Trends and Opportunities in Seismology: Based on a Workshop Held at the Asilomar Conference Grounds, Pacific Grove, California (1977)

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TRENDS AND OPPORTUNITIES IN SEISMOLOGY

Based on a Workshop Held at the
Asilomar Conference Grounds,
Pacific Grove, California

January 3-9, 1976

COMMITTEE ON SEISMOLOGY
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1977

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.

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FOREWORD

The Committee on Seismology concluded in the spring of 1975 that the field of seismology, which is important in many and diverse areas of national interest, should be reviewed and its future course charted. The Committee immediately set about the task of selecting a representative group to carry out this assignment at a week-long workshop. Seismology interacts with many other scientific disciplines and has numerous applications in engineering and in resources exploration and recovery. In all, 35 experts in the fields of geology, geophysics, and engineering, from academia, government, and industry, were invited to participate in the workshop and to address the many problems of national and global concern that require seismological expertise for their solutions.

This report is the result of their deliberations, and the writers hope that it will be useful not only to the scientific and technical communities but also to the decision-makers who are seeking solutions to critical national problems.

The report reviews the history, accomplishments, and status of seismology; assesses changing trends in seismological research and applications; and recommends future directions in the light of these changes and of the growing needs of society in areas in which seismology can make significant contributions.

Don L. Anderson, *Chairman*
Committee on Seismology

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We also express appreciation to the following: state geologists for providing information about legislation in their states concerning earthquakes and hazards, oil companies for information regarding employment of seismologists in the industry, universities for information regarding student enrollment and graduates at all degree levels in seismology, government agencies for general information about funding of and personnel in seismology, and professional societies for statistical information pertaining to membership characteristics.

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CONTENTS

II. BACKGROUND AND PROGRESS

SYNOPSIS AND RECOMMENDATIONS

This is a time for rethinking national goals and wide-ranging viewpoints about many things that affect the nation's welfare. Research organizations and individual scientists are being asked to identify potential, mostly short-term, payoffs to the nation through the use of their expertise. A main purpose of this report is to identify the returns in terms of the economy and public safety that can be realized by prudent investment in certain areas of seismology. For research in and applications of seismology, a number of government agencies have been assigned different responsibilities, and priorities are changing because of changing national perspectives. Meanwhile, the need for fundamental research continues even though the short-term payoff may not always be obvious. The current applications of seismology have grown out of the results of previous basic research.

Seismology was initially defined as the study of earthquakes and related physical phenomena. Seismologists seek to understand where, when, how, and why earthquakes occur and how seismic waves propagate in the earth. Many practicing seismologists today are not concerned with earthquakes *per se* but use the information derived from artificial seismic sources to map the interior of the earth for economic or scientific purposes. In addition, a number of problems that have grown in importance in recent years (e.g., reactor siting, earthquake prediction and the reduction of hazards associated with earthquakes, the search for new fuel and mineral resources) benefit from or require seismology for their solutions. In exploring for oil and gas, for example, seismic waves generated by small explosions or by vibrators are used to study, in fine detail, the upper few kilometers of the earth's crust. Expenditures for exploration are returned manyfold in the discovery of natural resources. Seismic waves from earthquakes and large explosions are used to study the earth's interior, to its center, and to determine large lateral variations in structure and composition. Seismology is the only technique by which the interior of the earth can be studied in any detail.

Because of the rapidly expanding capability of seismic methods, and their relevance to such areas as energy and public safety, the Committee on Seismology agreed that a report should be prepared for the benefit of national, state, and local decision-makers; educators; and the concerned public that would highlight current capabilities, anticipated improvements and applications, and changing trends and identify the role of seismology in solving critical national problems. To provide the foundation for this report, the "Workshop on Seismology" was held by the Committee during January 3-9, 1976, on the Asilomar Conference Grounds, Pacific Grove, California. Thirty-five seismologists, earthquake engineers, and geologists were invited to participate in the deliberations and discussions of the workshop and the writing of an initial draft of the workshop report, *Trends and Opportunities in Seismology*. Reviews of specific topics written before the workshop by scientists specializing in these topics provided background for the workshop.

Part I of the resulting report, entitled "Opportunities and Benefits," is the main product of the workshop. This part of the report deals with major areas of concern--geological hazards; exploration, energy, and resources; understanding the earth and planets--and discusses the roles of government agencies, the universities, and industry in realizing the benefits that seismology can provide. The recommendations developed throughout are summarized below.

Part II, entitled "Background and Progress," consists essentially of the background statements prepared before the workshop. The Committee concluded that these statements are important in their own right and should be included in the publication. They will give the reader insights into the historical bases and current status of many aspects of seismology.

GENERAL RECOMMENDATIONS

1. Seismology is largely an observational science. It is clear after nearly a century of experience that

global seismological observations are essential for understanding earthquakes and earth structure. To improve our understanding of national and regional problems it is fundamentally important to maintain and improve the quality of regional, national, and global observations; the storage and distribution of the resulting data; and the capability of analysis and interpretation. At present, seismic networks, particularly the global ones, are in a precarious state. The Worldwide Standardized Seismograph Network (WWSSN) has had chronic funding problems for both operation and maintenance because of the lack of a long-term funding plan. The High-Gain Long-Period (HGLP) network and the still-developing network of Seismological Research Observatories (SRO) are now funded by the Defense Advanced Research Projects Agency (DARPA), but this support could end as early as fiscal year 1978. Furthermore, support for strong-motion networks and for the Preliminary Determination of Epicenters (PDE) program is neither firm nor reliable.

In view of the central role played by these vitally important global sources of observations and related information, we recommend the following:

(a) A plan should be formulated for an orderly transfer of responsibility to the U.S. Geological Survey (USGS) for funding the long-term continued operation and maintenance of seismic arrays and networks, including global networks.

(b) A plan should be formulated for the National Oceanic and Atmospheric Administration (NOAA) to expand and increase its facilities for the long-term storage and distribution of observations from seismic arrays and networks, including global networks.

(c) The responsibility for formulating the recommended plans should be invested in an interagency initiative definitely to include DARPA, USGS, NOAA, and NSF, with continuing review and guidance by seismologists working outside the federal agencies.

(d) Stable and adequate funding be provided to the USGS for the necessary very long-term operation and maintenance of the seismic arrays and networks. (See pages 62-63.)

2. There is need for a well-formulated national program in earthquake prediction. Encouraging progress has been made toward achieving a reliable prediction capability. The social and economic benefits of such a capability will be great. Although current research results are

promising, the underlying physical principles of earthquake prediction are not yet fully understood. To reach the ultimate goal of predicting hazardous earthquakes, and especially the most damaging large earthquakes, will require (a) extensive fundamental studies in understanding earthquakes and their precursors, and (b) extensive long-term programs in monitoring earthquake and related tectonic activity in different tectonic and geographic areas.

We recommend a national program in earthquake-prediction research, with adequate funding to achieve the ultimate capability in prediction. It is essential that fundamental studies of earthquakes be included in this program. This effort should be carried out on a multiagency basis, including such organizations as the NSF Division of Earth Sciences, the NSF Division of Advanced Environmental Research and Technology, the USGS Geologic Division, and NASA's Applications Directorate. (See pages 25-30, 61-62.)

3. Many agencies of the federal government are concerned with information from the earth sciences.* NSF, USGS, DARPA, and several other agencies fund research in seismology. Apart from NSF, the research they support is usually directed toward specific mission objectives of the agency, often with only short-term objectives in mind. At present, no administrative mechanism exists to assure that the national capability in the earth sciences, including seismology, is efficiently employed in meeting the broader responsibilities of public agencies and that balance and stability are maintained in the national earth sciences program. The application of research results to everyday concerns should be made more effective, and long-range research programs should be designed to meet the needs of the science, the economy, and the public welfare.

It is recommended that an interagency committee be established, possibly under the Federal Coordinating Council for Science, Engineering, and Technology, to effect the needed planning and coordination. (See page 66.)

4. The sustained, broadly based fundamental research programs in seismology supported by NSF provide the base of scientific information needed for an attack on the problems discussed in this report, including earthquake hazards,

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*USGS, DARPA, AFTAC, ONR, BuM, ACDA, NBS, HUD, COE, BuR, NOAA, DOT, VA, ERDA, USNRC, BLM, NASA (see Glossary).

earth structure and dynamics, and resources. Moreover, many other federal agencies with significant seismology-related responsibilities--public safety, dams, transportation, homes and other structures, national defense, resources, energy and power, and water and other utilities--do not perform or provide for sufficient basic research to carry out their missions effectively. Hence, increased fundamental research is required to support this wide range of applications.

We, therefore, recommend that the current annual budget of the Geophysics Program of the Earth Sciences Division within NSF be increased to at least $6.0 million and further increased to at least $10.0 million over the next three years, to provide for the needed fundamental research. (See pages 61, 65.)

5. Over the past two decades, an increased national capability to detect and identify underground nuclear explosions anywhere on the globe has grown out of a major research program dedicated to this objective (DARPA's VELA Uniform program). This program is scheduled to terminate after fiscal year 1978. Clearly, it is in the national interest that the United States continue to have the capability to verify that other nations adhere to the nuclear-test restraints embodied in arms limitation treaties. It can be anticipated that new technical problems will arise and that our present detection and identification capabilities can be improved. A continuing strong research base in seismology is an essential ingredient in meeting national nuclear monitoring objectives of the future.

It is, therefore, recommended that basic research in seismology aimed at detection and discrimination of seismic signals from underground nuclear explosions continue to be supported by the Department of Defense. (See page 60.)

6. A survey of legislation pertaining to earthquakes and their effects revealed that as of January 1977, 23 states had adopted a statewide building code; that only a few states had legislation pertaining to earthquake hazards; and that only a few states have been conducting studies to evaluate the hazards.

We recommend that state and local governments employ technical expertise (seismological, geological, and engineering) to evaluate seismic hazards and, if necessary, (a) initiate or expand support of regional seismic networks and the installation of strong-motion instruments, *(b) develop legislative action and administrative procedures for mitigating earthquake hazards, and (c) monitor land-use development and construction for effective hazard reduction.* (See Appendix B.)

7. Observations of crustal movement and deformation in seismic zones are essential to progress in understanding earthquake processes, in prediction of earthquakes, and in the reduction of hazards induced by earthquakes as a result of permanent ground slip. Local, state, federal, industrial, and university programs in repeated gravity and geodetic surveys should be coordinated.

We recommend that observations of crustal movement and deformation in seismic zones be given high priority in a national program of geophysical and geodetic research. (See pages 27-38.)

8. The nation's future energy demands will probably require the construction of many nuclear power plants. In order to improve seismic hazard evaluation in areas of potential construction we recommend the following:

The U.S. Nuclear Regulatory Commission should increase its support for research related to earthquake hazards to nuclear power facilities, which will provide the basis for site selection and for structural-design criteria. (See page 63.)

RESEARCH RECOMMENDATIONS

The following recommendations concern specific scientific and technical problem areas and the specific research effort needed in these areas. The recommendations follow from discussions in the appropriate sections of Chapter 2, as indicated by the subheadings under which they are listed and the page numbers following each recommendation.

Understanding Earthquakes and Reducing Earthquake Hazards

9. Slow and permanent deformation and transient vibrational ground motion should be measured before, during, and after an earthquake with magnitude greater than 5 within a densely instrumented region. (See pages 21-23.)

10. Controlled experiments in which the triggering of earthquakes in the magnitude-5 to -6 range is achieved should be strongly supported. (See page 21.)

11. *To expedite progress in earthquake-hazard assessment and mapping, new or increased research efforts are required.* (See pages 30-36.)

12. *Deploy strong-motion instruments and, where appropriate, off shore seismic stations, in major seismic zones in the United States and cooperatively in foreign countries to increase substantially the probability of obtaining, during the next decade, suites of recordings of damaging ground motion from earthquakes of magnitude 7 and 8.* (See pages 23-24, 30.)

13. *Study the role of hydrological and geochemical processes in crustal deformation.* (See pages 38-42.)

14. *Develop reliable methods for measuring* in situ *stress at all depths in boreholes drilled into the hypocentral region of very shallow earthquakes (less than a few kilometers deep).* (See pages 41-42.)

15. *Detailed studies of the seismicity associated with large dams should be conducted at every opportunity.* (See pages 38-42.)

Exploration, Energy, and Resources

The textual discussion in support of the following four recommendations can be found on pages 42-47.

16. *Cooperation between universities and industry in controlled-source studies of the lithosphere should be continued and expanded.*

17. *A program in long-refraction profiles should be initiated to complement the program in deep-reflection studies of the Geodynamics Project.*

18. *Investigations for the fundamental seismological properties of rocks, including sedimentary rocks at high pressures and temperatures, should be carried out. They should include study of attenuation, compressional and shear velocities, and other parameters, especially to permit the differentiation between types of fluids filling intergrain spaces.*

19. *In view of the potential of seismology to ameliorate the hazards of underground mining, projects should be developed for and by the extractive industries that employ the full capability of current seismic technology.*

Understanding the Earth and Planets

The textual discussion in support of the following five recommendations can be found on pages 51-56.

20\. *Efforts, including greater interaction with other disciplines, should be intensified to determine the details of plate subduction and structure and their relationship to earthquake occurrence.*

21\. *Studies to bridge the gap between abrupt earthquake-related deformations and those that take place slowly over geologic time should be encouraged. These include new advances in very-long-period (VLP) studies, repeated geodetic measurements, and geologic studies such as dating of faults and marine terraces. These studies also have important implications for earthquake prediction.*

22\. *The development of theoretical and numerical methods in seismology, including more thorough application of inverse theory in determining the resolving power of given seismological data sets, should be emphasized more strongly.*

23\. *New technology, such as digital data recording and satellite transmission of data from permanent seismic stations in remote areas and on the ocean bottom should be implemented, and a VLP network for the study of low-frequency dynamical phenomena should be established.*

24\. *To realize Recommendations 22 and 23, laboratory data-handling and computing facilities should be improved and remote access to large regional and national computer facilities and data banks should be provided.*

I OPPORTUNITIES AND BENEFITS

1 INTRODUCTION

A scientific discipline is born through curiosity, nurtured through intellectual challenge, and supported to a large extent by human need. Seismology emerged as a recognizable discipline about the turn of the century. Previously, studies of earthquakes were made by people who would not have regarded themselves as seismologists but rather as engineers, geologists, applied mathematicians, or physicists. What is striking is that the activity called seismology has come into such a strong position in such a short time.

The intellectual challenges in seismological research are great, and they range from the search for a better understanding of the dynamics and physical state of the earth to an understanding of the effect of hydrocarbons on propagating seismic waves. Seismology is a vigorous field largely because its intellectual challenges are faced by well-trained people with diversified backgrounds and because it is intimately related to solution of problems that affect the well-being of people, such as those in natural hazards, resources, and land use.

The past two decades have constituted one of the most successful periods in the history of seismology in terms of basic scientific achievements and of accomplishments with potential for major contributions to society. The basic research and seismological facilities that led to these advances, including the establishment of the Worldwide Standardized Seismograph Network (WWSSN), received sustained support primarily from federal agencies such as DARPA, NSF, and NOAA, in particular from DARPA's nuclear-test-detection program. There have been notable improvements in instrumentation, standardization, availability of data, information processing, and theoretical understanding. This has led to an improved capability for the detection and identification of underground nuclear explosions, to an understanding of earth and planetary structure and composition and of the nature of the earthquake sources, to some mitigation of earthquake hazards, and to the future possibility of earthquake prediction. Parallel improvements in seismic prospecting have led, among other things, to the direct detection of hydrocarbons.

The emergence and development of the concept of plate tectonics and sea-floor spreading benefited greatly from seismological studies, and this concept, in turn, has provided new insights into the geological processes involved in the natural development, accumulation, and localization of mineral and fuel resources.

As an outgrowth of the conceptual revolution brought about by the findings of the geophysical, geological, and oceanographic studies in the 1960's, the International Geodynamics Project (IGP) was established to integrate the various related sciences in a comprehensive worldwide study of the solid earth as a system. The IGP is scheduled to end in 1979. The NRC's U.S. Geodynamics Committee is now developing an approach to solid-earth studies in the 1980's. Topics for consideration will include basic scientific aspects underlying a variety of societal needs, especially resources and mitigation of geologic hazards, and crustal dynamics, especially the origin and evolution of the continents.

Another area of major scientific interest is planetary seismology. Seismic waves are the only means for detailed study of the internal structure of a solid planetary body. Seismometers placed on the moon during the Apollo landings have provided the data used to determine the structure of the lunar crust and interior. Likewise, seismometers have been landed on Mars as part of the Viking mission to provide information on the structure of the Martian interior, and exploration of Venus and Mercury also will include the deployment of seismic instruments.

In terms of immediate benefits to mankind, earthquake-hazard reduction, including prediction, and finding new energy and other resources have high priorities. The study of earthquake phenomena has been a major topic of seismology since the beginning of modern science. There now exists real promise for the scientific prediction of earthquakes. However, bringing the prediction capability to a state where scientifically meaningful, routine forecasting can be done requires more research, testing, and extensive instrumentation in areas with known earthquake risk. Both the magnitude of this effort and the benefits that can result from it are so great that a major commitment on the part of the federal government is entirely justified. Yet, a long-range and adequate commitment to carry the work to completion does not now exist. It is unquestionably necessary to devote greater effort to this search for a complete fundamental understanding of the physical basis of earthquakes.

Seismic techniques are the most powerful tools used in exploration for oil and gas resources. More than 90 percent of all expenditures for geophysical exploration by the petroleum industry goes into the acquisition, analysis, and interpretation of seismic data. As the problems in finding new oil and gas fields have become more severe, the demands on seismic techniques have increased. Today it is possible to map the subsurface in great detail, and in the near future it may be possible to detect routinely the presence of hydrocarbons in the earth by seismic means. The savings this capability could bring about in drilling costs are immense. This example emphasizes the value of fundamental research that will result in improved interpretative methods. Incongruously, the prospects for expanded seismic research and exploration remain uncertain because of national and international economic and political considerations.

In recent years, there has been a new and important stimulus for the application of seismological techniques in the United States and in most developed countries around the world--the growth of environmental concern. The requirement for sophisticated site evaluation for construction of such major facilities as dams and nuclear reactors has greatly increased the demand for consultation and cooperation between the scientific and engineering professions. Many of the leading geotechnical companies are recruiting seismologists to work in teams with engineers to deal with these problems. This trend is greatly stimulating the development of strong-motion seismology, a subject that has been almost entirely absent from seismology textbooks.

Seismology will also play an important role in many aspects of geothermal energy exploration. It is becoming a major tool for the location and evaluation of geothermal prospects. In addition, fracturing, fluid injection, and withdrawal for heat exchange have inherent seismic risks and require careful seismic monitoring.

These new developments raise some major questions: Will seismology be given the opportunity to solve, in a timely manner, the wide range of problems affecting society for which seismological expertise is necessary? Are seismologists being trained appropriately and in sufficient numbers to meet the new challenges? Is basic research, a critical ingredient of all scientific and technical solutions, receiving the necessary attention? Is there good communication between the researchers and those in government and industry who face the problems? Are the observatories and seismic stations being adequately maintained and upgraded?

It is not clear that all of these questions can be answered affirmatively. At present, seismology is in a critical transition period. Its scope and capability have been expanded to include socially and economically important problems, mainly as a result of the significant research support it has received during the past 15 years under DARPA's VELA Uniform program. The objectives of this program are changing, and, as a result, its support for seismology has declined. This leaves a void in seismological research programs, and many essential facilities may be lost unless other sources of support can be found to ensure continuing and needed development of the science. In spite of the increasing capability and relevance of seismology to critical national needs and of the demonstrated large payoff on the investment in it, actual expenditures in the various seismological research areas have been declining or have remained virtually static during the last four or five years (see Appendix A, Figure A.5).

The field must continue to encourage innovation. Basic and applied research together provide a storehouse of ideas, equipment, and people with expertise to help solve national problems as they arise. We cannot predict all the possible benefits from basic and applied research. However, the prospects for spin-off benefits are much greater through basic research than from purely problem-oriented pursuits in which findings that do not provide immediately the sought-after answers are often regarded as extraneous.

In this report, we discuss those areas of opportunity that appear to us to be the timeliest. Social needs, intellectual challenges, and the facilities necessary for effective exploitation of opportunities dictate the recommendations that we have made. To reduce the hazards associated with earthquakes, to enhance our ability to find sources of energy and other natural resources, and to continue to improve our understanding of the earth and planets--all require the best seismological observations and call for fundamental research as well as applications.

2 AREAS OF OPPORTUNITY

UNDERSTANDING EARTHQUAKES AND REDUCING EARTHQUAKE HAZARDS

A primary goal of seismology is to provide the knowledge required to reduce loss of life and property resulting from earthquakes. One third of the population of the United States lives in places where significant losses from earthquakes are likely, and less than one tenth of the population of the country can be considered to be free of earthquake hazard. During its short history, the nation has been lucky that combinations of circumstances during our great earthquakes have kept the number of deaths small, some 1600 in all, and have limited the property losses to only a few billions of dollars. [See Figures 2.1(a) and 2.1(b).] It would be irresponsible for the nation to depend on the continuation of such good luck to protect the large population threatened by the inevitable future earthquakes, especially since trivial changes in the circumstances of several recent earthquakes, such as a difference of a few hours in the time of occurrence, would have resulted in truly major disasters.

Potential losses from earthquakes can be reduced by wise land-use practices and by preparing for them properly when such avoidance is not feasible. We now have a good idea of where in the earth large earthquakes occur most frequently, and we understand, in terms of plate tectonics, why they are localized in distinct zones. Nevertheless, nature sometimes surprises us with damaging earthquakes outside of the principal seismic belts--in the eastern United States, for example--and we do not yet know why these earthquakes occur at all.

Within regions subject to strong earthquakes, we can prepare for them by wise selection of construction sites and by proper design and construction of buildings, other

(a)

(b)

structures, and support facilities such as utilities, highways, and other "life lines." Some measures could be taken shortly before an earthquake, especially to reduce deaths and injuries, if reliable predictions of time, place, and magnitude were available. The ultimate step would be to prevent large earthquakes from happening at all by intervention in the earthquake-generating process. Although earthquake control is only a distant prospect, some experiments have already been carried out that demonstrate its basic credibility.

In allocating resources for research into ways to reduce the threat from earthquakes, we must seek an appropriate balance among the several available approaches. We know that some measures are effective: specifically, ground-motion estimation and seismic-hazard zoning on a regional, local, and site-specific basis and good engineering of structures for earthquake resistance. Efforts to improve these measures must be given high priority. The quest for techniques for reliable prediction of specific events is an exciting and promising one, even under the present conditions of minimal funding. But even complete success in the development of prediction techniques will in no way diminish the need for wise long-range planning and for sound engineering practices in earthquake-prone places. Much can be done to diminish the effects of future earthquake disasters at the time potentially vulnerable structures are built.

FIGURE 2.1 (a) Olive View Hospital, San Fernando, California. The San Fernando earthquake of February 9, 1971 ($M = 6.4$), caused three of the four extensions at the ends of the four wings of the hospital to break loose from the building and fall outward. Fortunately, at the early hour of the earthquake--6:00 a.m.--the stairwells and visitors' rooms in the extensions were entirely unoccupied. (b) Van Norman Dam, San Fernando, California, after the February 9, 1971, San Fernando earthquake. Fortunately for the residents in the valley below, the reservoir was about 25 feet below peak level at the time of the earthquake and, although most of the dam collapsed into the reservoir, the thin embankment that remained held until the reservoir could be lowered to a safe level. Eighty thousand residents of the valley were evacuated for four days while the reservoir was being drained. (U.S. Geological Survey photographs.)

