPANTS

Keiiti Aki
Department of Earth and Planetary Sciences
Massachusetts Institute of Technology

Rex Allen
U.S. Geological Survey
Menlo Park, California

Bruce Ambuter
U.S. Geological Survey
Woods Hole, Massachusetts

Walter J. Arabasz
Department of Geology and Geophysics
University of Utah

Dennis Ayden
Sprengnether Instruments
St. Louis, Missouri

Joseph W. Berg, Jr.
National Academy of Sciences
National Research Council

Niren N. Biswas
Geophysical Institute
University of Alaska

Gil Bollinger
Seismological Observatory
Virginia Polytechnic Institute
and State University

Larry Braile
Department of Geosciences
Purdue University

John N. Davies
Alaska Geological Survey

Paul Davis
Department of Earth and Space Sciences
University of California, Los Angeles

Elliott Endo
Cascade Volcano Observatory
Vancouver, Washington

Fred E. Followill
Lawrence Livermore National Laboratory
Livermore, California

Harry T. Halverson
Kinemetrics, Inc.
Pasadena, California

Roy E. Hanson
National Academy of Sciences
National Research Council

David P. Hill
U.S. Geological Survey
Menlo Park, California

N. Ross Hill
Gulf Research and Development Company
Pittsburgh, Pennsylvania

E. Gray Jensen
U.S. Geological Survey
Menlo Park, California

Leonard Johnson
Earth Sciences Division
National Science Foundation

G. Randy Keller
Department of Geological Sciences
University of Texas, El Paso

John A. King
Sprengnether Instruments
St. Louis, Missouri

Edi Kissling
Institute of Geophysics
Zurich, Switzerland

Einar Kjartansson
Department of Geology and Geophysics
University of Utah

Alan R. Levander
Gulf Research and Development Company
Pittsburgh, Pennsylvania

James Luetgert
U.S. Geological Survey
Menlo Park, California

Dieter Mayer-Rosa
Swiss Seismological Service
Zurich, Switzerland

Tom V. McEvilly
Department of Geology and Geophysics
University of California, Berkeley

Erwin McPherson
Seismograph Stations
University of Utah

Robert P. Meyer
Department of Geology and Geophysics
University of Wisconsin, Madison

Walter D. Mooney
U.S. Geological Survey
Menlo Park, California

James N. Murdock
U.S. Geological Survey
Albuquerque, New Mexico

David Okaya
Department of Geophysics
Stanford University

John Orcutt
Geological Research Division
Scripps Institute of Oceanography
LaJolla, California

Gary Pavlis
Geophysics Program
University of Washington

James C. Pechmann
Seismograph Stations
University of Utah

Robert A. Phinney
Department of Geology and Geophysical Sciences
Princeton University

David R. Pierce
Department of Earth and Space Sciences
University of California, Los Angeles

Keith Priestley
Seismological Laboratory
University of Nevada

Anthony Qamar
University of Washington

George E. Randall
Seismograph Stations
University of Utah

William D. Richins
Seismograph Stations
University of Utah

William J. Rihn
Kinemetrics, Inc.
Pasadena, California

Wilbur Rinehart
National Geophysical Data Center
U.S. Department of Commerce
Boulder, Colorado

Steve Roecker
Department of Earth and Planetary Sciences
Massachusetts Institute of Technology

Michael M. Schilly
Amoco Production Company
Denver, Colorado

David W. Simpson
Lamont-Doherty Geological Observatory
Palisades, New York

Robert B. Smith
Department of Geology and Geophysics
University of Utah

Scott B. Smithson
Department of Geology and Geophysics
University of Wyoming

Douglas Stauber
U.S. Geological Survey
Menlo Park, California

Don Steeples
Kansas Geological Survey
University of Kansas

Joseph M. Steim
Department of Geological Science
Hoffman Laboratory
Harvard Uniersity

Michael C. Stickney
Montana Bureau of Mines and Geology
Montana College of Mineral Science and Technology

Ta-liang Teng
Department of Geological Sciences
University of Southern California

George A. Thompson
Department of Geophysics
School of Earth Sciences
Standard University

Craig S. Ware
Sprengnether Instruments
St. Louis, Missouri