As we seek, in this report, to identify promising directions for new initiatives, we do not review systematically the excellent work in progress. This omission of specific reference to current research reflects our expectation that this work will continue, with adequate support, and our estimation of future directions and needs rests at least partly on anticipation of the successful completion of present work.

Several comprehensive reports on some of the topics covered here have been published by the National Academy of Sciences and the National Academy of Engineering in recent years. We refer the reader to these for information and discussion not repeated here (complete information on each of these documents is given in the Bibliography):

Earthquake Engineering Research, 1969
Earthquakes Related to Reservoir Filling, 1972
Strong-Motion Engineering Seismology: The Key to Understanding and Reducing the Damaging Effects of Earthquakes, 1973
Earthquake Prediction and Public Policy, 1975
Predicting Earthquakes: A Scientific and Technical Evaluation--With Implications for Society, 1976
Global Earthquake Monitoring: Its Uses, Potentials, and Support Requirements, 1977

Understanding the Earthquake Process

The prediction of earthquakes and destructive ground motion hinges on the thorough understanding of the mechanical processes leading to and constituting an earthquake. Both pre-earthquake phenomena and the ground motion caused by the earthquake are tightly linked with the faulting process itself. Detailed measurements of geophysical fields associated with near-source pre-earthquake deformation must be made, therefore, in the neighborhood of the seismic fault.

In contrast, our present concepts of the nature of the seismic source are derived mainly from seismic signals measured at large distances. Consequently, the models used by seismologists today are generally not able to describe the variety of observed near-source features completely.

We do not yet know what physical parameters are the most critical or the nature of the pressures and rock properties that cause an earthquake. The failure criteria of crustal rocks and the role of pre-earthquake deformations must be understood in order to calculate the re-initiation of motion of the fault and to determine the total seismic energy that is released. In addition, the material properties and the nature of the geology affect the amount of energy released and the characteristics of the generated motion.

In order to solve the above problems, a mix of theoretical, laboratory, and field studies is required. Theoretical work is leading to a model of the initiation and propagation of catastrophic failure in rock, and this work must continue if we are to understand earthquakes. (See Figure 2.2.) Theoretical models of material properties and studies of the influence of tectonic setting on strain accumulation and stress concentration must complement the laboratory results.

Experimental rock mechanics has been important in developing our concepts of the physics of the earthquake source, but extrapolation from the laboratory to nature has been only qualitative because of the difficulty of scaling both in size and time. We need to know the properties of the large-scale rock mass, i.e., the rock as it occurs in nature, with its ensemble of joints, fractures, and inhomogeneities. These studies should be directed toward determining the rheology of the rock mass, its strength and frictional properties, and, because fluids may play an important role in earthquake processes, its hydraulic transport properties. This research should be on a variety of scales, from conventional laboratory experiments to those using large testing machines and samples to full-scale studies of earthquakes. The range of temperatures and pressures in laboratory experiments should be representative of conditions in the earth's crust.

Laboratory studies are needed on the time-dependent mechanical properties of rock since these are poorly understood and may dominate processes at geological strain-rates. Friction studies should concentrate on the mechanism of stick-slip and the influence of fault gouge and fault topography on friction. These should be combined with theoretical and field studies of faults and fault-gouge material to aid the extrapolation from laboratory to nature.

Earthquake studies should be made using closely spaced networks of strong-motion seismographs to measure the source parameters, taking advantage of predictable events such as aftershocks, swarm earthquakes, and induced earthquakes.

FIGURE 2.2 Strain pattern in a rock sample subjected to high pressures in a laboratory experiment. Photograph of a double-exposed hologram of a sample of Westerly granite with copper jacket. Its dimensions are 1.75 cm by 5 cm. The hologram was taken through a 5-cm-diameter window in the wall of a pressure vessel. A confining pressure of 0.5 kbar was applied, with a superimposed axial stress of 6.1 kbar. The view is perpendicular to one of the faces. The fringes visible on this surface resulted from a deformation that occurred between the two exposures of the hologram. These fringes may be interpreted as a contour map of the strain accumulation, where the contour interval is one-half wavelength of the illuminating laser (He-Ne) light in the pressure medium, or approximately 0.42 μm. The major axis of the elliptical bulge is a precursory expression of the fault trace that developed at failure. (Provided by H. Spetzler, Cooperative Institute for Research in Environmental Sciences, Boulder, Colorado.)

Stress, strain change, and tilt measurements are needed. Experiments should be mounted at large reservoirs to measure the hydraulic diffusivity of the rock mass at depth and the source parameters of induced earthquakes. The Committee recommends that controlled earthquake experiments be carried out that would generate earthquakes in the magnitude range 5 to 6 and that an important aim should be to measure the source properties of the earthquake and the diffusivity and mechanical properties of the rock mass.

Information about the details of the earthquake-generating process can be gained by measurements of the volume in which preseismic anomalous behavior develops in association with earthquakes of different magnitudes. The spatial and temporal patterns of the appearance and disappearance of these anomalies, based on both pre-earthquake and postearthquake observations, are needed for the development of an adequate model of earthquakes.

Prediction of Ground Motion

Ground shaking is responsible for most of the loss of life and damage caused by earthquakes. The collapse and damage of man-made structures ranging from dwellings to dams occurs not only directly from shaking but also indirectly through shaking-induced ground failure, including landslides (see Figure 2.3), debris flows, and loss of bearing strength in foundation soils through liquefaction and differential settlement, and by large waves (seiches) in lakes, reservoirs, and rivers. An ability to predict the nature of ground motion would make it possible to reduce earthquake losses through appropriate earthquake-resistant design and construction of structures, to assess the earthquake risk to life and property, and to mitigate those risks through local land-use planning. Ground-motion prediction is based on empirical data and on wave-theory calculations, taking into account the expected properties of the earthquake (fault orientation, fault length, amount of slip, amount of stress change, depth) and the measured properties of the relevant earth materials. For the prediction of an earthquake to be as useful as possible in reducing losses, it must be accompanied by a prediction of the expected effects of that earthquake as well. Thus, if losses are to be significantly reduced, it is necessary to calculate the near-field ground motion that will be generated by the expected earthquake.

FIGURE 2.3 Turnagain Heights, Anchorage, Alaska, shortly after the major earthquake ($M = 8.4$) of March 27, 1964. The massive landslide destroyed many homes in the Turnagain Heights residential development. (U.S. Army photograph.)

During the last several years, there has been a large increase in the documentation, modeling, and efforts to predict ground motion, particularly at places close to the faults, where major damage usually occurs. This work has been stimulated by the need to predict accurately the seismic effects of large underground nuclear explosions and to develop conservative seismic-design criteria for nuclear power plants and other critical structures. The Earthquake Engineering RANN program of the National Science Foundation has also supported this work. The increased effort has provided many valuable new data and insights into the nature of ground motion and the generation of damaging motion. There are many areas, however, in which the scope or level of the work is inadequate and should be increased.

In the following paragraphs, opportunities and needs for research into near-field and far-field ground-motion effects are discussed. *Near field* refers here to distances from the causative fault within which significant vibrational damage to typical structures is common; *far field* refers to greater distances. For example, in this context, the limit of the near-field range extends about 15 or 20 km in all directions from the causative fault for magnitude-6.5 earthquakes to about 75 or 100 km for magnitude-8.5 earthquakes. For the larger earthquakes the fault itself may rupture over a distance of hundreds of kilometers.

Near-Field Motion Since most shaking damage to typical structures occurs in the near field, the greatest opportunities for research that will mitigate earthquake hazards lie in this area.

The most critical unknown in engineering seismology concerns the nature of near-field ground motion for earthquakes equal to or larger than magnitude 6. Seismologists need this knowledge to refine their source models. Unfortunately, there are no instrumental time-histories of ground motion recorded within 100 km of a magnitude-8 shock and only a very few within 15 km of a magnitude-6 earthquake (it is a possibility that strong-motion instruments recorded ground motions close to the recent great earthquake near T'ang-shan, China, but there is no information about this yet). In other words, we have too few strong-motion recordings to define damaging levels of near-field shaking adequately. In the absence of observational data, we must rely on theoretical models to estimate the nature of damaging ground motion. Without appropriate strong-motion data, there is, of course, little basis for checking the theoretical estimates. These data will also permit seismologists to determine more accurately the parameters in their models and to supply the engineers with more precise predictions of ground motion of future events. It is urgent, therefore, that faults likely to generate magnitude-7 and magnitude-8 earthquakes in the next few decades be monitored by adequate numbers of strong-motion instruments and that research in strong motion be carried out by both seismologists and engineers. Many major known active faults in California are now instrumented for this purpose, but there are many other candidate faults or seismic zones in the United States, particularly in Alaska, California, and Nevada, that should also be instrumented. To improve the rate of data acquisition, an international effort to obtain strong-motion records within 40 km of magnitude-7 earthquakes and within 75 km of magnitude-8 earthquakes is urgently recommended.

Substantial recent progress has been made by seismologists in the analytical and numerical modeling of ground motion in the frequency range 0.1 to 1.0 Hz using theoretical models of an earthquake source. Such models are used by engineers for evaluating the ground-shaking hazard to high-rise buildings and other large structures, such as dams and highway bridges, but empirical data are urgently needed to test and refine these models. The hazard to dwellings, low-rise buildings, industrial buildings, and nuclear power plants comes at ground-motion frequencies in the range of 1 to 15 Hz. Motion at these frequencies is more sensitive to the detailed distribution of stress or frictional strength on the fault surface than to the average stress or strength. Accordingly, theoretical models incorporating realistic variations in stress or friction on the fault surface are needed to predict high-frequency ground shaking adequately. Therefore, there is need for collaborative effort between the seismologists, who seek to understand the nature of the faulting process, and engineers, who seek to understand the response of structures to earthquake motions.

Additional theoretical effort must be directed toward developing finite-strain and finite-element models of wave propagation. The subject of near-fault wave propagation also deserves more attention, especially propagation through lateral inhomogeneities in the shallow crust, the development of wave modes at increasing distance from the fault, and the attenuation of ground motion. The adequacy of theoretical models can be judged by their ability to produce realistic time-histories of ground motion.

Standard strong-motion instruments provide useful information about ground motion in the frequency range from about 0.06 to 16 Hz, while resonant frequencies of long suspension bridges, for example, may be less than 0.06 Hz. Thus, design, construction, and installation of a new strong-motion instrument to provide a low-frequency recording capability is recommended in order to obtain new information for engineering purposes and also for studying the faulting progress.

Another important problem in engineering seismology today is the effect of nonlinear, high-strain soil response on ground motion. Numerical models of nonlinear soil response have been developed, but the utilization of such models awaits laboratory measurements of stress-strain relations in soils for cyclic shear strains in the range of 10^{-4} to 10^{-2}. Moreover, there is a need to test the results of numerical procedures by comparing model results to observations in the field. In view of the interest in offshore oil recovery near California and Alaska, the complete seismic response of ocean sediments is an important problem requiring immediate attention, along with the mechanism of submarine slides.

Elsewhere in this chapter, it is strongly recommended that controlled experiments be undertaken to generate earthquakes in the magnitude-5 to -6 range. Such experiments would provide a unique opportunity to obtain a wealth of new information about the generation and propagation of strong ground motion. Three-dimensional arrays of strong-motion instruments could document the effect of nonlinear soil response on shear waves as they propagate upward through the section. A dense array of surface instruments would provide information on the spatial coherence of ground motion over distances comparable to the dimensions of large structures (100 m or greater): for example, relative displacements between abutments might be a critical parameter for the design of long bridges and dams. Aftershock sequences of large onshore earthquakes (magnitude 7 or greater) also provide especially favorable opportunities for strong-motion studies employing dense arrays of instruments, if the instruments can be installed while the level of aftershock activity is sufficiently high.

Far-Field Motion At far-field distances, ground shaking is likely to be a hazard only for large structures with relatively long natural periods, such as high-rise buildings, dams, and long-span bridges.

There are well-documented differences among various regions of the United States in the rates of attenuation of modified Mercalli (severity of shaking scale) intensity with distance from the earthquake fault. This problem has received recent attention, but additional effort should be focused on interpretation of such differences in terms of regional variations in crust and upper-mantle velocities and attenuation rates and on more quantitative measurements of ground-motion attenuation throughout the United States.

Earthquake Prediction

Earthquake prediction is perhaps the most exciting research area in seismology today. Significant findings in the past few years give us increased optimism that prediction is indeed scientifically viable, and it is clear that we can benefit greatly from a successful earthquake-prediction capability. Few seismologists doubt that some clear physical precursors have, in fact, been detected preceding many earthquakes, including a number of large ones, and most seismologists are optimistic that we eventually will be able to identify and analyze physical precursors in a way that will allow consistent and socially significant earthquake prediction. Observed physical precursors to earthquakes include variations in the velocity of seismic waves, ground tilt, foreshock activity, changes in water-well levels, magnetic-field variations, and increase radon content in groundwater. (See Figure 2.4.) However, we probably have a decade of intensive research effort ahead of us--and perhaps several--before an effective prediction system can be established. Needless to say, how soon this objective can be achieved will depend critically on the level of funding. We do not yet know in detail how earthquakes will be predicted, and innovative new ideas, new hypotheses and models, and imaginative research effort will be essential.

Recent studies of the societal impact of earthquake prediction agree that there will be social, economic, and political problems to overcome--particularly during the developmental stages--but there also seems to be general agreement that the rewards from a successful prediction program will far outweigh the problems. It must be kept in mind that other significant techniques of earthquake hazard reduction, such as condemnation or rehabilitation of old buildings, also involve difficult social, economic, and political problems. In any event, research into the basic nature of earthquakes will continue even in the absence of a specific effort in prediction; but to some degree the ultimate test of our understanding of the nature of earthquakes will be our ability to predict them.

We have already been successful in predicting some earthquakes, but the most difficult problems still remain: Are the techniques that seem to have worked in predicting small earthquakes applicable to large earthquakes--the only ones of real social significance? Do the same techniques apply to all earthquakes? Can prediction be accurate enough to be of use? Will the false-alarm and failure rates be acceptable? Will the public be willing to accept the trial-and-error period during which the system is being developed and perfected? What would be the total cost of an instrumental system capable of predicting all hazardous earthquakes in the United States?

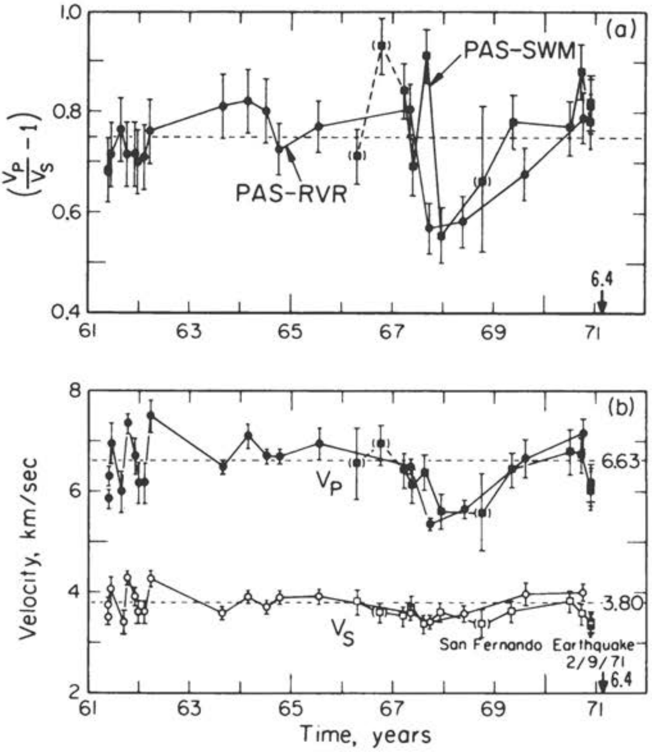


FIGURE 2.4 Variation of $(V_p/V_s - 1)$, V_p, and V_s before the San Fernando earthquake for the PAS-SWM station combination. Data from the PAS-RVR combination are shown for referencing during the same time period. (D. L. Anderson and J. Whitcomb, "Time Dependent Seismology," *J. Geophys. Res. 80*, No. 11, 1497, 1975.)

Initial enthusiasm for earthquake prediction in the United States centered largely on apparent successes in identifying systematic changes in seismic velocities prior to earthquakes, together with the apparent ability of the so-called "dilatancy models" to explain these and other claimed precursory phenomena (see Figure 2.5). Much of this enthusiasm still remains, but the initial euphoria has been somewhat tempered by recent detailed studies suggesting either that these phenomena are not as universal as had been hoped or that they are considerably less

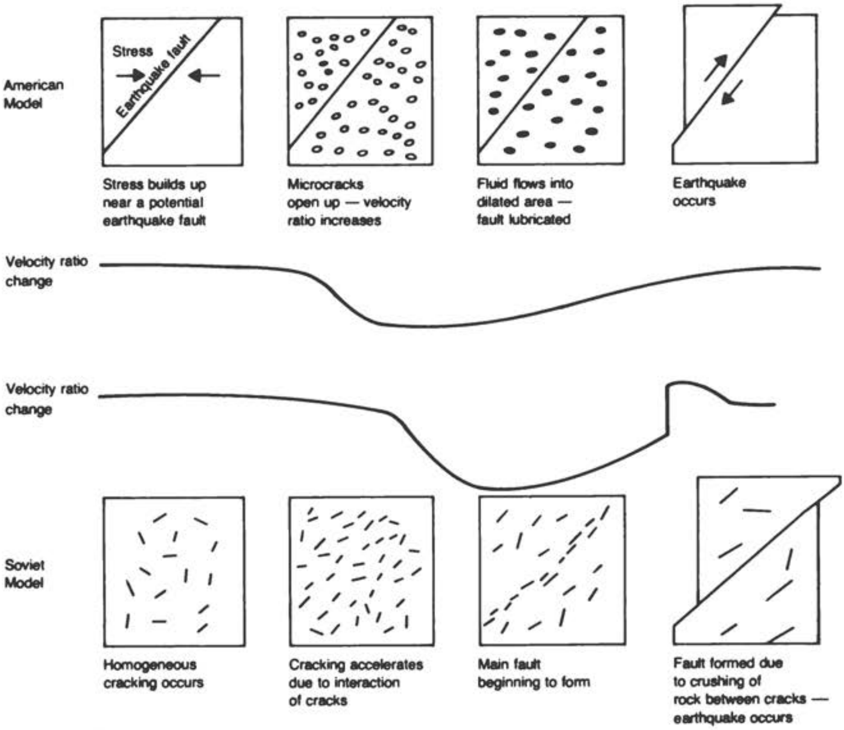


FIGURE 2.5 Two hypothetical models are currently being advanced to explain the behavior of precursors before an earthquake. The "American" model holds that the opening of microcracks in rock under pressure, and their subsequent filling with water, explains precursor behavior. The "Soviet" model suggests that the cracks lengthen and join to form an earthquake fault, and a drop in stress level before an earthquake causes precursor changes. (W. F. Brace, *Technology Review*, March/April 1975.)

intense or occur in smaller volumes than had been expected. However, seismologists in the People's Republic of China successfully predicted an earthquake of magnitude 7.3 in Haicheng, China, during February 1975, and saved thousands of lives by evacuating buildings on the day of the earthquake. It has also been reported that the Soviets issued a successful warning in April 1976, with consequent saving of lives. However, the apparent failure of the Chinese to predict the devasting T'ang-shan earthquake of July 27, 1976, only emphasizes that techniques for prediction are far from perfected, as the Chinese scientists themselves have consistently recognized. There seems to be general agreement about several points. One, in particular, is that basic to everything else is the development of more satisfactory theories of the earthquake process. Regardless of what physical parameters are found to be the most critical, it is likely that a densely spaced array of continuously recording field instruments will be necessary both to delineate the anomalous areas and to demonstrate, through measurements of numerous events, that a specific method works. For these dense arrays, new inexpensive and portable instruments need to be developed for installation in critical test areas during the research period, particularly instruments that can measure distances precisely, such as a continuously recording three-wavelength geodetic device. An absolute gravimeter with microgal sensitivity may prove to be an effective, low-cost way to detect precursory elevation changes. Laser satellites, reflectors on the moon, and galactic radio signals provide inexpensive and repeatable distance and elevation surveys if their resolution can be reliably increased to the centimeter level. These techniques offer hope of continuous monitoring of plate motion as a means of achieving a better understanding of the accumulation in the rocks of strain responsible for earthquakes. Even with their present resolutions, these techniques may be useful for detecting large short-term changes. Precise leveling and gravity observations will help us to gain an understanding of the processes going on or during preseismic deformation of the crust. Trilateration must be expanded, along with continuous records of stress release, in order to measure pre-earthquake fault slip.

The following measures will improve our capability to gather the needed data and should be supported by appropriate agencies--in particular, the National Bureau of Standards, the National Geodetic Survey, and the National Aeronautics and Space Administration:

(a) Perfection of a transportable, absolute-gravity measuring device with microgal sensitivity;

(b) Development of a program of systematic combined precise leveling and gravity observations, using the best available gravity meters;

(c) Expansion of the program of continuous measurement of preseismic fault and uplift movements by means of creep meters, triangulation measurements, tilt meters, and continuously recording geodimeters and gravimeters;

(d) Improvement of very-long-baseline interferometry, lunar laser ranging, and satellite ranging techniques and the development of Shuttle-based laser- and radio-ranging systems to provide reliable and accurate positions with resolution at the centimeter level.

In order to observe many precursors in a short time, especially before large earthquakes, we must significantly increase our collaborative studies with other countries where large earthquakes occur. Large earthquakes are infrequent, and to obtain the necessary data quickly it is necessary to instrument many seismic areas at once. We should take advantage of situations, both domestic and international, in which the expectation of an earthquake is great.

Earthquake prediction has become the focus of major national programs in Japan, the Soviet Union, and especially the People's Republic of China--all of which give it higher priority and have more highly organized efforts than does the United States. The Chinese claim that earthquake predictions in that country have already been successful in saving countless lives, and these claims seem to have a basis in fact.

There have been several reports of aberrant animal behavior preceding earthquakes. The Chinese, in particular, noted this and may have made some use of it in predicting the earthquake of February 4, 1975. It is noteworthy that there has been no activity related to this subject in the United States, but it is currently receiving increasing interest. This will have to be a collaborative study between geophysicists, animal behaviorists, and biologists, both to document the phenomena and to determine what stimuli the animals may respond to.

Issuance of Earthquake Predictions An accurate earthquake prediction can save lives and reduce damage. An erroneous prediction, however, can cause serious economic, social, and legal problems. The public will look to seismologists to provide them with their best judgment on the possibility of earthquake occurrence. In fulfilling this responsibility, seismologists must exercise the greatest care in their statements and publications to avoid unwarranted public apprehension and social disruption.

It is recommended that seismologists obtain peer review before issuing a prediction of a potentially destructive earthquake. If the predicted earthquake is in a foreign country, the appropriate scientists in the country should be notified as soon as it is decided to issue the prediction and provided with the relevant data.

Seismic-Hazard Assessment

The basic principles of earthquake causes and effects, as developed by geophysicists and geologists, must be communicated to and understood by architects, engineers, planners, public officials, and the general public so that appropriate action can be taken to minimize the destructive effects.

A major factor in the mitigation of earthquake hazard is the development of seismic design criteria for safe and economical construction. Certain areas of the country are more subject to earthquake hazard than others, and maps and supporting technical information are needed to depict the geographic distribution of the various degrees of hazard. In current usage, a distinction is made between hazard and risk. *Hazard* refers to the seismic shaking, fault offsets, landslides, and water-related effects that might occur; *risk* includes both the characteristics of the ground motion and its possible consequences in terms of damage, injury, and deaths. In general, seismology is concerned with seismic hazard rather than risk.

Zoning for seismic hazard has come to be generally accepted in many parts of the world. Therefore, important opportunities in seismology exist first in establishing appropriate procedures for seismic zoning and second in the preparation of realistic maps that indicate the various degrees of seismic hazard, which ultimately influence the degree of risk. For the architect and engineer, seismic zoning provides a description of the potential earthquake forces and effects to which a structure or facility may be subjected, permitting them to provide relatively safe sites and adequate design. For the urban planner and government official, seismic zoning provides a basis for establishing regulations for public safety and intelligent use of the land. With the growing importance of seafloor structures for energy exploration and other uses, hazard-zoning maps in offshore areas will be needed. For major or critical structures such as nuclear power plants and major offshore structures, information that is site-specific is normally required.

In the process of seismic-hazard assessment, it is important to take into account how the resulting information will be used. Seismic-hazard maps are needed at various

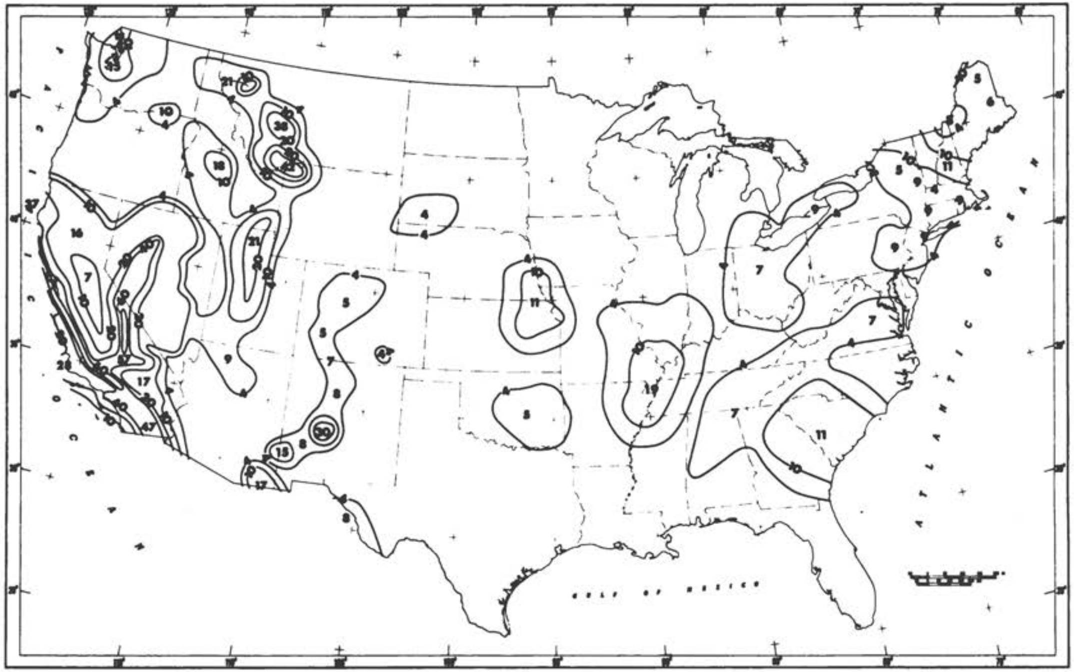


FIGURE 2.6 Map shows expectable levels of earthquake shaking hazards. Levels of ground shaking for different regions are shown by contour lines, which express in percentages of the force of gravity the maximum amount of shaking likely to occur at least once in a 50-year period. Maps of this type are preliminary and subject to revision as more information is analyzed.

scales to serve different purposes: national maps identify major seismic zones (see Figure 2.6), regional maps relate hazard to local geology, and site-evaluation maps deal with hazard variations in the vicinity of proposed or existing building. There is an urgent need for rapid and inexpensive techniques for assessing the probability of occurrence of hazardous earthquake effects at specific sites over broad geographical regions. Techniques for estimating a given hazard at a particular site may be too expensive for use over a large area such as a city or county. New or improved statistical criteria are required for prediction of specific hazardous effects, especially ground failure (on the land surface and under the water on the continental shelves and slopes).

A specific kind of information is presented by the maps as contours of peak expected ground motion with a specified recurrence interval to reflect the effects of both near and distant earthquakes. (See Figure 2.4.) The motion might be expressed in terms of particle velocity or acceleration. Data on which the maps and site-specific surveys are based include the history of past earthquakes and tectonic features that serve as seismic sources. The time history of shaking is an important but often neglected parameter that is now amenable to approximation with present models of the seismic source.

Among the major factors affecting the evaluation of the seismic hazard are recognition of the seismogenic structures, especially east of the Rocky Mountains, and estimation of the maximum earthquake and the long-term frequency of occurrence of earthquakes associated with each geological structure. These problems pose major difficulties in evaluating the safety of nuclear-power-plant sites in the eastern United States.

Seismicity in the western United States is higher than in the East, and seismically active faults are more readily identified in the West by standard surface geologic mapping. East of the Rocky Mountains, earthquakes are fewer and the seismogenic structures are often obscured by vegetation and thick sedimentary cover. Only a few currently active faults are recognized in the eastern United States, and none of these has generated large earthquakes in historic time. An intensive effort is needed to define the seismogenic structures responsible for current and historic earthquake activity in the East.

We specifically recommend (1) deployment of dense seismograph networks in selected areas of known current seismicity to obtain precise locations of microearthquakes that might be used to define the seismogenic structure and (2) application of high-resolution geophysical exploration techniques to define buried geologic structures in the epicentral regions of major historic earthquakes.

In addition to the problem of recognizing seismogenic structures east of the Rocky Mountains, there is the more fundamental problem of not knowing the tectonic processes responsible for the eastern U.S. earthquakes. West Coast and Alaskan earthquakes are recognized as responses to the interaction between major crustal plates--the Pacific and American plates--but there is no generally accepted tectonic model to explain the occurrence or distribution of eastern U.S. earthquakes. Development of such a model is an urgent need.

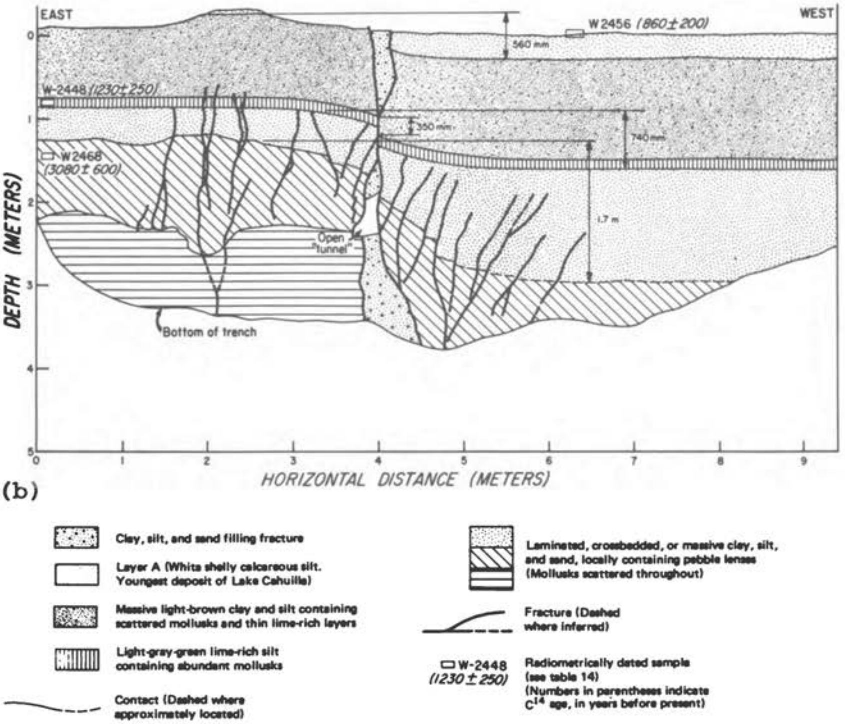
Because recorded earthquake history is short and large earthquakes are relatively infrequent on any fault, estimated recurrence rates based only on the historical record are not reliable. Geologists have learned to recognize the evidence of distinct episodes of slip on faults, and if the dates and amount of slip of these episodes can be fixed, the prehistoric record becomes available for analysis. To do this, methods of dating events of the past 500,000 years with greater accuracy and resolution than those now employed are required. Promising newer dating techniques include paleomagnetic, amino acid, hydration rind, tephrochronology, and fission-track methods. Trenching should be carried out in active fault zones to gain information about three-dimensional patterns of the faulting and the history of faulting over extended intervals of time [see Figures 2.7(a) and 2.7(b)]. An important problem for land use in the vicinity of active faults is the amount of displacement on subsidiary and branch faults and the width of the shear zone of a particular fault segment.

A useful improvement in the earthquake intensity scale would be the expansion of the description of each intensity grade to include modern structures and appurtenances. Other aspects of the scale need consideration: for example, the steps between levels are not uniform and ground motion and ground response become more important at the higher intensities.

Seismic-hazard zoning will be improved by the results of a program of systematic relocation of earthquakes that occurred before the advent of modern computer-location techniques. The more reliable positions of these earlier events, relative to population centers and specific geological structures, will be useful in clarifying the true hazard situation.

(a)

FIGURE 2.7 (a) Trenching a fault zone as part of a U.S. Geological Survey investigation. (Photograph by R. E. Wallace, U.S. Geological Survey.) (b) Prehistoric faulting. Profile of south wall of trench across main break, Borrego Mountain earthquake of 1968, showing progressively greater offset of older strata and bending of strata (drag) across the branching break. All deposits appear to be lacustrine, although some are possibly fluvial or eolian. Some deposits east of the break have been removed by erosion. Surface water that entered this fracture in July 1968 eroded the tunnel and caused surface collapse along the break within 30 m of the trench. (Illustration by M. M. Clark for U.S. Geological Survey Professional Paper 787, p. 118, The Borrego Mountain earthquake of April 9, 1968.)



(b)

Seismic Hazards at Nuclear-Power-Plant Sites Safety of operation of a nuclear power plant is critical for the protection of the surrounding population. Evaluation of the seismic hazard at proposed plant sites is a primary, often dominant, factor in deciding the engineering design basis to resist earthquakes. The earthquake hazard may determine whether nuclear power is feasible for meeting energy requirements in seismic regions.

In 1973, the U.S. Atomic Energy Commission, recognizing the fundamental constraint on site selection imposed by seismic hazards, published *Seismic Geologic Siting Criteria for Nuclear Power Plants* (Appendix A, 10CRF, Part 100, *Federal Register,* November 1973). The criteria require that geological and seismological information be presented by the applicant to the licensing agency. Thus, as an important element in power-plant site selection, seismology can contribute in an essential way to the solution of a critical national problem.

The U.S. Nuclear Regulatory Commission (USNRC) may eventually require the installation of seismographic networks to monitor local earthquake activity in the neighborhoods of existing and proposed nuclear power plants. Such networks and the interpretation of the data they provide call for additional involvement of seismologists in the USNRC safety effort. Information from these networks will both enhance the safety of the individual plant and provide basic data for the general task of seismic-hazard assessment.

Earthquake-Related Geologic and Hydrologic Hazards and Land-Use Planning

The principal natural hazards associated with earthquakes, ranked in general order of importance, are (1) ground shaking; (2) ground failure, including landslides, debris flows, loss of bearing strength related to soil liquefaction, soil compaction, differential settlement, and ground cracking; (3) surface faulting; (4) permanent changes in ground elevation; and (5) water-related effects, such as tsunami, seiches, and floods. The nature and severity of these hazards differ from region to region and from site to site. The earthquake hazard will be very high on sites directly astride an active fault, on unstable hillslopes, or on water-saturated, poorly consolidated sediments. Because the individual hazards relate to geologic and hydrologic features, which, in part at least, can be mapped or shown to have certain geographical distributions, land-use planning can contribute to the reduction of these hazards. Earthquake risk can be greatly reduced by avoiding the more hazardous areas or by modifying the design of structures to accommodate the problems of a particular site.

Land-use planning may be implemented in a variety of administrative and regulatory ways. Although no national land-use policy yet exists, some states have instituted land-use measures. In California, for example, earthquake hazards have been recognized in several zoning and safety acts, which require actions by county and city governments and private developers. Individual federal agencies have adopted policies concerning earthquake hazards to federal installations or to private development over which the federal government has regulatory control. Nonetheless, the development of land-use techniques to minimize earthquake hazards is in an embryonic stage. Many of the procedures used have been adopted only since 1971.

Various kinds of research are urgently needed to improve our ability to assess specific hazards. We need to know, for example, where surface faulting will occur, how often, how large the slip displacements will be in each episode, and how the slip is distributed along the fault and across the fault zone. Detailed data from dense networks of special instruments deployed on and near active faults will be required for more satisfactory descriptions of slip in a variety of geologic settings.

Increased research effort including theoretical, laboratory, and field studies is strongly recommended to improve understanding of the physical processes that control all modes of ground failure. New techniques for the rapid and inexpensive evaluation of ground failure over city- or county-sized areas are needed for the statistical assessment of ground-failure hazard. A special recommendation is that field studies of unstable hillslopes be carried out to quantify factors affecting the stability of the slopes under seismic shaking. Pore pressure and rates of fluid movement should be monitored, and the role of material properties investigated.

Permanent changes in ground elevation constitute a significant hazard in coastal seismic zones, particularly those characterized by vertical tectonics. In view of the growing coastal and offshore development, a major effort is recommended to determine the recent geologic history of vertical deformation along the coasts of California, Oregon, Washington, Alaska (except the Arctic coast), and Hawaii and to assess the hazard of elevation changes.

Various water effects related to earthquakes may present serious hazards. Tsunami, or seismic sea waves, are a major hazard to low-lying coastal areas, particularly around the Pacific Ocean. The Tsunami Warning System of NOAA provides early warning of an impending tsunami from distant coastal earthquakes. However, we cannot yet predict accurately, on a real-time basis, the height of wave run-up. Research on this problem is recommended. To improve the capability of early recognition that a tsunami is on its way, the emplacement of deep-ocean water-pressure recorders should be implemented.

Local waves and seiches generated by landslides into bodies of water, by submarine slides, or by seismic waves from distant great earthquakes constitute an extremely serious local earthquake hazard that should be carefully evaluated in deciding land use. This hazard is particularly prominent in fiords along the Pacific coast of Alaska.

The possibility of floods from failures of natural or man-made dams should be minimized not only by careful engineering but also by judicious land use and by monitoring dam behavior. Maps of potential flooding as a result of sudden dam failure should be prepared for areas downstream from all major dams in seismically active regions of the United States by the agencies responsible for the operation of the individual dams. Viable dam-failure warning systems should be established for dams in seismically active regions also.

For effective mitigation of earthquake-related hazards, state, county, and local governments should employ technical expertise (seismological, geological, and engineering) at each level of government to (a) evaluate the earthquake hazards affecting its jurisdiction, (b) assist in developing legislative actions and administrative procedures for mitigating the earthquake hazards, and (c) monitor land-use development and construction for effective hazards reduction.

Earthquake Modification and Control

Within the last decade, convincing evidence has been obtained that human activity can stimulate movement on faults and even trigger earthquakes. "Triggering" means that the physical changes that may touch off an earthquake may be caused by human activity but the energy released is of tectonic origin. Activities shown to have triggered earthquakes and other fault movements are impoundment of reservoirs, injection or withdrawal of fluids in deep wells, mining out of large cavities, and underground nuclear explosions. However, for every underground nuclear explosion thus far, the explosion energy has greatly exceeded the energy released by the largest earthquake it triggered.

Modification of the tectonic environment and stimulation of seismicity by these activities may be inadvertent and undesirable, or it may be deliberate, for the purpose of relieving tectonic stress and reducing the likelihood of a severe earthquake. For earthquake activity generated by fluid injection, a good understanding has been developed of the operative mechanism. This understanding was applied in the Rangely oil field of northwestern Colorado in a successful earthquake-control experiment. Criteria should be developed to guide deep-well injection procedures to reduce the danger of inadvertent earthquake triggering. This would constitute a form of earthquake control and a means of reducing one possible environmental effect of a widespread engineering practice.

Among the human activities that have caused earthquakes, only reservoir impoundment has triggered shocks that have caused death and major damage. The numerous examples of reservoir impoundment and associated seismic activity include Lake Mead in the southwestern United States, which, in 1936, was the first to show this phenomenon; Hsingfengkiang Dam in China, where impoundment was followed three years later, in 1961, by a magnitude-6.1 earthquake; Kremasta Lake in Greece, where a magnitude-6.3 earthquake in 1966 caused 1 death and 60 injuries; and Koyna Dam in India, where a magnitude-6.4 earthquake in 1967 caused 177 deaths and 2300 injuries.

It first became apparent in 1965 that seismic activity could be induced by fluid injection in deep wells when the spatial and temporal association between fluid injection in a well at the Rocky Mountain Arsenal and earthquakes in the Denver, Colorado, region was observed. Injection in the well ceased in 1966 and, following three earthquakes of magnitude 5 in 1967, the earthquake activity dropped to a very low level. Studies begun in 1965 at the Rangely oil field in northwestern Colorado, which was undergoing water flooding for secondary oil recovery, have shown that the rate of earthquake activity can be increased by fluid injjection and decreased by fluid withdrawal (see Figure 2.8).

The development of geothermal deposits for energy production involves both the withdrawal of fluids and their

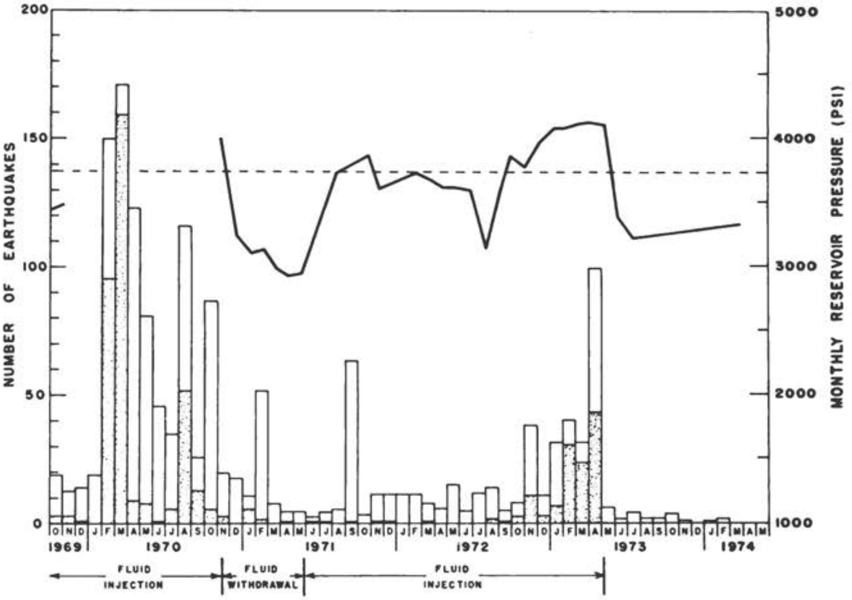


FIGURE 2.8 Frequency of earthquakes at the Rangely oil field, Colorado, as related to injection and withdrawal of fluid, October 1969 through May 1974. Stippled bars represent earthquakes within 1 km of experimental wells; clear areas represent all other earthquakes. Pressure history of Well Fee 69 is shown by heavy line, as compared with predicted critical pressure (dashed line) and numbers of earthquakes. (C. B. Raleigh, J. H. Healy, and J. D. Bredehoeft, *Science 191*, 1230, March 26, 1976.)

reinjection. Thus, two actions known to have triggered earthquakes are involved. Because geothermal areas are anomalous zones in the earth's crust, induced earthquakes must be considered as possible environmental effects of geothermal-energy exploitation, and we thus have an added motive for wanting to understand this phenomenon thoroughly.

Role of Fluids in Earthquake Triggering The earthquakes associated with reservoir impoundment were at one time attributed to slip on faults resulting from the weight of the reservoir. An alternative explanation is suggested by the experience at Denver and Rangely, where the earthquakes were attributed to increase in pore pressure by fluid injection. It was determined that the reservoir rocks in the vicinity of the earthquakes were stressed to near-failure condition prior to fluid injection; the increase in pore pressure then effectively reduced the confinement of the fault by the pressures in the rocks, thus permitting the slip. The pore pressure at which the slip occurred was close to that predicted by theory.

Some Unresolved Problems of Inadvertent Earthquake Stimulation For all the activities known to have the potential for inducing earthquakes, we need to know how to identify those characteristics of the site and of the planned operation that determine whether earthquakes will result. This problem is well in hand only for fluid injection.

Because we cannot judge well if we have changed the seismic regime in a region unless we know what it was before we acted, it is vital that baseline seismicity data covering a sufficiently long time period to be representative of the activity in the region be accumulated beforehand.

A number of specific technical problems must be solved before we can understand the general one. Among these are: What is the mechanism by which stress is amplified so that a small change in one place produces a very large change elsewhere? What is the relative importance of the loading effect of the water and the increase in pore pressure in the rocks beneath a reservoir in the stimulation of earthquakes? Does the chemical action of water on the rocks known as stress corrosion play a significant role in weakening the materials? Where does the water entering the reservoir bed go and how fast? What is the pattern of migration of the seismicity associated with a reservoir once that activity begins?

The answers to these questions can be gained by detailed study of a few good cases. Information about the relevant site factors can be gained by mapping the geology, especially the faults, measuring *in situ* stress repeatedly at points distributed through the region, and monitoring the pore pressure in boreholes. Geodetic measurements to determine crustal deformation should be made before and after filling the reservoir, and continuous tilt and strain measurements at points around the reservoir should be taken.

Baseline seismicity data and evidence that the seismic regime has been changed can only be obtained by establishing an adequate seismic network before construction and then continuing to operate it afterward.

To apply the Hubbert-Rubey theory to reservoir-induced earthquakes, it is necessary to know a great deal about the flow of water in the rocks below the reservoir. The hydraulic permeability of the materials to form the bed of the reservoir should be measured before impoundment. A pattern of boreholes should be drilled around the reservoir for repeated measurements of both pore pressure and *in situ* stress, preferably using methods beyond our present capability of measurement. The feasibility of tagging the reservoir water chemically should be studied in order to develop methods for following the water that enters the rocks.

The hydraulic diffusivity of crustal rocks is a basic parameter in geophysical studies. Experiments based on reservoirs, including the use of occasions when lake levels are lowered or raised, can yield data basic to the understanding of both induced and natural earthquakes.

Additional mathematical modeling of reservoir situations in which both load effects and pore-pressure effects are included should be encouraged.

EXPLORATION, ENERGY, AND RESOURCES

Oil and Gas

Energy requirements in the United States and throughout the world continue to increase. For at least the next several decades, hydrocarbons will remain the primary energy source and the main exploration target. During the past several years, the exploration effort has declined significantly (see Figure A.7). Seismic methods play, by far, the most prominent role in exploration for energy resources.

Economic and political considerations are important in developing and applying new technology. The United States needs to have a clearly defined National Energy Policy that includes projected needs and anticipated supplies. We suspect that a thorough study will show that demand will exceed supply for the rest of this century. If so, seismic methods of exploration must be improved and their implementation encouraged.

Today, the petroleum industry spends nearly a billion dollars a year exploring for oil and gas by seismic means (see Figure 2.9), and it has numerous industry research organizations studying problems of exploration through seismology. Applied research techniques for exploration originate essentially within the industry.

FIGURE 2.9 Field seismograph crew. The two trucks in the foreground are equipped for "vibrating," i.e., generating seismic waves; the recording truck is in the background. This exploration technique (reflection seismology) provides detailed geologic information of the upper 5 or so kilometers of the earth's crust, which may lead to the discovery of oil and gas deposits. (Courtesy of Western Geophysical Company.)

There are many general scientific problems within seismology that are of potential short-range and long-range importance to exploration. Industry depends critically on publicly financed research and privately and publicly financed education to support the long-term potential. Much of the basic seismological research is done in the universities, and more interaction between academic and industrial research is needed.

In trying to establish the overall fabric of a sedimentary basin, oil company earth scientists would benefit greatly from basic reconnaissance data on the structure of the entire crust, obtained well below the range of the drill and well beyond the zone of direct economic significance. This widely spaced but accurate and detailed information on the crust, to perhaps 50 km depth, could provide an essential feeling for the distribution of gross rock types and for regional structure. Combined with surface geologic information and the less expensively obtained but ambiguous data from gravity and magnetic geophysical measurements, this information can provide the necessary constraints to guide industry's detailed and costly seismological search for oil and gas reservoirs. This deep reconnaissance information can only be found with seismic methods. Deep data are not normally collected during routine, detailed but areally limited, exploration operations, which typically examine only the upper crust, where drilling is feasible (see Figure 2.10). This information can best be sought through close cooperation among industry, the universities, and the government; a start in this direction has already been made under the U.S. portion of the International Geodynamics Project. With NSF support, a university consortium has been formed to examine the feasibility of deep seismic-reflection profiling. This

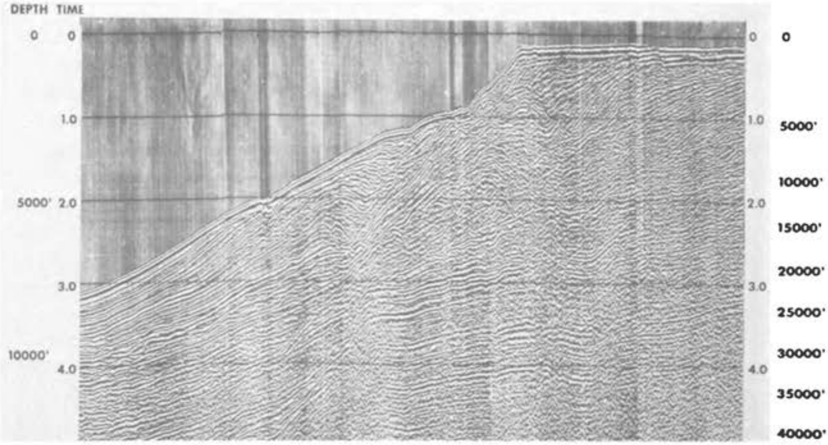


FIGURE 2.10 A 72-km seismic record section from offshore Africa. Data shown here were recorded as the ship, which carried both sources and a detector cable up to 2500 m long, sailed along a line from relatively shallow water across the continental slope. The individual records making up the section resulted from summing seismograms with different source-to-detector separations but common reflecting points. (Photograph from Exxon Production Research Company.)

consortium, with industry cooperation, is applying sophisticated exploration technology for deep crustal studies, and initial results (see Figure 2.11) indicate that significant geological knowledge of the deep crust is obtainable. We recommend that long refraction profiles be included in this program.

We expect that studies of this kind will be important to society because of their wide applicability to the pragmatic problems of finding oil, gas, and minerals; of developing geothermal energy; and of understanding the diverse basic processes that formed the crust in different areas. We recommend that seismological reconnaissance programs reaching depths greater than 10 km be supported and expanded.

Another kind of broadly important research seeks to understand the physical properties of fluid-filled sedimentary rocks, which control the propagation and reflection of seismic waves induced artificially in the search for oil and gas. The detection of hydrocarbons in nonstructural traps, which potentially may contain as much oil and gas as has already been found in structural traps, depends on our understanding of these properties. Although scientists in one or two industrial laboratories continue to study rock properties, the number of such scientists dwindles year by year, in part because of emphasis on tasks associated with the immediate and pressing energy problem. Here also, industry is looking to the universities and the government. Thus, even though the knowledge of attenuation of seismic waves, compressional and shear velocity, and the effects of pressure and temperature on these parameters promises to be an important indicator of rock type or of the particular fluid within a given rock type, most of these theoretical and laboratory studies will have to come from academic-based investigators. This work is essential to a broad segment of the industrial and scientific community and not in the purview of a single industry. We recommend that this fundamental work be accelerated and supported both by government agencies and increasingly by industry.

Before closing this brief discussion of an aspect of seismology critically important to an energy-pinched country, we should consider the special needs of education. In recent years, oil and gas companies have turned from hiring men and women trained only as geologists or only as geophysicists to those with strong backgrounds in both fields. We feel safe in predicting that the future belongs to "explorationists"--geologists facile with geophysical

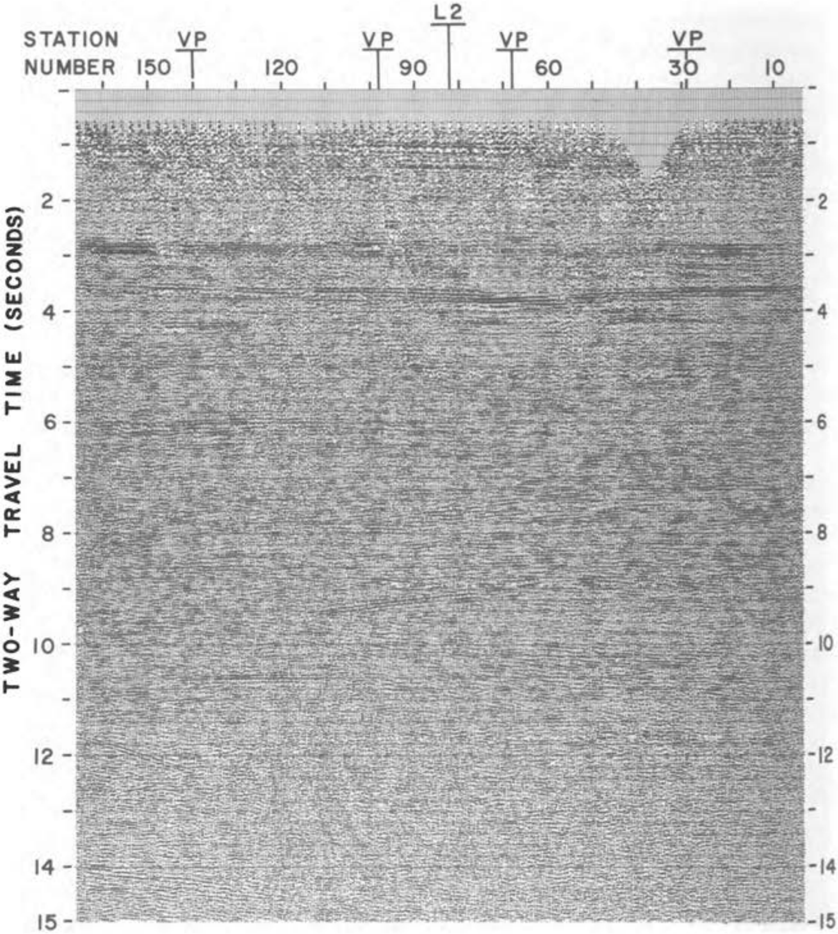


FIGURE 2.11 One of the several seismic sections recorded in Hardeman County, Texas, during a test of deep profiling capability by the Consortium for Continental Reflection Profiling (COCORP). The length of the profile is 16.6 km, and recordings were made down to 15 sec of two-way travel time. The top of the crystalline basement, at 1.6 sec, yields a date of 1265 ± 40 m.y. from cuttings in a nearby well. Deep reflectors as well as out-of-plane diffractions are observed and have been correlated on cross lines in the area. A preliminary paper on the results of this test was published in the September 1976 issue of the *Bulletin of the Geological Society of America*. (Sidney Kaufman, Cornell University.)

techniques and geophysicists familiar with geological concepts and methods. In industry, the ratio of those preferring the formal title of geologist rather than geophysicist has decreased from 6 to 1 to 2 to 1 in recent years, and the trend seems to be continuing. We cannot predict the number of explorationists needed even five years from now, for there are too many unknowns. One trend seems likely to continue: increasingly, foreign oil and gas companies will demand manning by their own nationals. Geophysicists must not expect to be exempt from the consequences of this trend.

Coal

Although the public may find exotic energy sources (solar, geothermal, tidal, for example) more interesting, our greatest exploitable source of energy is coal. In this country, the locations of many massive coal deposits are known, and a large and expensive exploration effort such as that needed to find petroleum is unnecessary for coal. Consequently, seismic methods are used mostly in the exploitation of known coal deposits--in solving problems that arise when mining is planned or is in progress. If the need for coal should ever justify the cost, and if mining it were practical to depths as great as 3000-4000 meters, seismic exploration for coal would become practical, as deep coal seams strongly reflect seismic waves. It is already practical to trace shallow coal beds with high-resolution seismic techniques, primarily for the purpose of detecting faults and other irregularities ahead of the mining operations.

Seismology has many roles in the extraction of coal from the earth. In European mines, transducers listen to the sounds of fracturing in pillars left to support the mine roof. A rapid increase in the fracture rate gives warning of impending failure. Similarly, the sounds of microfracturing warn of a rock burst. In this country, the sands that overlie some coal seams must be mapped if roof collapse is to be avoided; seismic mapping is the only practical means. When a valuable coal bed extends from land out under a lake or the ocean, there is the danger of roof collapse where the coal bed approaches the lake or ocean bottom. In water-covered areas, seismic-reflection quality usually is excellent and the coal bed usually can be mapped clearly.

Recently, the greatest coal mine disaster in history occurred in India when a water-filled abandoned shaft collapsed and flooded an active mine. In this country, a short field test showed that abandoned shafts can, under favorable conditions, be mapped seismically. When a mine collapses, any trapped miners must be found quickly. One experiment indicated that seismic detection of sounds made by miners is difficult, but the amount of experimental work was limited.

Often, coal seams are not continuous and of constant thickness but are faulted, or cut by sand or shale channels, or the coal grades into shale. Seismic waves transmitted between boreholes may be used to determine bed continuity, permitting an operator to plan and execute a rational and economical mining program. Detection of bed terminations is possible using reflection microspreads on a coal face. Bed continuity can also be determined by coring, but whether coring or seismic mapping is preferred depends on the relative cost of the two methods, on data quality at the mine, and on the scale of subsurface control desired.

A reader might conclude from the above discussion that coal companies use seismic techniques routinely. They do not. The methods we have described for improving mine safety and for aiding coal extraction have barely been tested. With the entrance of research-minded petroleum companies into the coal picture, we anticipate that the potential contributions of seismology will attract more interest. At present, only the small but continued research of the Bureau of Mines impacts on this area. Before seismology can play more than a trivial role, either an expanded research effort by a governmental organization will be required or the coal industry must establish an institute devoted to its problems.

Geothermal Energy Sources

Seismic techniques offer perhaps the most definitive information of any exploration tool, except drilling, about the detailed subsurface structures and physical properties of the earth. Nevertheless, these methods, many of which are well developed for finding oil, detecting nuclear explosions, evaluating earthquake hazards, and other studies, have not yet been applied in a significant way in geothermal exploration and exploitation. The problem seems to be that their utility and importance have not yet been clearly tested; moreover, methods such as reflection studies must be adapted to volcanic terrain before they can be of great value in developing geothermal power.

Many of these methods are most useful in exploring for hot rock and magma, types of geothermal energy that have not yet been developed commercially. Thus, geothermal-energy development is an area of opportunity, in which application of seismic techniques should in the long run have considerable impact in solving a national problem.

Geothermal energy is currently being exploited in areas where a few favorable hydrothermal systems transport significant amounts of heat to shallow depths. Yet the resource potential is over 30 times greater if hot igneous systems could be tapped directly and nearly 11,000 times greater if high heat flows in the upper 10 km of the crust could be exploited. A significant geothermal resource, equal to about half of the hydrothermal resources and probably more rapidly exploitable than igneous or hot-rock systems, is geopressured sedimentary reservoirs under the Gulf Coast, where hot water (140 to 190°C) saturated with methane occurs at depths of 2 to 4 km at pressures of around 1 kbar.

Seismic methods can be used effectively to explore for and evaluate geothermal reservoirs. Reflection techniques, widely developed in the oil industry, can be used to locate faults, bodies of hot rock, and boundaries between steam and water in the ground. Reflection work, however, has been mainly in layered sedimentary rocks rather than volcanic rocks. Many new problems associated with geothermal terrains must be solved before reflection technology can be applied in a large way. In geopressured areas, reflection methods can be quite effective in outlining the depth and extent of hot, high-pressure zones.

Studies of seismic noise have been widely discussed, but not fully evaluated, as a prospecting tool in geothermal areas. Modern techniques of array processing of noise, which have not yet been applied, offer the capability to pinpoint local noise sources.

Detailed seismologic research in geothermal areas can provide much information of importance to other aspects of seismology. For example, geothermal areas provide an excellent laboratory for studying the role of fluids and fluid pressure in fracture and earthquake generation. Travel-time-delay and attenuation studies in Yellowstone Park are providing the first detailed data on the structure of a major thermally anomalous region, postulated by some to be a plume rising through the mantle (see Figure 2.12).

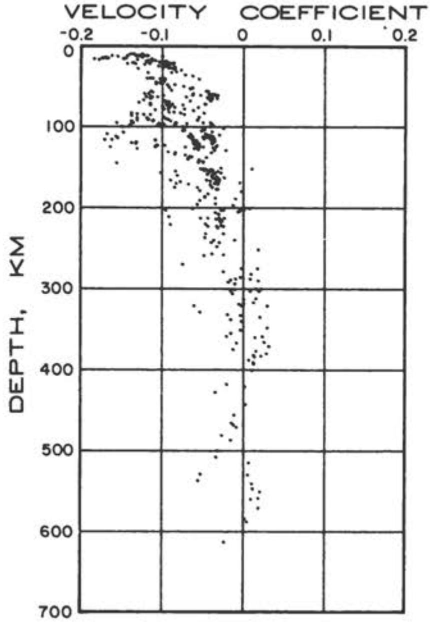


FIGURE 2.12 Velocity coefficient (ratio of observed to average normal velocity) as a function of depth under the Yellowstone caldera. The coefficient is computed from observed relative *P*-waves telemetered from USGS network stations in Yellowstone National Park, supplemented by portable stations to the northwest and southeast of the Park. The results suggest a body with a southeast-trending profile approximately 430 km long, centered on the 50-km-wide caldera. (P. L. Ward, USGS.)

Minerals

From a cost-effectiveness standpoint, exploration seismology must compete with present and future developments in the traditional, nonseismic geophysical tools of the mineral industry. Except for the specific cases of coal, discussed above, and salt and sulfur found in conjunction with the hunt for petroleum, mineral deposits occur in environments that make difficult seismic targets. The hunting grounds of petroleum geophysicists are layered, sedimentary subsurfaces. Hard minerals also are found in sedimentary subsurfaces, but often they are associated with igneous and metamorphic rocks. The ore bodies have irregular, diffused, or transitional boundaries, and the mineralization is highly disseminated. Ore in layer-like subsurfaces can be found seismically; ore in disseminated form may be found through resolution of the geology by seismic means.

UNDERSTANDING THE EARTH AND PLANETS

The Earth

Fundamental to our understanding of the earth is a knowledge of its physical structure and composition of the nature of seismic sources. Over the past decade, great strides have been made in our understanding of the crust and upper mantle, primarily through the close interaction of seismological observations and analysis with the concepts of plate tectonics. This interaction, coupled with dramatic new developments in instrumentation, particularly for the very-long-period measurements, and with new techniques for resolving gross earth data, is stimulating exciting new research into the structure, composition, and dynamics of our planet. The unfolding of new ideas about the earth has stimulated an unprecedented period of expanded interdisciplinary cooperation and research among seismologists and workers in such fields as geology, tectonophysics, petrology, material sciences, and geomagnetism.

The rewards are many. The results must necessarily serve as the foundation for the search for mineral and energy resources and for the mitigation of earthquake hazards. Planetary seismology will benefit because what we learn about the earth, and the methods we use, will have direct application to studies of other solid planets. In terms of long-range national interest, advances in nuclear-test monitoring are inseparable from progress in our understanding of the earth.

The development of plate-tectonics theory has prompted a re-evaluation of old concepts about the structure of the crust and upper mantle. We have revived, but on a rigorous basis, the concept of a rigid lithosphere, containing the crust, overriding a weaker asthenosphere; the distinction between lithosphere and asthenosphere is based on their long-term strength characteristics. Investigations of the lithosphere under the North American continent are clearly not up to the level of the high-resolution studies in Europe. Initiation of new studies and expansion of current effort are needed to investigate the deep continental lithosphere. These should include continuous profiling by long reflection-refraction measurements and the application of the high-resolution continuous-reflection profiling so successfully used by the petroleum industry. The latter technique shows promise of revealing fine structure throughout the crust and in the upper mantle. It may well enable us to map features of the crust and upper mantle on a scale approaching that of maps of surface geology.

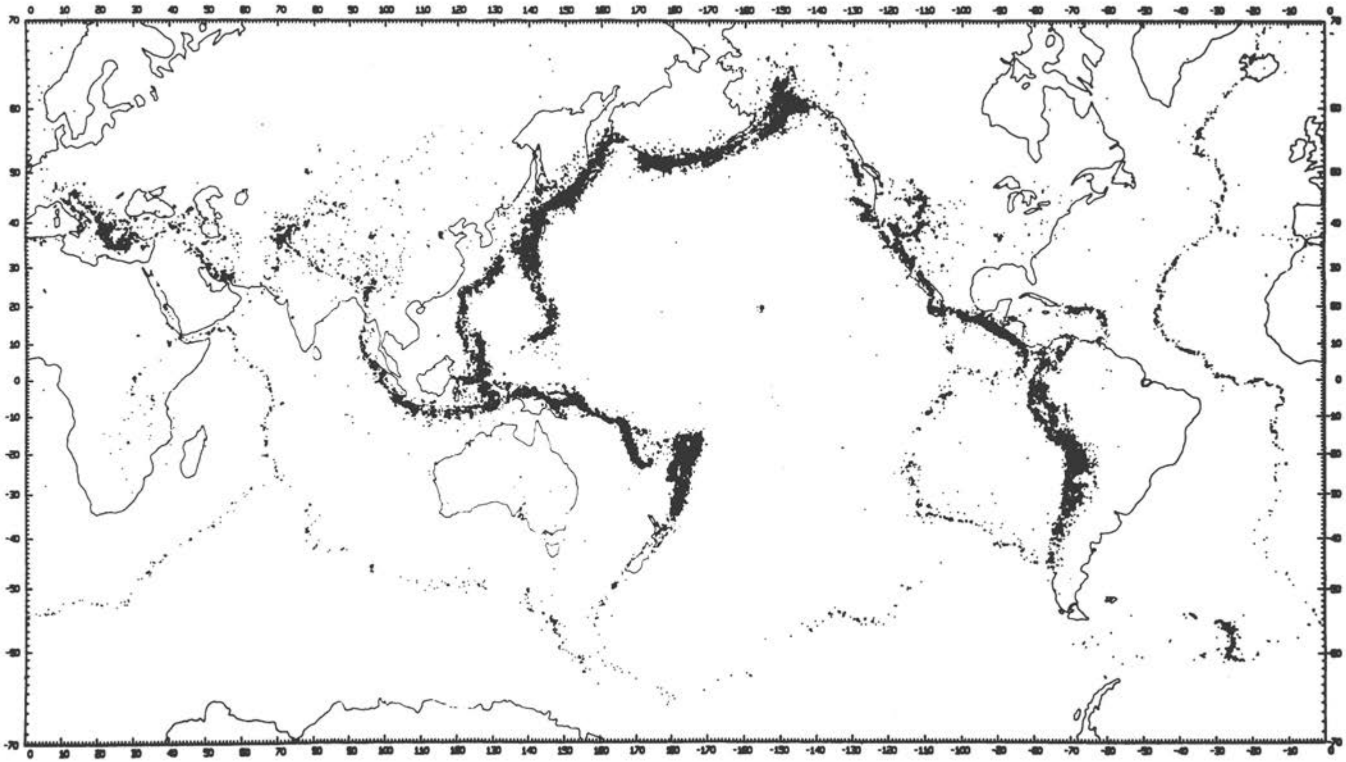


FIGURE 2.13 Seismicity of the earth, 1961-1967, ESSA, CGS epicenters, depth 100-200 km. (M. Baragangi and J. Dorman, *Bull. Seismol. Soc. Am. 59*, No. 1, 371, February 1969.)

A major factor in the development of the plate-tectonics concept of earth dynamics was the Worldwide Standardized Seismograph Network (WWSSN), established in the 1960's to provide a body of standardized data needed for fundamental research in earthquakes, global tectonics, and the structure of the earth's interior. The network has served this purpose well and now constitutes the largest single source of reliable high-quality data for such studies. It has become, necessarily, the very core of seismology, a largely observational science. Among the most recent developments is a program to establish 13 Seismic Research Observatories (SRO's) at sites around the world, each consisting of an advanced digital-recording seismic system. The SRO's will be installed and operated by the USGS under the sponsorship of DARPA. Together with the High-Gain Long-Period (HGLP) stations installed in recent years, they will form an overlay network of about 25 digital recording observatories to complement the WWSSN.

The development of reliable ocean-bottom seismometers (OBS) for long-term recording of seismicity, particularly along ridge crests, fracture zones, and near subduction zones, and for long-range reflection-refraction profiling promises to advance dramatically our knowledge about tectonic processes beneath the ocean and about the structure of the oceanic lithosphere. There is a need for further studies of this type and for permanent, continuously recording OBS units in remote oceanic areas to extend our detailed knowledge of the earth beyond just that part of it beneath the continents.

The interaction of continental and oceanic lithosphere at plate margins (see Figure 2.13) is critical to our understanding of plate movements and of the generation of earthquakes. More cooperative, interdisciplinary studies are needed at continental margins, particularly in view of the almost certain commercial application to the exploration for gas and oil.

In conjunction with these studies of the lithosphere, there is a need for an increased understanding of the relationship of earthquakes to tectonics and geology. Large, destructive earthquakes do occur in the interiors of plates. In many areas, plate boundaries are ill-defined and the lithospheric structure may be very complex. The geometry and rates of relative motion of lithospheric plates need better definition in some regions of the world. A better understanding of the distribution of stress in the earth, obtained from surface geodetic and stress measurements and from earthquake studies, may answer some of these questions. These kinds of information will provide greater insight into the temporal and spatial interdependence of earthquake sources, both interplate and intraplate. We must consider the question of whether seismic gaps are regions of a seismic creep or of high stress, and we must investigate the foreshock-mainshock-aftershock dynamical character of large earthquakes. The relationship of volcanoes to plate motions is also not well understood.

The details of upper-mantle phase changes and composition first evolved from a fruitful joining of seismological data with petrological considerations. However, it was not until the introduction of plate tectonics that we finally began to understand that mantle earthquakes are intimately related to the dynamics of plate subduction, as are the large observed lateral variations in mantle properties near plate margins. Although we do not yet fully understand mantle earthquakes, it now appears that they all occur within subducted plates or remnants of plates. It is also evident that a knowledge of the directions of the stresses and of the spatial distribution of mantle earthquakes is a key to the understanding we seek. As an excellent example of the power of combined theory and observation, we have been able to make rough calculations about the structure of the subducted plate, taking into account various considerations such as thermal conduction, friction, phase changes, velocity of descent, density contrast, and the various forces that come into play at the plate boundary. These details of plate subduction and structure and of their relationship to earthquakes are among the most important keys to an improved understanding of the earth.

Of no less importance are the nature of the lower mantle and of the core-mantle boundary, because in these regions are clues to some of the major dynamical processes within the earth. There is now considerable evidence for lateral variation and change in composition in this region, primarily from the scattering of seismic waves that have passed through the core. The seismic mapping of these lateral variations is currently an undertaking of great interest. Closely related to questions of lower-mantle variability are those of core stability and whether compositional gradients exist in the core as well. These are questions for which studies combining normal-mode and body-wave data are needed.

One additional important development is that with new instrumentation we may now be able to measure some of the very-long-period (VLP) dynamical phenomena, such as the dynamical tides. In the past, seismologists were limited to studies of abrupt seismic sources because the existing technology was not sufficiently advanced for study of long-term dynamical effects. New instrumentation now allows us to open up the whole important area of dynamical source mechanics, i.e., seismic-source phenomena with very long-time characteristics (see Figure 2.14). This requires a global network of high-quality, broadband, digitally recording VLP instruments. A network of 12-18 stations would be desirable for the study of earthquakes of magnitude 6 or greater.

Lack of knowledge about the inelastic properties of the earth represents a major gap and is one of the most pressing problems in seismology. Such knowledge can contribute

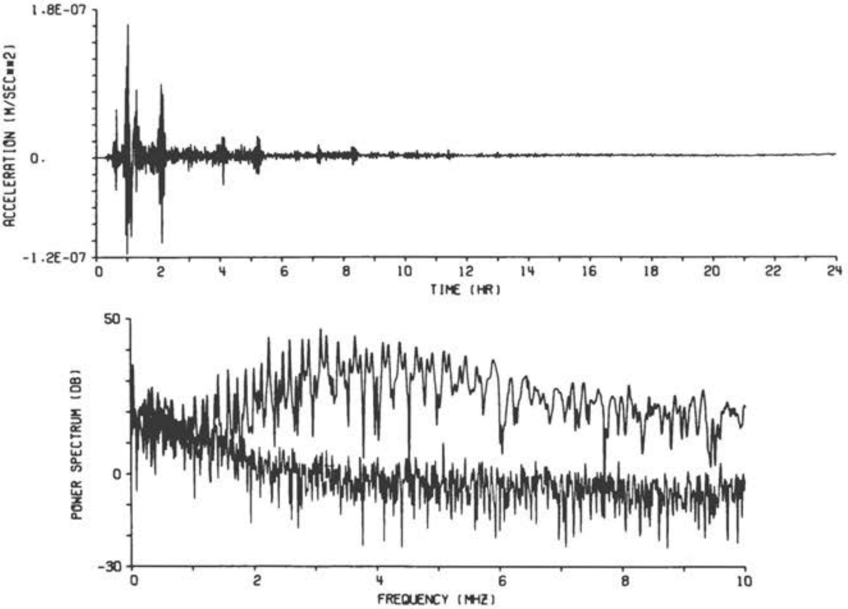


FIGURE 2.14 VLP records for the Guatemala earthquake of February 4, 1976. The top panel shows the time series for 24 hours after the earthquake recorded on the IDA station at Sutherland, R. South Africa. The bottom panel shows the power spectra of the earthquake (upper curve) and the 24-hour period before the earthquake (lower curve). The zero-decibel level corresponds to 5×10^{-16} m^2 sec^{-3}. (Photo courtesy of Ray Buland.)

to an understanding of the rheology of the earth and is also necessary in the interpretation of structural features and earthquake source mechanisms. In order to determine the structure of the earth from broadband seismic data, it is necessary to incorporate the effects of seismic-wave attenuation. The use of synthetic seismograms in the quantitative study of the amplitudes of seismic waves is a recent advance in this area, but further observational, theoretical, and laboratory investigations are needed. A related deficiency that also has impact on much of seismology is our poor understanding of the role of scattering in wave-propagation phenomena.

The Planets

Knowledge of the structure and compositon of planetary interiors is fundamental to an understanding of the origin, formation, and evolution of the solar system. The only

FIGURE 2.15 Seismometer in position on the moon. (NASA photograph.)

available method of studying the detailed structure of solid planetary bodies is by means of seismic waves. In only six years, seismic observations have led to a revision of the pre-Apollo concepts of the structure and composition not only of the moon but also, through interference, of the planets. Installation of seismic networks is an important goal in future exploration of the planets.

The Appolo lunar seismic network (see Figure 2.15) continuously transmits data, and two seismometers were included on a recent flight to Mars. Analysis of seismic data from these and more advanced systems will enable seismologists to determine the existence and properties of a crust, a liquid or solid core, and a planetary mantle. The rate of seismic-energy release reveals the level of tectonic activity and tells something about the thermal state of the planet.

The detailed exploration of the moon, Mars, Mercury, and Venus will necessarily include seismic techniques, and it is important that the national space program continue the timely development of suitable seismic techniques and instruments. The severe environmental conditions, especially on Venus and Mercury, data-transmission difficulties over the interplanetary distances, and weight and power limitations are major problems.

3 REALIZING THE BENEFITS

Seismology can make significant contributions to many pressing problems of society. Energy, environment, hazard reduction, and national defense are important areas in which seismology plays a key role. Many government agencies, as well as industrial, utility, insurance, and business groups, require earthquake statistics on a national or international basis. If these needs for information are to be met, seismological observations must be obtained from adequate national and international networks over long periods of time, measured in decades. A broad data base and the body of distilled knowledge it gives rise to are built up painstakingly over the years through the work of many individual scientists in cooperation with their colleagues in many parts of the world. It is axiomatic that there must be a high order of cooperation and coordination in the acquisition, processing, and dissemination of these data, with strong, long-term, stable financial support by the federal government. Seismological stations are required, here and abroad, to provide timely information on destructive earthquakes to relief groups and others who require it; to provide key information for research in earthquake occurrences, processes, and wave propagation; and for study of earth structure and composition.

In this chapter, we examine the role that the federal and state governments, the universities, and industry must play if opportunities are to be realized and responsibilities met. The payoff can be immense.

THE ROLE OF THE FEDERAL GOVERNMENT

Many federal agencies need strong research programs to help them achieve their mission objectives. These agencies are encouraged to implement, support, and maintain such programs. In the past, research support for seismology has come from a number of agencies, each supporting applied programs appropriate to its mission. We have already mentioned a number of agencies of the federal government that conduct programs that rely heavily on information from the earth sciences. A more complete list includes USGS, NSF, BuM, AFTAC, ONR, ACDA, HUD, COE, BuR, NOAA, DOT, VA, NBS, ERDA, USNRC, BLM, AFOSR, AFGL, DARPA, and NASA (see Glossary).

We recognize the value to each agency of supporting that research necessary to an expeditious solution of its problems, but we are concerned that many agencies, in fact, have often not sponsored or carried out research for which they have a need--basic and applied. We recognize, as well, that diversified multiagency support to the research community--with the implied differences in philosophies, missions, and techniques--can in the long run help to strengthen and increase the flexibility of the science and its ability to aid in the solution of social as well as scientific problems.

Needs for and Uses of Seismic Information

The Department of Defense has a continuing need for seismological information and capability. The VELA Uniform program of DARPA has provided the major funding for research in seismology for most of the last 15 years (see Appendix A), in support of its mission to improve the detection and identification of underground nuclear explosions. It is important to recall that at the beginning of the VELA program, DARPA found it necessary to devote considerable resources to the upgrading of networks, to data dissemination, and to the support of a strong basic-research program. It set up the WWSSN and a data-handling facility (through NOAA), a program of seismic-refraction profiling (through the USGS), and a strong basic-research program through a number of agencies (AFOSR, AFCRL, and ONR). Its legacy is a significantly upgraded science in terms of modern instrumentation, a cadre of well-trained people, and a vastly increased knowledge of earthquakes, earth structure, and earth dynamics.

There will be a strong and continuing public interest in verifying that other nations adhere to nuclear-testing restraints embodied in arms-limitation treaties recently negotiated or to be negotiated in the future. It can also be anticipated that new technical problems will arise, perhaps associated with the emergence of new nuclear powers remote from the United States or with potential benefits that may be derived from nuclear explosions serving legitimate peaceful purposes, e.g., mineral recovery, petrochemical storage, or geothermal-power production. A continuing strong research base in seismology appears to be essential in meeting national nuclear-monitoring objectives of the future.

The DOD has still other requirements, or particular capabilities, affecting the field of seismology. For example, the ONR has expertise and facilities for increased work in the important area of ocean-bottom seismology. Because the oceans cover more than two thirds of the surface of the earth and so little is known about the seismicity of the ocean bottom, major advances could be expected from such increased effort. The Navy should continue its efforts in this field, since many naval facilities are located in earthquake zones and are subject to tsunami damage. The Army can look to seismology to aid in such problems as secure communications and battlefield surveillance. The Air Force faces the problem of the effects of earthquakes and microseisms on missile-guidance systems and of the earthquake hazard in general to air bases and other installations. The DOD can also provide the use of its worldwide facilities and logistic support to advance the seismological programs of other government agencies.

We recommend that DOD maintain an in-house capability in seismology together with a grant and contract program, as necessary, to keep alert to the possibilities of seismology for the solution of many problems.

Although support for NSF's Division of Earth Sciences for basic research in seismology has increased from a few hundred thousand dollars per year in 1960, to $1.7 million in the late 1960's, to a current $3.0 million, funding has not been consistent with the growth of the field. As pointed out elsewhere in this report, seismology is in a critical transition period. In spite of the increasing relevance of seismology to critical national needs, expenditures in the various seismological research areas (by other agencies) have been declining or have remained virtually static during the last four or five years.

The field must continue to encourage innovation. Funding of basic research must be increased to provide the foundations for the applied programs of other agencies. There are still large gaps in our understanding of fundamental seismic processes. However, there is no lack of excellent research proposals; in fact, the number of proposals for needed research has increased far more rapidly than available support, therefore,

The Committee recommends that NSF's current annual budget for basic research in seismology be increased to at least $6.0 million and further increased to $10.0 million over the next three years to provide for the needed fundamental research.

The NSF's RANN program in earthquake engineering was set up in 1971 with an annual budget of $2.5 million, which rose to $8 million in 1972, and has decreased to $7.2 million today; however, the annual average over the past five years has been only $6 million. While most of this budget is devoted to structural engineering and soil mechanics, it should be noted that $0.7 million annually funds the strong-motion program operated by the USGS and that an equal amount supports seismology-related research. About $0.5 million is directed to studies of societal problems related to earthquake prediction. Engineering as well as seismology has much to gain from research devoted to the determination of seismic risk, and this effort merits increased support.

A primary purpose of this report is to call attention to the changing federal-support picture in seismology and to its impact on the science. The two most significant changes are (1) the assignment of lead-agency responsibility to the USGS for a national program in earthquake-hazard mitigation, together with responsibility for the U.S. national earthquake observatories, the WWSSN, the publication of *U.S. Earthquakes,* the calculation and publication of worldwide earthquake locations, and operation of the strong-motion accelerometer network and (2) withdrawal of major support of seismology during the next few years by the VELA Uniform program of DARPA. The ultimate effect of these two changes would be to concentrate within the USGS the responsibility for the bulk of federal activities in seismology.

Earthquake prediction and hazard evaluation may eventually be an applied science, but the fundamentals are not yet fully understood. The present national program in prediction includes only a limited amount of basic research and is strongly oriented toward the search for empirical precursors. The scientists of this country have the technical and intellectual tools to make substantial progress during the next decade toward the development of methods for predicting earthquakes. We strongly recommend that the amount of money available for prediction research be substantially increased to a level commensurate with its value to the nation and sufficient to achieve progress at a rate compatible with our best technical capabilities. These funds must be allocated in a sensible way among all involved government agencies, universities, and industrial laboratories and between basic theoretical research and observational studies. Persistent and patient long-term support is essential.

The USGS has a new and important role in seismology and has made progress in the complex area of earthquake prediction in a short time and with inadequate funding. However, we feel compelled to point out several potential problem areas. It is necessary to be sensitive to possible problems that might result from concentrating the major research effort in any field of science in a single research-oriented federal agency. The USGS is a strong, highly competent research organization, and it might be expected, therefore, that the larger portion of its research funds would tend to be allocated to its own projects because of time requirements and the specificity of its mission. Great care must be taken to assure that there is an appropriate balance, in such an agency, between support for an external research program and for its own strong in-house research program. Finally, there is the need to assure the sustained health of vital service-oriented functions within a research-oriented organization. However difficult in the light of short-term mission goals, adequate, stable, long-term support is required, and must be provided, for seismic observatories and global-seismicity monitoring.

The national seismic observatories and networks and the worldwide network of seismic stations with wide dynamic range and strong-motion instruments provide essential data for all studies in seismology. Continued operation of these networks, and of the services that include the calculation and distribution of earthquake information, must be supported as the lifeblood of seismology. In the next decade, there must be continuing maintenance of the present basic U.S. capability in observational seismology, but, in addition, the growing demands for risk mapping and for information vital to nuclear-power-plant siting, the expected population growth, and the growing capability for earthquake prediction require updating of instrumentation and data-analysis techniques. Therefore, adequate funding is a requisite for the uninterrupted operation and timely upgrading of these most basic facilities and services. High-frequency instruments (1-15 Hz), broadband instruments (periods of 1-30 sec), and digital recording are important aspects of the necessary upgrading.

NOAA has the responsibility for collecting data bases in seismology both as a national effort and through the World Data Centers (WDC-A, U.S.A.; WDC-B, U.S.S.R.; WDC-C, France). Data from other geophysical subdisciplines are also collected. The NOAA Data Center is operated as a service for users, including seismologists. It is recommended that representatives of agencies with specific interests in these data bases (DARPA, USGS, NOAA, and NSF) collectively formulate plans for future operations that include increased facilities for the long-term storage and distribution of observations from seismic arrays and from both U.S. and global networks.

It is generally believed that future energy demands of the nation will require the construction of a large number of nuclear power plants. Quite properly, siting regulations for such facilities require that severe criteria be met concerning earthquake safety. Because of the great costs involved in the design of reactors and in construction delays, much effort has already been expended by the power industry, consultants, the regulatory agencies, and others to develop safety procedures based on seismological information. Yet, the evaluation procedures developed have proven to be fraught with difficulties, and long delays have been more the rule than the exception. Resolution of the problem requires support for specific aspects of seismology related to seismic site evaluation by the U.S. Nuclear Regulatory Commission (USNRC). Such support should be not only for research in prediction of strong ground motion but also for training a new generation of seismologists. It is recommended that the USNRC increase the support budgeted for investigation of earthquake hazards to nuclear-power facilities.

ERDA has the major responsibility for energy research and development for the nation and should therefore review its program in seismology. The discovery and assessment of many geothermal reservoirs will depend on seismological methods, and the use of seismic methods to discover and circumscribe fossil-fuel deposits is well known. Moreover, additional research is needed in seeking new applications of current methods and techniques and in developing new and more effective techniques.

The apparent absence of support within ERDA for site-safety studies for the current generation of light-water reactors is a serious omission. In addition, increasing emphasis must be placed on establishing seismic criteria for the siting and design of fossil-fueled and other power stations.

Another national activity that involves seismology is our space program. NASA is, of course, the principal focus of effort and source of funds for planetary seismology. Work on the lunar seismograph began in the mid-1960's. A network for four seismometers emplaced on the moon in the period 1969 to 1972 still transmits data. These instruments have yielded our first understanding of the interior of another planetary body. In addition, a seismometer included on the Viking mission is now operating on Mars.

NASA is developing satellite ranging, very-long-baseline interferometry (VLBI), and lunar-laser-ranging techniques for observing the rate and measuring the motions of the tectonic plates and of crustal deformations. In connection with earthquake prediction, geodynamics, and other programs, the ARIES and SAFE projects are designed to measure earth strain on the San Andreas fault using interferometry satellite techniques; these projects will furnish data complementary to those obtained by geodetic means on the ground. We believe that several elements of the scientific community, in particular earth scientists, should be involved in the evaluation and direction of this program.

Needed Action

Many of the agencies that have missions requiring seismological and earthquake engineering expertise do not have such expertise on their staffs. The management of millions of dollars worth of programs requires such expertise for planning and implementation consistent with the national interest. A few recent examples of major U.S. earthquake disasters show the reason for this concern by the Committee on Seismology. Following the Hebgen Earthquake of 1958, the "earthquake dam," on the verge of eroding away, presented a hazard to people downstream along the Madison River; it was the task of the U.S. Army

Corps of Engineers to avert this potential disaster, and it did--and, fortunately, no large aftershock washed out its effort. The Great Alaska Earthquake of 1964 caused major damage to buildings, harbors, and transportation facilities, and organizations such as DOT, HUD, and the Army Corps of Engineers were heavily involved in the reconstruction effort. The San Fernando Earthquake of 1971 was a moderate earthquake on the fringe of Los Angeles, a densely populated city; DOT, HUD, VA, and the Army Corps of Engineers were involved in assessment of damage to structures, in the cleanup following the earthquake, or in guiding reconstruction; the disaster could have been far more catastrophic except for fortuitous circumstances, primarily the early hour of occurrence. Recent catastrophic earthquakes in Guatemala, Italy, China, Turkey, New Guinea, and the Philippines should alert us all to the potentially extreme nature of the hazards of earthquakes and to the potential vulnerability of many public installations, including power, water, and other public service installations.

*It is recommended that appropriate expertise in seismology be added to the staffs of federal agencies whereever required to help formulate and manage programs.**

Most of the major national problems that exist in the fields of energy, resources, and the environment, all of which involve seismology and other earth sciences, are currently being undertaken by several different federal agencies. For example, energy problems occupy units of ERDA, USNRC, USGS, BuM, EPA, NSF, and the GAO.

It is critically important in terms of economy and mission effectiveness that the earth-sciences-related efforts of these agencies be coordinated and that good communication be maintained among the various program units. Such coordination and communication will serve equally to avoid duplication, foster cooperation, identify research needs, and identify steps needed to augment high-priority national programs.

At present, no administrative mechanism exists to assure that the national capability in the earth sciences is efficiently employed in meeting the broader needs of

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* The VA set up an Earthquake Committee with a seismologist on it in 1971 when severe damage was done to VA hospitals in the San Fernando Valley following the February 9, 1971, earthquake. The Corps of Engineers consults with seismologists frequently. These are examples of the kinds of mechanisms that should be exploited more fully.

all agencies and that balance and stability are maintained in the national earth-sciences program. As a result, implementation of research results is not so effective as it could be, and many long-range research programs needed to meet future agency and national problems have not been undertaken. Therefore,

We recommend that, in addition to the informal IGDG, *a formal Interagency Committee on Earth Sciences be established, possibly under the Federal Coordinating Council for Science, Engineering, and Technology, to effect the needed planning and coordination.*

THE ROLE OF STATE AND LOCAL GOVERNMENTS

State and local governments have an important stake in our understanding of earthquakes and have an opportunity through legislative and funding actions to increase considerably the data base upon which planning and zoning decisions are made. Appendix B provides the reader with a current status report on federal and state governmental legislation pertaining to the earthquake hazard. It is noteworthy that some states that have a history of earthquake hazards have neither conducted studies to assess this hazard nor enacted building-code legislation.

The Los Angeles building code requires the installation of strong-motion instruments in new high-rise buildings. This has had a major impact on the growth of understanding of earthquake ground motions. In 1971, the California State Legislature passed the Strong-Motion Instrumentation Program Act. This program is administered by the California Division of Mines and Geology and supported by construction fees collected by cities and counties. The Act provides that strong-motion instruments will be placed in geographical areas not yet covered, in representative buildings and structures, and on representative soil and rock sites throughout the state.

Experience in California indicates how state and local governments, private industry, and the universities can collaborate in solving a critical local problem. Other local and state organizations should be encouraged to take similar steps. Consideration should be given to increasing the development and use of instrumentation supported by such programs to include longer-period instruments and conventional seismic networks, which will provide data relevant to prediction.

THE ROLE OF INDUSTRY

For many decades, the oil and mineral industries have been responsible for key parts of the seismological activities in the United States. In particular, seismic instrumentation, exploration techniques, and data processing have evolved to a sophisticated level through the resources of the prospecting industry.

About three fourths of all seismologists in the United States are employed by industry, and nearly all of these are engaged in activities related to exploration for hydrocarbons. Nearly all B.S.-level seismologists are employed by industry. At the doctorate level, the picture is different, with less than one fifth of Ph.D. seismologists being employed by industry and the rest distributed between government and academia in approximately a 3 to 2 ratio. The employment pattern at the master's level is intermediate between those at the baccalaureate and doctoral levels. (See Appendix A for a detailed discussion of seismological manpower.)

About half of industry's hirees at the bachelor's and master's levels have not had specialized training in seismology. Solid grounding in mathematical, physical, and geological fundamentals is most desirable. This kind of education is normally furnished by the major universities to their undergraduate and first-year graduate students. Graduate programs are considered by the oil industry to be adequate for supplying the specially oriented research scientists. It is noteworthy that industrial laboratories devoted to research in seismic exploration employ numerous scientists whose terminal degrees are not in seismology but are in such subjects as physics, applied mathematics, and electrical engineering. It is important that geophysics departments in the universities emphasize geophysical and geological aspects of exploration to provide industry with needed expertise and to increase the employment opportunities of graduating students. It is equally important for industry to recognize that new techniques can emerge from university research.

An informal visit-exchange program between seismologists of major industrial laboratories and university departments has grown up more or less spontaneously and provides a communication link regarding employment possibilities and some basic-research programs.

It is desirable that the relationships between industry and the academic community grow and extend to additional industrial laboratories and university departments. The most effective path to such growth will be through increased involvement of the university departments in exploration-oriented research. This must be done by active cooperation with industry in the form of scientific exchange and of research support, possibly through granting institutes, funded on an industry-wide basis.

THE ROLE OF THE UNIVERSITY

Universities provide the core of basic research in seismology and the trained manpower that are essential to the work of other organizations. At the undergraduate and master's levels, they have the obligation to provide a broad education in the mathematical, physical, and geological sciences that will produce graduates not only with the competence but also with the flexibility that is so essential in a diverse and ever-changing field such as seismology. As seismology is largely an observational science, it is important that the student be thoroughly familiar with the fundamentals of designing, implementing, and managing the results of seismological experiments. In addition, enough practical experience and technological detail should be provided so that students can assess the various employment opportunities and be competitive in seeking those opportunities. At the Ph.D. level, the university program should be guided by the premise that today's students must be prepared to take on difficult and unknown future problems as they arise at the frontiers of knowledge. This can only be achieved by maintaining a vigorous research program in which faculty and students work together on current major problems.

It is recommended that geophysics departments develop new courses that anticipate future advances and needs in geophysics. Courses in rock physics, the theory of wave propagation in heterogeneous media, and the design of data-collection and processing systems are particularly useful background for geophysical exploration. Courses in rock physics, geological aspects of geophysical measurements, and seismically induced geological hazards are important for work in engineering geology and seismic-hazard reduction. Graduating students at all levels who have this added background will find better employment opportunities and will be able to contribute more effectively to the national efforts in exploration and in hazard reduction.

The universities provide several other services as a matter of tradition growing out of their early and continuing research interests. For example, the development, installation, and operation of seismic instruments; the location of earthquakes; and the preparation of earthquake bulletins and maps have been traditional university functions. Universities in the United States began monitoring earthquakes in a systematic manner around the turn of the century, and their records are invaluable for present-day studies of potential earthquake hazards. The traditional pattern has been for universities to set up and slowly expand their seismic networks in a state or part of a state, with financial assistance from the state and sometimes from parts of the private sector that are concerned about the effects of earthquakes. The long-term stability of university programs has been ideal in providing the continuity so necessary to programs of this type and should be continued.

Recently, the federal government has started installing seismic networks in some regions for special studies, but these are generally project or mission oriented and are not meant to provide the long-term or regional monitoring that is essential for hazard evaluation. Typically, a small area might be monitored intensively on a short-term basis for the purpose, for example, of learning how to predict earthquakes or to evaluate the seismic characteristics of a potential site for a major installation. Often the universities and the federal government collaborate in this type of work.

It is essential that state and local governments and concerned private institutions continue, and expand where possible, their support of university programs in collection and analysis of seismological data. This type of effort meets a continuing public need for which federal funding is either not adequate in amount, not sustained for a long enough time, or both. These kinds of seismological data are essential for both basic and applied research and are a vital ingredient in the training of students. This comprehensive involvement of the universities in all phases of the seismology effort is vital if the foundations of the science are to be maintained. Guidance from outside must be continually forthcoming in these areas so that the universities can improve, grow, and be responsive to the needs of the community.

Public service is another role of the universities to which seismology can make a particularly important contribution. In view of the universities' expertise, long-term commitment, and extensive information and data libraries, it is only natural that the public should turn to them for assistance in problems related to seismology. The services that the universities can provide cover a wide range; they include such things as publishing earthquake bulletins and distributing other general information to the public; providing immediate earthquake locations to critical installations and agencies; advising government on energy and hazard problems; and providing a fundamental resource of basic research and related information to governmental agencies, industry, consulting firms, and the general public. It has always been difficult to obtain acknowledgment and financial support for these university efforts, but in view of the increasing need for public information and guidance with respect to energy and hazard problems, the universities must find ways of continuing, and even expanding, these services.

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APPENDIX A
MANPOWER, EDUCATION, AND FUNDING

SEISMOLOGICAL MANPOWER AND THE EDUCATION OF SEISMOLOGISTS IN THE UNITED STATES

There has been a substantial increase in the number of professional seismologists in recent years, from an estimated 3800 ± 500 in 1968 to 5500 ± 1000 in 1975. Included in the 1975 estimate are 150 university seismologists (2 percent), 400 federal seismologists (8 percent), and an estimated 5000 seismologists (90 percent) working for oil companies and petroleum service companies. In this section, we review the status of employment and education in seismology over the past several years. Most of the data reported here were compiled from questionnaires sent to oil companies, petroleum service companies, mining companies, universities, state geological surveys, and federal agencies.

It is estimated that about 200 students graduate each year with degrees in geophysics and that the great majority of these have specialized in seismology. However, seismology is different from most other disciplines in that it also draws many people initially trained in other fields (mathematics, physics, engineering, geology, etc.), who are then retrained to work as seismologists. Moreover, many of the students who do graduate work in seismology obtained their baccalaureate degrees in other disciplines. Many seismologists believe that some diversification of this kind is healthy for the science because the specialized backgrounds in the various associated disciplines that these "recruits" bring with them are useful for a variety of tasks in seismological work. It is also important that the seismologists have training in geophysics in general, since an understanding of geophysical methods other than seismology is often necessary to solve problems in seismology.

A majority of the companies surveyed indicated a strong demand for seismologists at the B.S. and M.S. levels, the M.S. particularly. However, the hiring and retraining of B.S. and M.S. graduates from other fields by the oil companies and petroleum service companies (the major employers) is substantial, totaling 50 percent or more from 1967 through 1975. A student desiring to work in this field can choose from about 50 universities in the United States offering academic training in seismology. The majority of these universities offer courses at the undergraduate and first-year graduate level.

Figure A.1 shows the total number of students taking geophysics courses as well as the number majoring in geophysics during the years 1961-1975. Statistics show that most of the geophysics majors will eventually work in seismology for an oil company or a petroleum service company (90 percent). It can be seen in Figure A.1 that the number of geophysics majors has remained virtually constant for more than a decade. During the same period, on the other hand, the total number of workers in the discipline has been continually increasing, as shown in Figures A.2 and A.3. This suggests that the universities may have been training too few seismologists at the B.S. and M.S. levels and that the number of transfers from other disciplines may be disproportionately large.

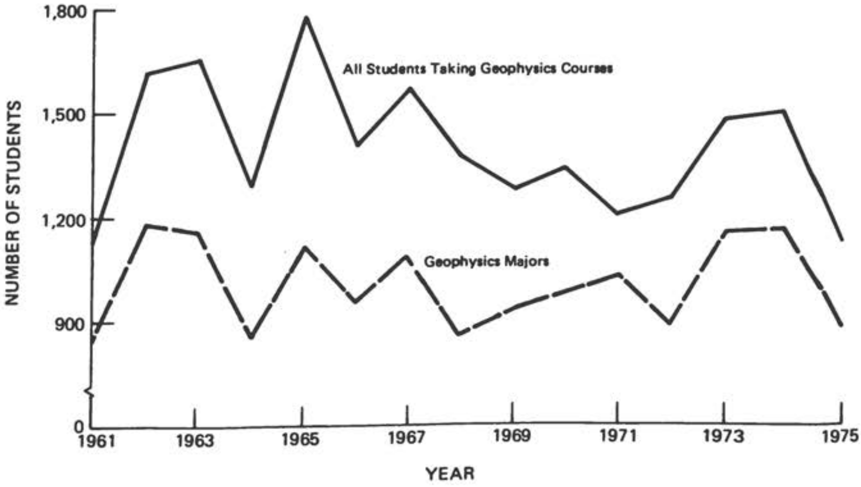

FIGURE A.1 Total number of students taking geophysics courses and total geophysics majors. (Data from the American Geological Institute.)

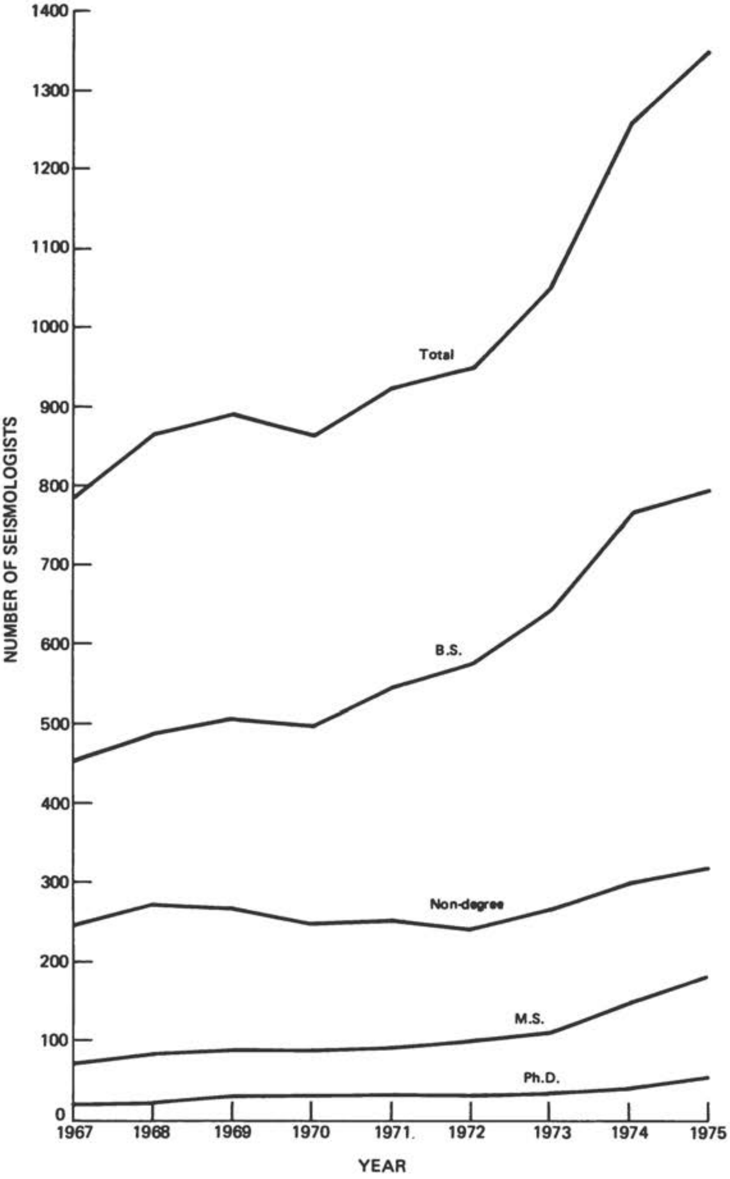

FIGURE A.2 Seismology and the petroleum industry. The graph shows the breakdown of seismologists according to their degrees, based on the complete returns of 11 oil and service companies, probably representing 25 percent of all seismologists working in industry.

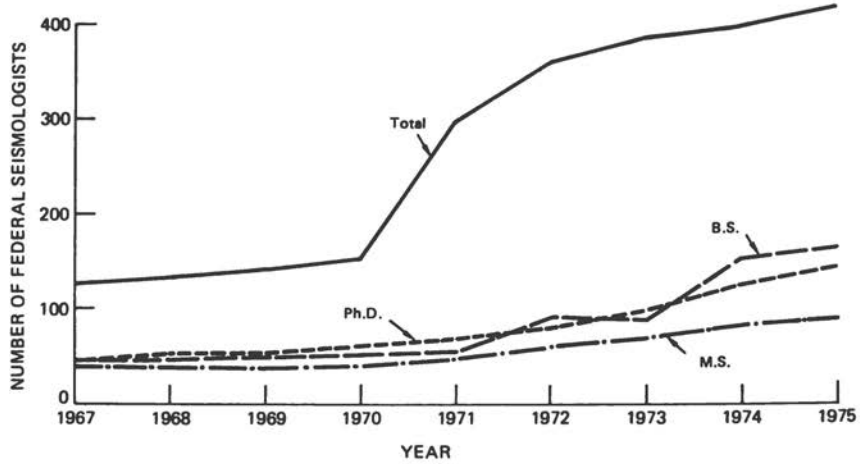

FIGURE A.3 Seismologists in the federal agencies.

About 20 universities train all the doctorate recipients in seismology. Figure A.4 shows the numbers of Ph.D. seismologists graduated annually between 1950 (7) and 1974 (28). To date, job opportunities have been sufficient to absorb all of these graduates.

Only 14 seismologists were employed by state geological surveys--by six of them--in 1975, and funding for seismology by these state surveys has been essentially in the form of salaries for their staff seismologists. Most state surveys do not employ seismology or seismologists in their work,

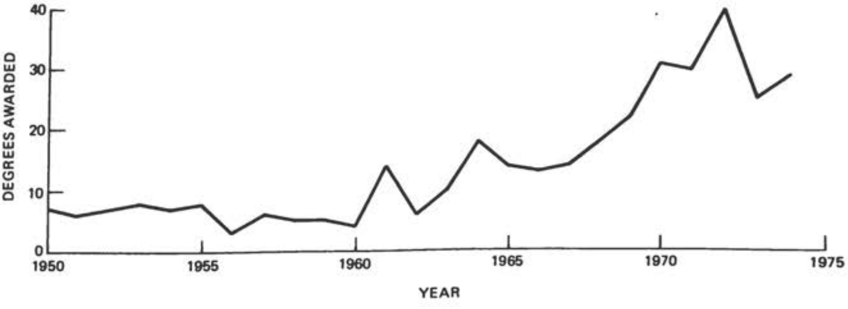

FIGURE A.4 Ph.D.'s granted to geophysicists with theses in seismology. (Based on NAS compilations of theses titles.)

although some use consultants or part-time assistance in seismology. Some states have indicated an interest in increasing their seismic work in the future. The Alabama State Geological Survey, for example, plans to install seven new seismographs in the state.

THE FINANCIAL INVESTMENT IN SEISMOLOGY

Federal Seismology is a young science, and the early stages of its growth were indebted to a few outstanding men working more for love than for money. The growing acceptance of seismology as the basic exploratory tool of the petroleum industry in the 1930's helped spur research in instrumentation and in wave propagation. During this time, and until the mid-1950's, most funding for seismological research was small, perhaps never exceeding $1 million per year for all universities and with little of that from federal sources. In the late 1950's, the problem of detection and identification of underground nuclear explosions became critical in efforts to reach international peace agreements, and seismology was called upon to aid in solving this problem. The science rose to the challenge, and major changes were brought about by the infusion of about $350 million over a period of 15 years, including about $2 million to $5 million per year in research monies to universities and nonprofit organizations. Since that time, most academic seismological research has been funded by the federal government.

Figure A.5 shows the history of federal funding in seismology between 1967 and 1974* with dollars normalized to the 1967 value. The total expenditures of the federal government decreased by about 27 percent between 1967 and 1975 for work in seismology ($28.4 million to $20.8 million). The total research support, exclusive of that for hardware and facilities, was down in 1975 by 13 percent from a peak value of $17.4 million in 1972. In 1972, universities and other nonprofit organizations were funded at $12.9 million (1967 dollar equivalent), and in 1975 this research was funded at a level of $9.8 million--a decrease of about 25 percent from the 1972 level.

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*For details of prior funding see NRC Committee on Seismology, *Seismology: Responsibilities and Requirements of a Growing Science. Part I, Summary and Recommendations; Part II, Problems and Prospects* (National Academy of Sciences, Washington, D.C., 1969).

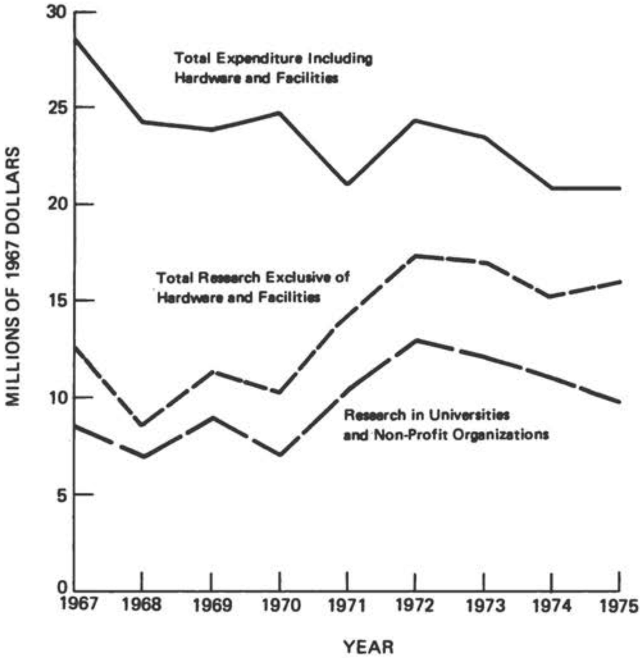

FIGURE A.5 Federal expenditures for seismology, 1967-1975. (Based on information provided by federal agencies.) Note that this does not include expenditures for engineering seismology, which are shown separately on Figure A.6.

Figure A.6 shows federal expenditures for earthquake engineering, which peaked in 1974 at $6.4 million but decreased by 25 percent since then to $4.8 million in 1975. These monies are spent largely on work done by federal government employees and to support strong-motion seismometer arrays and data dissemination.

Nonfederal Investment in Seismology at Universities
Based on the information gleaned from the questionnaires sent to the universities, $0.7 million* was granted to universities in 1975 by private enterprise to support research, and $1.7 million was provided by the states. A large fraction of this money is used to support seismograph networks.

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*All dollars are normalized to the 1967 value.

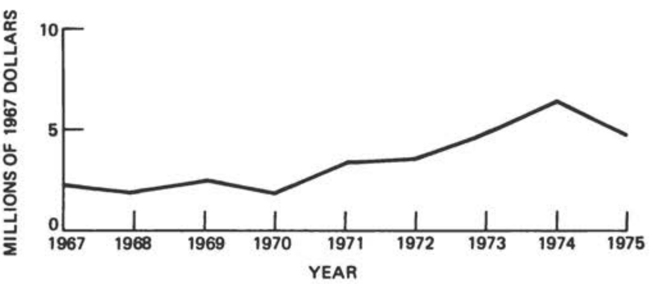

FIGURE A.6 Federal expenditures for engineering seismology. (Based on information provided by federal agencies.)

Investments by Industry The investment in seismology by petroleum companies reached a peak in 1974 of about $345 million for the United States and about $825 million for the world (both figures converted to 1967 dollars). As shown in Figure A.7, these investments grew steadily from 1970 to 1974. However, expenditures for 1975 show a decrease (in terms of constant dollars), indicating a large decrease in exploration both in the United States and in the world at a time when energy requirements everywhere are becoming more critical. For the next decade or two, petroleum must be a prime target for exploration--but it will also be much harder to find than in the past. As one might expect, this search has become increasingly more expensive, and, moreover, government regulations have put more constraints on the explorationists.

Figure A.8 shows the average number of seismic crews exploring on the U.S. continent and in U.S. waters from 1944 to 1975. The peak of exploration activity was in 1952, when the number of exploration crews in the field averaged 650. The number of crews fell to about 200 in 1970 but increased again to a maximum of 334 in July 1974. The number has been falling relatively steadily since then, to 240-250 in the spring of 1976.

Benefits from Investments The benefits from investments in seismological research are many: some are tangible and measurable, such as money, while others are less tangible and perhaps difficult to measure, such as human safety. One impressive tangible benefit, shown in Figure A.9 to be over $4 billion for 1974, is the total federal income from bonuses and rentals from mineral and fuel resources

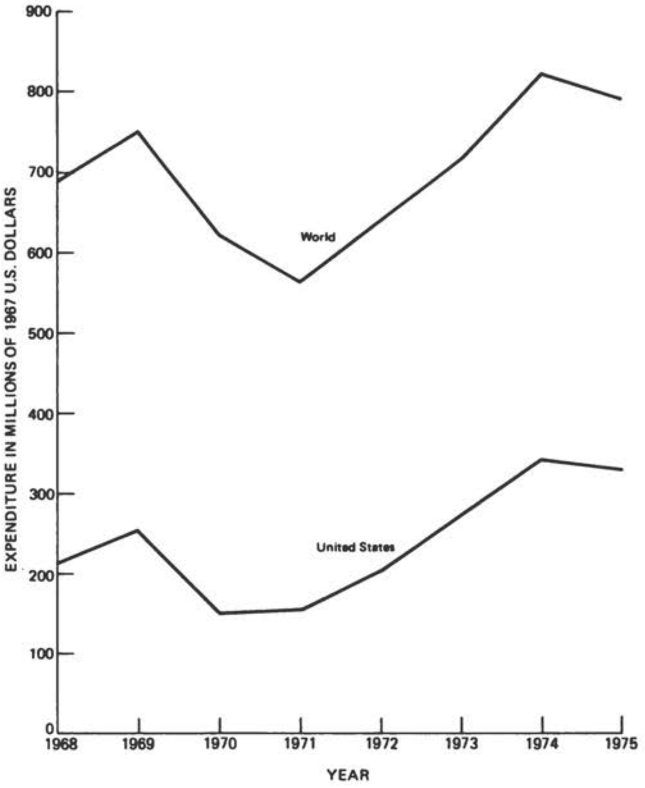

FIGURE A.7 Petroleum seismic expenditure in the United States and the world. Petroleum seismic expenditures account for over 90 percent of the total geophysical expenditure. United States expenditure is over 40 percent of the world. (Compiled from data published in *Geophysics*, by the Society of Exploration Geophysicists.)

on leased federal Indian lands. Over 99 percent of this relates to petroleum exploration and production. This benefit resulted from the application of seismology in finding oil and gas.

There are many intangible benefits from seismological monitoring and research. A few of the more outstanding ones are the following: reliable detection of underground nuclear explosions; a better understanding of the processes

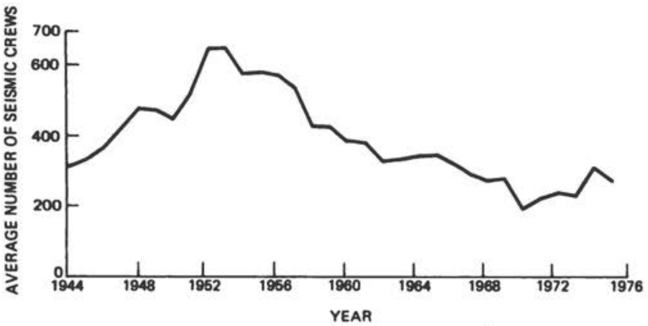

FIGURE A.8 Average number of seismic crews exploring in the United States and U.S. waters. (Compiled from data published in "Geophysical Activities" in *Geophysics* by the Society of Exploration Geophysicists. Data for May 1974-July 1975 were furnished by the Society.)

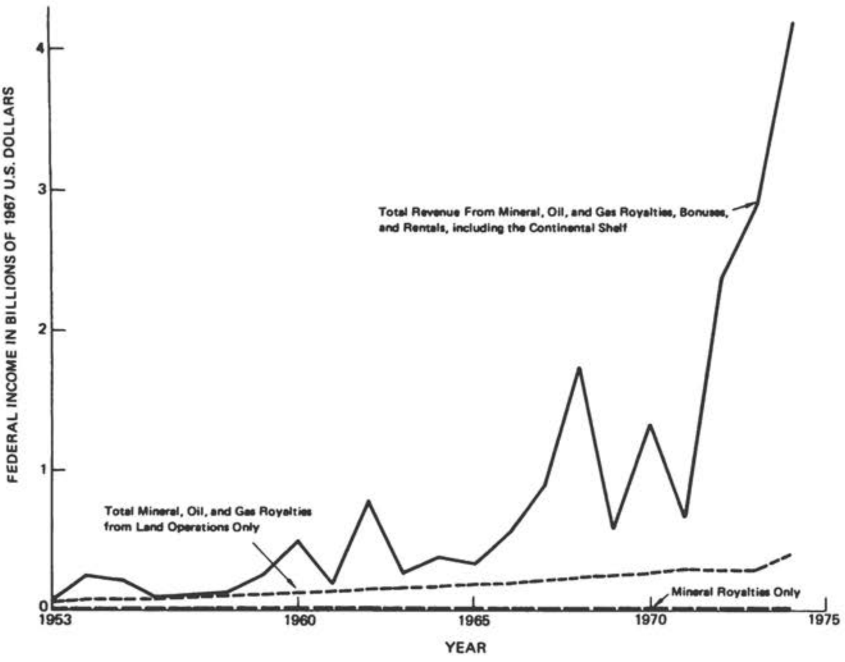

FIGURE A.9 Federal income from royalties, bonuses, and rentals on mineral and fuel resources on leased federal and Indian lands, 1953-1974. (Compiled by U.S. Geological Survey.)

that shape and are constantly reshaping the surface of the earth; security in the location of power plants; safety in the location of dams; improved knowledge about areas of earthquake hazards; and last, but among the most important, a clearer insight into the composition and structure of the earth. It is clear that the past investment in seismology has been rapaid manifold and that the future investment promises equal, or even greater, returns.

APPENDIX B
LEGISLATION PERTAINING TO EARTHQUAKE HAZARDS AND EARTHQUAKE DISASTER

Legislation has been enacted both by the federal government and by various states pertaining to disaster relief following earthquakes and to pre-earthquake measures to limit the degree of potential disaster accompanying and following an earthquake.

THE FEDERAL GOVERNMENT

The most important federal legislation pertaining to earthquake effects is the Disaster Relief Act of 1974 (Public Law 93-288). This act defines the various major disasters that may cause loss of life, injury, property and income loss, and other devastating aftereffects and describes the assistance that can be provided by the federal government to state and local governments and to individuals both for disaster preparedness and for disaster relief following a major event. Earthquakes, of course, are included among the disasters listed; and, in December 1975, the federal government assigned to the U.S. Geological Survey the task of carrying out the federal responsibility to issue warnings and provide other information about potentially disastrous earthquakes. Other agencies and private organizations have responsibility for disaster-relief following an earthquake.

THE STATES

Various states use one of several nationally recognized model building codes. The Uniform Building Code (UBC) of 1976, formulated by the International Conference of Building Officials, is a much used guideline that nine states have adopted, with special modifications for their own particular needs. About 23 states have comprehensive statewide building codes.* Earthquake-risk provisions are included in the UBC, and states that have adopted the UBC (California, Montana, Alaska, New Mexico, Indiana, Idaho, Minnesota, Oregon, and Washington) thus have earthquake coverage in their codes. Several other states, or local jurisdictions within them, have limited or nonmandatory codes or regulations. It is uncertain to what extent these codes and regulations provide for mitigation of earthquake hazards. Legislation is pending or studies are being conducted in West Virginia, Florida, Oklahoma, Kansas, Utah, Colorado, and possibly other states. In the legislation of about one third of the states, earthquakes are included among the disasters they define, there are provisions for disaster assistance, there are provisions for insurance to be written, land-use planning provisions include earthquakes, and emergency procedures are specified.

California has enacted extensive legislation pertaining to earthquake hazards and required safety measures. The following letter by Robert Streitz of the California Division of Mines and Geology summarizes California's earthquake-hazard legislation.

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*Based on December 1976 survey data provided by the Office of Building Standards and Codes Services, Center for Building Technology, National Bureau of Standards.

February 18, 1976

Dr. Joseph W. Berg, Jr.
Executive Secretary
Office of Earth Sciences
National Research Council
2101 Constitution Avenue
Washington, D.C. 20418

Dear Dr. Berg:

In response to your letter of January 14, 1976, I have summarized below most of California's legislative measures (Statutory Codes) dealing with earthquake hazards and seismic safety. All of these statutes have had minor revisions or amendments and are common targets for legislative review.

Field Act (1933)

Provides a procedure for the design and construction or alteration of earthquake-resistant public school buildings for the protection of life and property. Requires that: plans be prepared by a qualified person, design be checked by an independent state agency, construction be continuously inspected, an architect or structural engineer supervise the work and prepare plan changes as necessary to overcome unforeseen field conditions, and verified reports be filed by the architect, contractor, engineer, and inspector that approved plans were complied with in construction.

Garrison Act (1939)

Requires that school buildings that have been inspected and found to be structurally unsafe (includes seismic hazards) must be repaired, replaced, or reconstructed.

Riley Act (1939)

Provides that all buildings, except certain farm-type buildings and dwellings, shall be constructed to resist lateral forces caused by an earthquake according to a specified formula.

State Building Standards Law (1953)

Established the State Building Standards Commission to adopt and publish a single state building code compiled from regulations adopted by various state agencies. Its purpose is to eliminate conflict, duplication, and overlap in state building regulations. (The adopted state code is published in Title 24 of the California Administrative Code. Lateral-force requirements were adopted from the Uniform Building Code in 1963. The Uniform Building Code was adopted by reference in 1971 as the basic regulations in Part 2 of Title 24, CAC in 1971.)

Joint Committee on Seismic Safety (1969)

Created a technical committee to review: (1) available scientific and engineering knowledge relating to reduction of risks of damage due to earthquake and related geologic hazards, (2) adequacy of existing disaster plans, (3) contingency plans for recovery, reconstruction, relocation, and redevelopment relating to postearthquake activities, (4) the use of lands subject to seismic hazards, and (5) local government organization to determine how loss due to earthquakes may best be reduced.

Seismic Safety Element: General Plan (1971)

Requires that the general plan of each city and county include, in addition to other elements, a seismic safety element consisting of an identification and appraisal of seismic hazards such as susceptibility to: (1) surface ruptures from faulting, (2) ground shaking, (3) ground failures, or (4) effects of seismically induced waves such as tsunamis and seiches. This element shall also include an appraisal of mudslides, landslides, and slope stability as necessary geologic hazards that must be considered simultaneously with these seismic hazards.

Strong-Motion Instrumentation Program (1971)

Calls for the purchase, installation, and maintenance of accelerographs in geologic environments (free-field sites) and structures throughout the state by the Division of Mines and Geology upon recommendation of an advisory board. The program is funded by a fee system based on building permits in each city and county.

School Sites (1971)

Prohibits the construction of a school building on a geological fault. Calls for geological studies of school sites to assess the potential for earthquake damage from surface fault rupture, ground shaking, ground failure (including landsliding, lateral spreading, lurching, differential compaction, ground cracking, and liquefaction), and tsunamis and seiches.

Alquist-Priolo Special Studies Zones Act (1972)

Requires the State Geologist to delineate special studies zones to encompass potentially and recently active fault traces. Prior to the approval of construction of a structure for human occupancy within such zones, the city or county shall require a geologic report defining and delineating any hazard of surface fault rupture. Single-family wood frame dwellings not exceeding two stories are exempted. Also requires that the seller of real property located within a special studies zone, or his agent, disclose to any prospective purchaser that the property is located in such a zone. This act is intended to assist cities and counties in the exercise of their responsibility to provide public safety in hazardous fault zones.

Hospital Safety (1972)

Requires analysis, review, and approval of hospital plans and specifications and inspection of hospital construction. The enforcement of hospital building regulation is preempted by the state but allows local jurisdication stricter standards. Establishes a Building Safety Board to advice on seismic structural safety of hospital buildings. Requires periodic review of hospitals to assure that the hospital is prepared to resist damage from earthquakes. Calls for the review of geological data by a certified (registered) engineering geologist and structural design data by a certified (registered) structural engineer. Funded by a fee system based on a percentage of the construction costs of each hospital.

Seismic Safety Commission Act (1974)

Calls for the creation of a Seismic Safety Commission to coordinate earthquake related programs at all levels of government and to report annually to the Governor on its findings, progress, and recommendations relating to earthquake hazard reduction. In connection with earthquake hazard reduction the Commission shall be responsible for, among other duties: (1) setting goals and priorities in the public and private sectors, (2) requesting appropriate state agencies to devise criteria to promote seismic safety, (3) recommend program changes of state, local and private agencies to reduce earthquake hazards, (4) review reconstruction efforts after damaging earthquakes, (5) gather, analyze, and disseminate information, and (6) encourage research.

Oroville Earthquake Damage: AB 2488 (1975)

Allows brand owners of alcoholic beverages to replace without cost beer or distilled spirits offered for sale by a retailer which was destroyed or damaged by the Oroville earthquake of August 1, 1975.

State Mining and Geology Board (1975)

Requires the State Mining and Geology Board to represent, in addition to other duties, the state's interest in the development of geological information necessary to understand and use the state's terrain and information pertaining to earthquake and other geologic hazards. The board must also report annually to the Governor and Legislature its recommendations for research projects relating to earthquakes and other geologic hazards and provide a public information program on earthquakes and other geologic hazards, among other activities.

If we can be of further assistance, please give me a call.

Sincerely,

Robert Streitz

Robert Streitz
Geologist

RS:lhp

Letter from State of California Department of Conservation, Division of Mines and Geology, Division Headquarters, Resources Building, Room 1341, 1416 Ninth Street, Sacramento, CA 95814.

II BACKGROUND AND PROGRESS

4 INTRODUCTION

Seismology is the study of motions in the earth and related physical phenomena. These motions may be induced by natural phenomena such as earthquakes or they may be induced by man such as by the use of explosives. The sources wave types, propagation, and effects of these motions are important topics for seismological research. The base of knowledge that is drawn upon for seismological studies is exceedingly broad, involving such related disciplines as geology, physics, mathematics, all aspects of geophysics, chemistry, geochemistry, rock mechanics, engineering, and perhaps more. To study earthquake sources, for example, it is necessary to have firm foundations in geology, mathematics, physics, and rock mechanics; to study the propagation of seismic waves in the earth, it is necessary to be versed in geology, mathematics, physics, and chemistry; and to study the effects of earthquakes on structures, it is necessary to be knowledgeable in engineering, geology, physics, rock mechanics, and mathematics. The discipline is far too broad for one to be expert in all of its aspects; therefore, close cooperation among specialists of differing backgrounds, nationally and internationally, has been vital to its orderly development.

Earthquakes occur in many parts of the world. When sufficiently large, the energy released at a source is propagated in different wave types to all regions of the earth's surface and interior--even the deepest parts of its core--and the signals are received by seismographs distributed around the world. Some information can be gleaned about the earth from each earthquake as it is recorded at each station, but the totality of what has been and will be learned can only be obtained by studying the records of many earthquakes at all distances. Seismology is the only method used for detailed investigations of the interiors of the earth and other planets. Seismologists all over the world have worked together in exchanging data and ideas since the birth of the discipline. Thus, the international aspects of seismology are critical to its effectiveness and growth as a science and are discussed in Chapter 19 of this part of the report. The current revolution in thinking about earth structure and processes benefited greatly from international cooperation.

The concept of "plate tectonics" states that a small number of rigid plates form the earth's outer surface and that the movement of these plates relative to each other is responsible for earthquakes and the building of mountains and is associated with the deposition of ores, burial of plant and animal life (to form fossil fuel), and many things more. Our present understanding of this revolutionary concept is only in its infancy. Much is still unknown, including the answer to the underlying question of why the plates move at all. When we know much more about why and how the plates move, we will have the basis of a much better understanding of many things about the earth, including the prediction of earthquakes.

The use of seismology as a fundamental and powerful tool in our search for a greater depth of understanding about the earth's structure, composition, and dynamics has only been practicable since the turn of the century. In this short time, seismology has provided the basic knowledge that is used for predicting volcanic eruptions and seismic sea waves, for finding deposits of oil and gas, for determing the vibrational criteria that are used for structural design so as to mitigate earthquake effects, for estimating various hazardous effects related to earthquakes, for predicting earthquakes, and for many other purposes. Seismology is truly a discipline that has many frontiers, and our knowledge is still far from complete in any of these areas.

Part II of this report provides the reader with overviews of many important aspects of seismology. Each chapter was written to provide a historical summary, state of the art, outlook, or combination of these in a particular aspect of seismology, to serve, initially, as background for Part I. Later, it became apparent that these papers could be a useful adjunct to the published report, providing for many categories of reader up-to-date summaries of what is known and what is being done in these diverse, but interrelated, components of the discipline. Students and others who may want to go further into these subjects may contact the authors directly for advice and references.

5 THE BIRTH AND EARLY GROWTH OF SEISMOLOGY

The scientific study of earthquakes evolved from mankind's desire to understand, and perhaps thereby to mitigate, this major cause of natural disasters. Because the places of origin of western culture (the eastern Mediterranean) and of eastern culture (China and Japan) are regularly subjected to earthquakes, we find references to seismic activity in the earliest literature. European concern about earthquakes was greatly increased by the Lisbon earthquake of 1755, which took about 60,000 lives, but it was not until the last half of the nineteenth century that seismology began to emerge as a quantitative discipline within geophysics. Although not recognized for some decades, the theoretical foundation of the science had been laid by several of the great applied mathematicians of the nineteenth century through their work in elasticity and elastic-wave theory and in acoustics. The arrival of the British mining engineer, John Milne, and his colleagues in Japan shortly after the Meiji restoration, and their subsequent fascination with the frequently felt earthquakes, stand as milestones in the evolution of the science.

The transition of seismology from the study of earthquakes as a local phenomenon to a geophysical discipline on a global scale began with the first detection of a teleseismic signal, by E. von Rebeur-Paschwitz in Hamburg, in 1889, and with his realization of the implications of this discovery for investigations of the earth's interior. A new era in the study of planet earth began with von Rebeur-Paschwitz's appeal, made at the International Geological Congress in Dresden, in 1892, for the creation of a global network of seismograph stations.

Prepared by Carl Kisslinger, Director, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, 80302.

The first 15 years of the twentieth century were truly remarkable with regard to the development of seismology. Almost every important problem within the scope of the science was at least crudely formulated, and first solutions to many were achieved. Outstanding theoretical contributions came from England, especially in the work of H. Lamb and A. E. H. Love, and from Göttingen, Germany, by the group led by E. Wiechert. B. Galitzin of St. Petersburg was another giant of this time. The first travel-time curves were produced by Milne in 1903, Oldham in 1906, and Wiechert and Zoeppritz in 1907. The principles of inverting the travel-time data to obtain the velocity-depth structure of the earth were developed by Herglotz, Wiechert, and Bateman. The iterative, least-squares procedure for locating an earthquake from observations of seismic-wave arrival times, still in use, was published by Geiger in 1910.

The discovery of the Mohorovičić discontinuity (the boundary between the crust and mantle) under Europe in 1910 and the first calculation of the fluid-core radius by Gutenberg in 1914 established the basic shell structure of the earth's interior. Gutenberg's calculation, based on crude and limited data, is truly remarkable: the best modern analyses have been able to change it by only a few tens of kilometers at most. The proof that the mantle is solid called for a profound change in the thinking of geologists, who had generally accepted the idea of a molten interior with only a thin solid crust. The vastly improved understanding of the earth acquired within these few years was unmatched until the last decade, when the concepts of sea-floor spreading and plate tectonics provided another enormous advance.

Meanwhile, the great contribution of this early era to another problem, the physics of the earthquake process, came from the United States. The elastic-rebound theory, with slip on a fault as the mechanism of seismic-energy release, was proposed by H. F. Reid on the basis of observations associated with the great California earthquake of 1906. This model has, to the present, held up well on its broad principles. Indeed, the data from repeated geodetic surveys, the basis of Reid's hypothesis, are being gathered now as a key element in the effort to learn how to predict earthquakes. Another landmark of this early period was the development of the seismological program of the Jesuit colleges and universities, started in 1900 and culminating in the creation of the Jesuit Seismological Association in 1925, under the leadership of J. B. Macelwane.

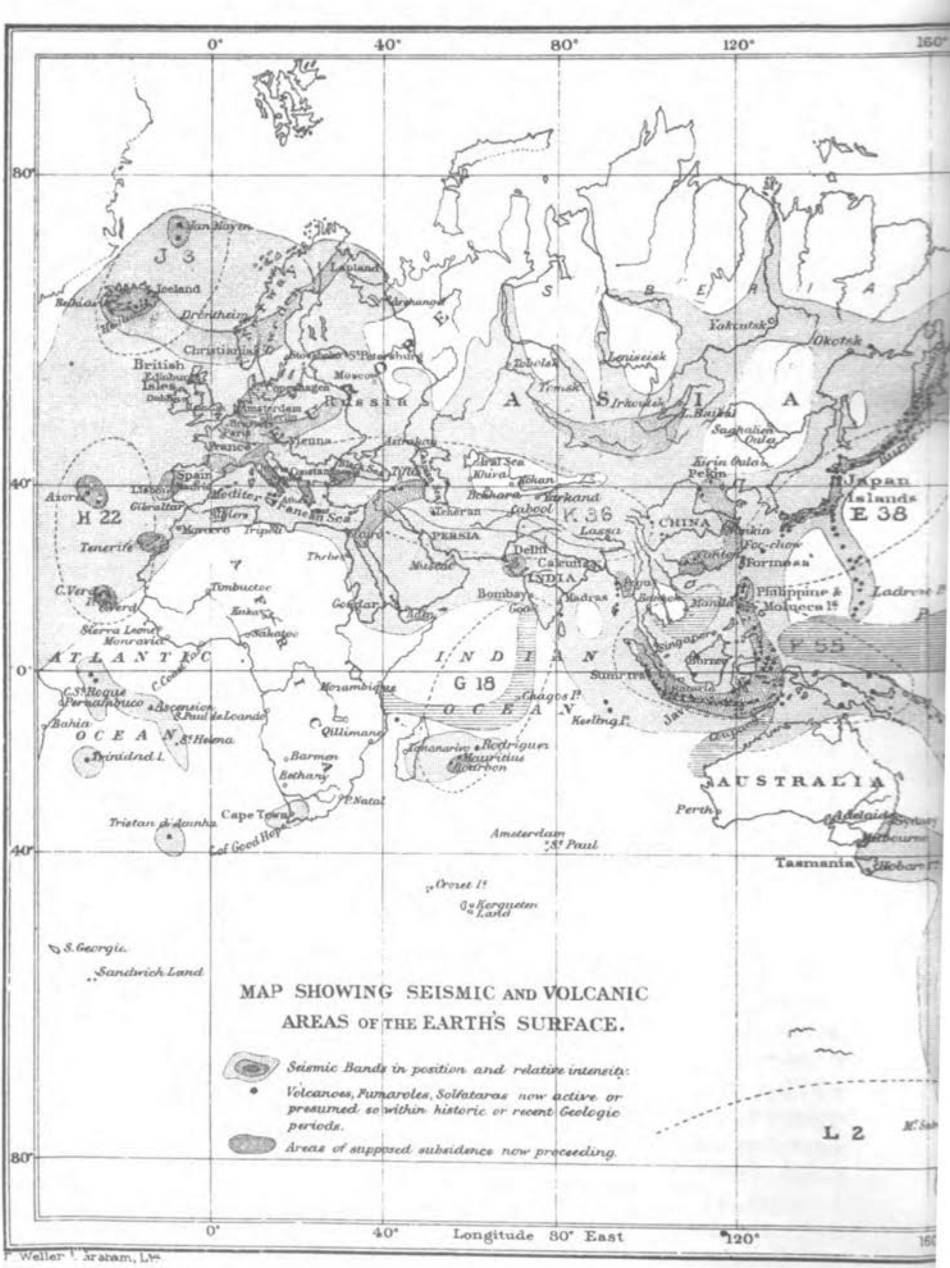
This effort offered a model of a coordinated observatory network with broad geographic coverage.

Rapid improvements in instrumentation followed Galitzin's application of the electromagnetic transducer and galvanometric recording to the seismograph, in 1912. Galitzin instruments, especially the modified version developed by Wilip to provide improved linearity of response and stability, became the primary equipment in many observatories. Other important inventions were the Wood-Anderson torsion seismograph in 1925, the quartz-rod strain seismograph in 1935 and the variable-reluctance transducer for seismograph applications in 1932 by Benioff, and the application of the zero-length spring to systems suitable for detecting long-period vertical motions by LaCoste in 1935. Unfortunately, a fundamental requirement of a good seismograph observatory, a completely reliable clock, was not met until after World War II, when crystal clocks became readily available.

In spite of all the progress in instrumentation, seismology was in a poor state in terms of the general standards of physical science because of the lack of properly calibrated instrumentation systems with uniform response characteristics at most of the world's observatories. Individual stations did have calibrated systems, and the equipment installed in widely separated places during the International Geophysical Year (1957-1958) provided valuable experience that was put to good use when the VELA program brought the opportunity to establish the Worldwide Standardized Seismograph Network. Until the VELA program, seismology was primarily dependent on a handful of dedicated workers, usually with minimal resources.

The main features of the geographical distribution of earthquakes were known by the end of the nineteenth century. A map in Milne's 1886 book, *Earthquakes*, shows in broad form the Alpide and Circum-Pacific belts, as well as some centers of activity in the mid-Atlantic and under other parts of the oceans (see Figure 5.1). Because these early seismicity maps were based on reports of felt earthquakes, and therefore dependent on the distribution of population, they do not show the seismic belts as continuous features. It is especially interesting that California is not indicated as a place of strong and frequent activity, an impression that was abruptly changed only 20 years after this map was published.

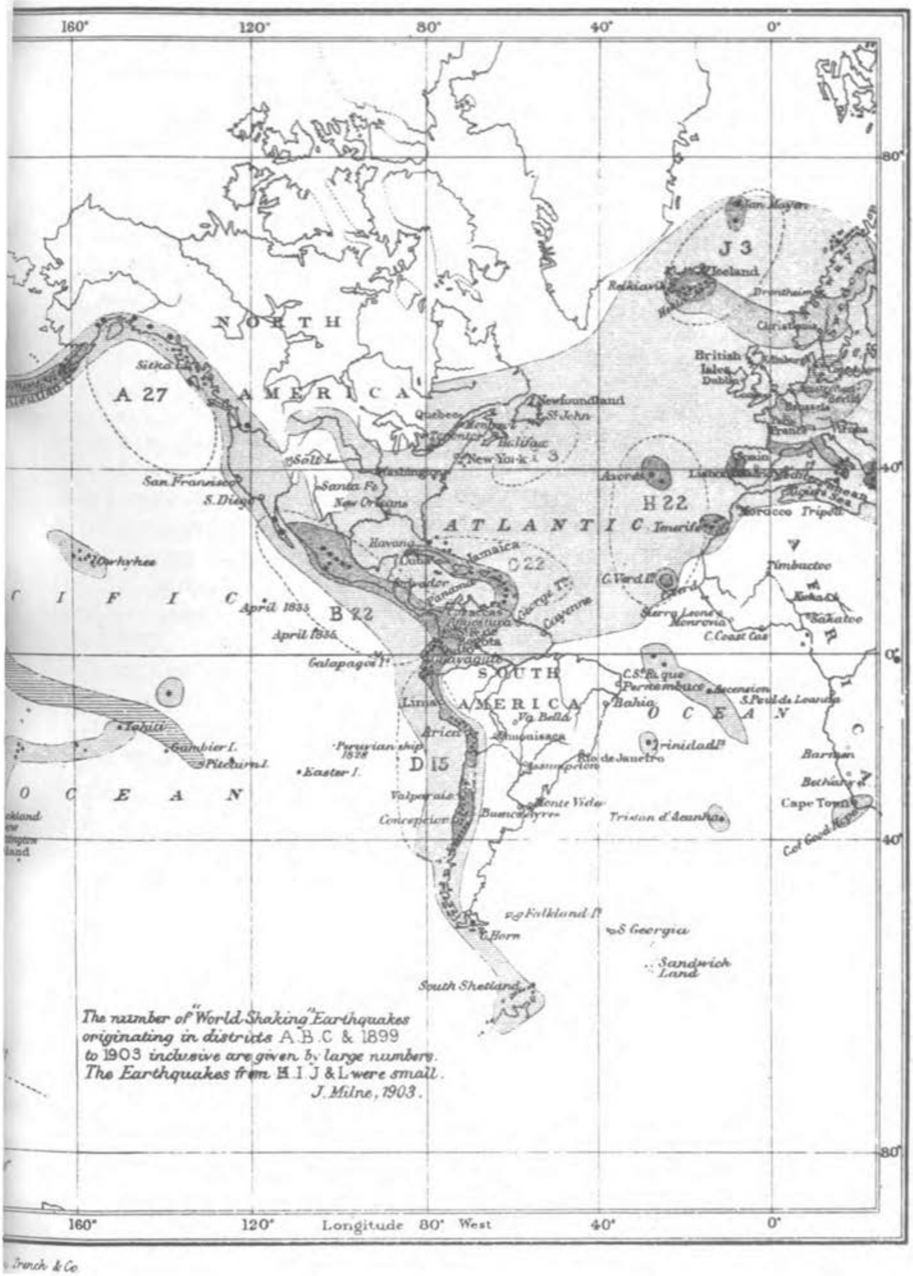
Only with the development of instrumental seismology and the ability to detect and locate moderate and large earthquakes wherever they occurred did an accurate picture



F. Weller & Graham, Ltd

London:

FIGURE 5.1 Milne's seismicity map. The map shown was published in a 1910 revision of Milne's 1886 book,



Earthquakes; although it contains some additions, it is essentially the same as the 1886 map.

of the seismicity of the earth emerge. An important synthesis of this knowledge was provided by Gutenberg and Richter in 1947.

In particular, the high rate of earthquake activity associated with the undersea ridge systems was not even suspected until instrumental observations were available. It was not until after 1961 and the deployment of the Worldwide Standardized Seismograph Network that locations of submarine earthquakes were accurate enough to show that the earthquakes along the undersea ridge systems could be associated with the detailed features of the ridges in a systematic way. This discovery was one of the key links in the chain of evidence supporting the theories of seafloor spreading and plate tectonics.

Theoretical studies in earthquake statistics and elastic-wave theory were carried on during the 1920's and 1930's by Harold Jeffreys and his colleagues, especially Stoneley and Bullen, in England, and by a group of Japanese researchers. Improved travel-time curves were developed. The theory of elastic surface-wave dispersion was expanded and applied to the interpretation of seismograms, but it was not until the 1950's that the full power of this method was brought to bear on studies of earth structure. By the beginning of World War II, the main features of a seismogram were understood, at least qualitatively, in terms of the propagation of body and surface waves. A fundamental improvement in the accepted model of the earth was Inge Lehmann's discovery of the existence of the inner core in 1936.

A major controversy that was not settled until the late 1920's was the existence of earthquakes with hypocenters below the crust. Early seismologists called the surface-wave portion of a seismogram the "principal" portion and thought of the body waves as "preliminary arrivals." It is not surprising, therefore, that these observers did not accept readily the idea that the sequence of pulselike body waves, without surface waves, that are characteristic of deep focus events are true earthquake signals. Even today we do not fully understand the physics of faulting at great depths, but plate tectonics does account for the localization of deeper earthquakes in the particular places where they occur.

The fault-origin concept of earthquakes predicts a definite pattern of radiation of seismic waves, and observations of this pattern can be used to derive the orientation of the fault plane and the direction of slip (focal mechanism). Nakano derived the basic theory in

1923, and Byerly, in 1938, developed a technique for applying these principles to the distribution of the polarities of compressional-wave arrivals. The use of shear-wave particle-motion directions in focal-mechanism analyses was developed in the 1950's, with Stauder as a leading contributor.

A great surge of activity followed World War II. Surface-wave methods for determining crustal structure, long known, were applied widely to such problems as the structure beneath the oceans, and the theory was expanded to account fully for higher modes. The first tentative identification of the earth's free oscillations was made by Benioff in 1954, but it was not until the 1960's that suitable data became available to enable the identification of large numbers of normal modes and their interpretation in terms of earth structure. During the 1950's, all the techniques of today's conventional seismology were further developed and the stage was set for the first infusion of massive resources into the field, which came with the decision to establish Project VELA Uniform, the program of research directed toward solving the technical problems of monitoring underground nuclear explosions.

This brief review of the history of seismology would be deficient without at least mentioning the several services that were created to accumulate, process, and distribute earthquake data and hypocenter solutions, namely, the International Seismological Summary (ISS), in England, the *Bureau Central International de Seismologie,* in France, and the Seismology Division of the U.S. Coast and Geodetic Survey (USCGS), Washington, D.C. The ISS and the USCGS have since been succeeded by new organizational forms. The pattern these three services set for careful, comprehensive analysis of the worldwide earthquake data has been a powerful influence toward the excellence of the quality of the work being done today.

6 NUCLEAR TEST MONITORING AND ITS SCIENTIFIC RAMIFICATIONS

A major expansion in seismological research was initiated in the United States in 1959 to solve problems that had been revealed during the previous year while negotiations were in progress for a treaty banning nuclear-weapons testing. It had become apparent that existing capabilities to monitor underground nuclear explosions in foreign countries were not adequate for national or international needs.

In response to a request by the Department of State, the Special Assistant to the President for Science and Technology appointed a "Panel on Seismic Improvement" to examine the explosion-detection problems. The Panel recognized that the existing problems reflected deficiencies in fundamental seismological knowledge and proposed a program of research to improve national detection capabilities.* It was subsequently agreed that the Department of Defense would accept the responsibility for conduct of the proposed research, and the Defense Advanced Research Projects Agency (DARPA) was assigned the mission of devising improved means for seismic detection. The ensuing program, initiated along the lines recommended by the Panel, was known as the "VELA Program."

Funding for the VELA Program commenced with $7.5 million in fiscal year 1960 and increased to $31 million in fiscal year 1961. Although a significant fraction of this money

*"The Need for Fundamental Research in Seismology," Report of the Panel on Seismic Improvement, Department of State, July 1959.

Prepared by Carl F. Romney, Director, Nuclear Monitoring Research Office, Advanced Research Projects Agency, 1400 Wilson Boulevard, Arlington, Virginia 22209.

was used to pay for large explosions to produce seismic signals for research purposes, it is fair to state that the greater part of the funds, which were applied to procuring equipment and conducting experiments, theoretical studies, and similar conventional activities of seismological research laboratories, increased such activities by more than an order of magnitude in a single year. As often happens during attempts to create a "broader base" of research in a short time, some inefficiencies resulted. By and large, however, such inefficiency was minimal, since seismology had long been an underfunded field in need of more modern equipment and increased access to computers and with numerous excellent ideas ready and waiting for the means to begin research. Then too, since the detection research had to attack the most fundamental problems of seismology, there was a high degree of correspondence between VELA-oriented studies and those that seismologists would have chosen for other reasons. The end result was that the laboratories rapidly and efficiently rose to a new level of activity and competence, which has been sustained to the present.

In formulating their recommended research program for solving problems associated with detection and identification of nuclear explosions, the Panel on Seismic Improvement had noted that the work would also "result in dramatic advances in our knowledge of the earth's interior, of the mechanism of earthquakes, and of elastic wave propagation." Experience since that time continues to affirm that advances in seismic detection are inseparable from advances in the major subdivisions of the science of seismology. Indeed, DARPA has found it necessary to sponsor research on almost every aspect of seismology in pursuit of improved detection capability. For that reason, and because of the magnitude of the stimulus provided to seismology, it is difficult to separate the contributions of the VELA Program from the general great expansion and progress of the science as a whole. It is easy, however, to identify many areas where significant advances in our understanding of the earth and its processes, as well as in our capability to conduct research, depended heavily on VELA support. A representative listing of examples includes the following:

1. Development of a greatly improved worldwide seismic network for the provision of research data. Although the collection of data is in itself not research, every physical science is enriched and motivated by new data resources--seismology and other geophysical sciences even more so than

most. In retrospect, perhaps the most imaginative and far-reaching recommendation of the Panel on Seismic Improvement was to equip seismological stations throughout the world with standard calibrated seismometers, modern recorders, and accurate timing systems. This recommendation led to the establishment of a worldwide network of about 125 standard seismic stations; this network continues to be the largest single source of reliable data for teleseismic studies.

2. Introduction of seismic-array technology and provision of array data for classical studies of earthquakes and the earth. This led to the extension of worldwide seismicity studies to significantly lower magnitude than had been possible in the past, the discovery and analysis of new seismic phases, and greatly improved understanding of microseisms.

3. Development of digital seismic-recording systems specifically for classical seismological research and the associated computerized analyses of seismic data. This has become such an important research tool that further work is now in progress to upgrade selected stations of the worldwide seismic network by providing increased long-period sensitivity and digital recording. These upgraded "Seismic Research Observatories" will supply the high-dynamic-range digital data that are becoming essential to the sophisticated analyses that are integral parts of research along the forefront of modern seismology.

4. Greatly improved seismic-travel-time curves, dispersion curves, and measurements of rate of decay of seismic-wave amplitudes with distance--all primary tools for investigating the internal constitution of the earth.

5. Precise delineation of seismicity associated with major tectonic features of the earth (midocean ridges, subduction zones, transform faults) and determination of characteristic focal mechanisms. This work depended strongly on data from the Worldwide Standardized Seismograph Network, on improved travel-time curves derived from observations of nuclear explosions, and on development of computer routines for accurate and consistent epicentral location.

6. Determination of fine structure of the earth's core, including proof that the inner-core boundary is a sharp transition, based in part on measurements of seismic phases that can only be detected with seismic arrays.

7. Development of inversion techniques for routine use on surface-wave velocity and body-wave travel-time data and approximate solution to wave propagation and ray

tracing in complex three-dimensional structures (e.g., a descending slab).

8. Demonstration of large-scale regional differences in upper mantle structure through surface-wave analyses and determination of quantitative characteristics and finer structural detail of the mantle through measurement of seismic body waves from explosions.

9. Demonstration of the existence of descending slabs in subduction zones through measured seismic velocity and amplitude anomalies (one of the best examples is based on data from the Longshot explosion--a nuclear explosion in the Aleutian Islands conducted for seismic research).

10. Development of improved theoretical models of earthquake mechanisms, including effects of source dimensions and rupture propagation.

7 INSTRUMENTATION AND DATA PROCESSING

Before 1960, about 1000 seismographs were operating around the world. The design, methods of recording, and procedures of timing were varied, and the instruments were poorly distributed geographically. Nevertheless, these instruments were adequate for the study of travel times of seismic waves of short-period amplitudes and, in some cases, of surface waves with periods as long as minutes. Before 1940, most of the major discoveries about the structure of the earth came from the study of travel times.

A better understanding of earth structure and of earthquake-source mechanisms required improved instruments of standard design, all operating in the same well-calibrated configuration. This requirement was first recognized and met in the seismic-prospecting industry and led to the success of the reflection seismograph. The need to discriminate between earthquakes and explosions spurred the development of the Worldwide Standardized Seismograph Network (WWSSN) in the early 1960's. Although there are only about 125 WWSSN stations around the world, they are operated in an identical standardized fashion. This network has provided the data needed for fundamental research in seismology and global tectonics. It has served this purpose well, contributing essential data during a period of accelerated progress in the understanding of earthquake and tectonic processes.

The WWSSN, together with major national networks, will be the principal source of earthquake data for years to

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come, but improvements are needed if the network is to keep pace with the data needs of the seismological community. Since the 1960's, there have been significant advances in instrument technology, digital recording, computer processing, and our understanding of the structure of earth noise in the long-period band. Through careful design and control of the operating environment, several groups have been able to increase usefully (by more than an order of magnitude) the operating sensitivity of long-period seismographs, for periods above about 20 seconds, compared with that of the WWSSN system.

As computers become larger and faster and as recording systems become more reliable, the use of digital data becomes more attractive. The seismic prospecting industry "went digital" in the late 1950's and successfully employed methods of time-series analysis developed during the Second World War. Digital seismographs for the study of earthquakes and nuclear explosions were developed in the 1960's, but a global network of such instruments has only recently been established.

Among the recent developments is a program to upgrade selected stations of the WWSSN under the sponsorship of the Defense Advanced Research Projects Agency (DARPA). Thirteen Seismic Research Observatories (SRO), consisting of an advanced digital-recording seismograph system in which data are derived from a broadband borehole seismometer package, are to be installed globally by the U.S. Geological Survey (USGS) at widely distributed locations. Together with the High-Gain Long-Period (HGLP) seismograph system installed in recent years and the growing network of very long-period gravimeters, they will form an integrated network of about 40 digital-recording observatories to complement the WWSSN. One advantage in the borehole siting of the SRO instrumentation is that wind-generated noise in the long-period band is considerably reduced at depths of 100 m or more. Most of the data from the integrated SRO/HGLP network will be recorded in both analog and digital formats, with a dynamic range of over 100 dB for the digital data.

The principal purpose of the expanded WWSSN is to provide data for research; thus, its success depends on making the data accessible to researchers. For years, conventional seismograms have been sent to the Environmental Data Service (EDS) of the National Oceanic and Atmospheric Administration, or to its predecessors, for microfilming, and copies have been distributed to subscribers. This service will continue, but for the integrated network the reproduction of seismograms or film chips from the digital tapes is being considered as an alternative to the collection and processing of station seismograms from the same location. The reproductions are superior to the conventional seismograms in several respects, for example, they have greater dynamic range and can be plotted at any magnification. A complementary data-management system is being established by DARPA to process, store, and disseminate data collected from the digital-recording network and from seismic arrays in Montana, Alaska, Norway, Korea, and Iran. The array data will be analyzed by automated event-detection and event-associated processors to produce a summary that will list events and their associated parameters. The event summaries, associated waveforms, and raw array data will be placed in a mass data store to be augmented later by SRO-network data as tapes are received from the stations. Access to this data bank will be provided through the Seismic Data Analysis Center, in Alexandria, Virginia, and, as in the case of the WWSSN, the data will be available to the international seismological community.

The introduction of seismic-array technology brought a new dimension to conventional seismology. From the relative arrival times of a seismic wave across a closely spaced array of seismic sensors, seismologists were able to obtain almost a direct measurement of its phase velocity. With knowledge of the distance to the source, this apparent velocity in turn can be used to infer earth structure. The use of arrays also led to the development of a wide range of data-processing techniques for signal enhancement. For example, by cross-correlating the signal between sensors and summing at the appropriate time lags, the signal-to-noise ratio for an arriving seismic wave can be improved by the square root of the number of sensors for short-period signals and by up to a factor of 10 for long-period body and surface waves. Needless to say, this has considerably lowered the detection threshold for seismic signals and led to the identification of many new seismic phases.

Many studies of the structure of the earth and of the mechanism of the earthquake source require observations at periods longer than can be obtained, except from large earthquakes, from the current operating instruments of the WWSSN or SRO/HGLP networks. Small ground motions at these longer periods can be recorded by strainmeters, tiltmeters, superconducting gravimeters, and gravimeters with electrostatic feedback. High-quality seismic data, for periods greater than 40 seconds, are currently being recorded digitally for only a few stations in the world. Digital recording, in conjunction with active filters, can provide a dynamic range of over 100 dB for periods between 2 minutes and 1 hour. Data from these instruments can be used for earthtide studies and for investigations of earth structure and the earthquake mechanism using free oscillations and surface waves. High-sensitivity borehole strainmeters covering the same period range, as well as secular strain, have also been developed.

The development of the laser as a source of coherent optical radiation has permitted the application of interferometric techniques to the problem of earth-strain measurement. Application of this technology has resulted in improved stability of laser interferometers and second-generation two- and three-wavelength ranging devices for long-base-length measurements through the atmosphere. The latter type of instrumentation appears to provide an order-of-magnitude improvement in the precision of crustal-deformation measurements.

A major problem in seismology is that seismic stations, by virtue of their locations, record seismic waves that have traveled primarily through continental earth structure, whereas oceanic structure can only be inferred. In view of present ideas about lateral variations in earth structure, it seems inevitable that deployment of continuously recording ocean-bottom seismographs will eventually be needed in remote oceanic areas. This could be accomplished with satellite telemetry links as soon as financial and technological constraints permit. Over the past decade, technological improvements in ocean-bottom systems have advanced to the point where these sytems are now routinely used for short-term seismicity studies on ridge crests and in fracture zones and for long-range refraction profiles.

A greater demand for large numbers of inexpensive seismic stations for use in studies of regional seismicity and microearthquakes has led to the engineering development of low-cost seismic-data-acquisition and telemetry systems. The USGS now installs, or supports the installation of, many new seismic stations of this type each year. This great increase in the rate of data acquisition has not yet been matched by comparable developments in data handling and analysis. For example, routine analysis of data from local seismic networks is still based on Develocorder film records, although real-time computer processors are under development. Currently, these processors can provide "scan lists," indicating times and approximate locations and magnitudes of earthquakes that it detects, in order to facilitate the reading of the film records, and it can provide periodic station-performance checklists to aid in troubleshooting and maintenance of the network.

The recordings of strong ground-motions within a few tens of kilometers of large earthquakes provide information that is vital in the engineering design of earthquake-resistant buildings and other structures and in understanding earthquake source mechanisms. Recordings of this type have accumulated slowly since about 1940. The San Fernando earthquake of February 1971 was extremely significant in this respect; because of the large number of strong-motion instruments installed in the Los Angeles area at that time, the total amount of such data available to seismologists was more than doubled by this single event.

8 GEODYNAMICS AND PLATE TECTONICS

The concept that the positions of the continents and oceans are not fixed has gathered strength since the beginning of this century. This concept led to the proposal of continental drift following the breaking up of two huge protocontinents. A major impetus to the acceptance of this idea was the suggestion of sea-floor spreading derived from studies of the properties of the ocean floor in the vicinity of the midocean ridges. A major recent unifying synthesis of these ideas is the concept of "plate tectonics." In this framework of ideas, the outer shell of the earth, the lithosphere, is relatively cool and rigid compared with the softer, more fluidlike interior and is broken into a number of pieces, the lithospheric "plates," which move about relative to one another over the more plastic interior. It is theorized that the system of plate motions is part of the earth's system of convecting heat from the interior. Hot material ascends beneath the world-encircling system of submarine mountain chains, the midocean-ridge system, where plates are moving away from one another. This material cools and is added to the edges of both diverging plates, thereby forming the suboceanic lithospheric plates. Eventually, the material descends back into the interior along another world-encircling system, the subduction zones, where suboceanic plates underthrust adjacent plates and move downward. Continents were built of material segregated from the interior during the history of the earth, and, being less than the interior, remain at the surface.

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The long-term relative motions of the plates are well known. It was the determination of these motions by means of interrelated data of paleomagnetism, marine geophysics, and seismology that led to support for the plate-tectonics model.

The impact of these developments on earth science has been profound, as evidenced by the flood of publications during the past 10 years in both the technical and popular literature. The plate-tectonics model has provided the framework for attacking fundamental problems of the earth's structure, composition, and history as well as such problems of immediate practical concern as the location of energy and mineral resources and the prediction of earthquakes.

Three related developments in observational and analytical work were primarily responsible for the effective contribution of sesimology to plate tectonics.

The first was the establishment of a worldwide network of seismographs sensitive to long-period (15-100 seconds) waves. These instruments were developed in the 1950's. They were deployed worldwide on a limited basis during the International Geophysical Year (IGY) program and then extensively during the early 1960's as part of the Worldwide Network of Standardized Seismographs (WWNSS). The resulting data have had a profound effect throughout the field of seismology. A number of findings were of special pertinence to plate tectonics. Analysis of surface-wave dispersion showed differences between oceanic and continental structure. Surface-wave studies also provide convincing evidence of the existence of the low-velocity zone beneath oceanic areas. First motions of compressional and shear waves from earthquakes are determined from the long-period seismograms and yield easily determined and reliable focal-mechanism solutions. These solutions can be used to infer the directions of relative motion for earthquakes at plate boundaries or the orientation of principal stresses for earthquakes within plates (including descending slabs). The long-period data have also proved essential for the study of other characteristics of the earthquake source that are of importance to plate tectonics, such as the seismic moment and the magnitude of stress relieved by the earthquake.

The second major development was the vast improvement in the number and quality of determinations of the locations of earthquakes that took place during the period of about 1957 to 1965. This improvement was a product of the large increase in the number of seismograph stations throughout the world (notably with establishment of the WWNSS), the centralization of data-collection and analysis facilities, and the use of high-speed computers. The Preliminary Determination of Epicenters (PDE) program, now part of the National Earthquake Information Service of the USGS, regularly locates about 5000 earthquakes worldwide per year. This service, absolutely essential to the science of seismology as a whole, provides the key data for the determination of plate boundaries and subducted slabs and for the study of many other aspects of seismicity and tectonics.

The third development was the intensive study of specific regions of seismic and tectonic activity. Studies of particular regions produced crucial evidence for various aspects of plate-tectonics theory. These regions are: Japan, where earthquake studies have a long history and from which important evidence for subduction emerged; Alaska-Aleutians, notably the studies of the Alaskan earthquake of 1964 and studies related to nuclear tests in the Aleutians; the Tonga/Fiji region and South America, where stations were set up under the Upper Mantle Project to study deep-focus activity; and the San Andreas transform-fault system of California.

Studies of the relationship between tectonics and seismology were greatly encouraged and stimulated by the Upper Mantle Project (UMP) of the 1960's, and this productive relationship has continued under the International Geodynamics Program, which has carried forward and extended the work of the UMP.

Seismology continues to play a key role in the development of plate tectonics for two primary reasons. First, the relative motions of two plates along their common boundary are directly manifested by earthquakes. Thus, the locations of earthquakes within narrow and essentially continuous, world-encircling zones outline the plates, and the geometry of the faulting causing the earthquakes determines the direction of relative movement of adjacent plates. For example, the Alaska earthquake of 1964 and the Chile earthquake of 1960, among the largest known recent earthquakes, occurred at the contacts between suboceanic lithospheric plates and adjacent continental plates. In each case, the suboceanic plate is being thrust beneath the continental plate along an inclined zone of contact (the Benioff zone). During the past 10 years, numerous studies of the locations of earthquakes and of the causative faulting have defined the configurations and motions of plates in many tectonically active regions of the earth.

At the same time, such studies have also revealed complex areas, generally where plate boundaries appear to cross continental areas--where single, simple, discrete plate boundaries do not appear to exist but are replaced apparently by larger regions of more diffuse and complex deformations. Studies of such areas are still in an early stage.

The second major contribution of seismology is the product of the study of the propagation of seismic waves in the earth and the consequent inferences about earth structure. The idea that there exists a softer, possibly partially melted subtrate beneath the lithosphere, called the asthenosphere, was associated with one of the major discoveries of the 1950's, the so-called "low-velocity zone." At depths greater than about 70 km beneath the oceans, seismic-wave velocities were found to decrease with increasing depth and then to increase again at depths of several hundred kilometers. This decrease in velocity is thought to result from the partial melting of the material because of the high temperatures at those depths. Further seismic work showed that the low-velocity zone probably coincides with a region of high attenuation or absorption of seismic waves. An association was made between the seismic low-velocity and high-absorption zone and at least the upper part of the asthenosphere. Thus, the lithosphere-asthenosphere structure based upon the long-term strength characteristics of the material, i.e., a strong, relatively rigid lithosphere overlying a weaker asthenosphere, could be associated with a seismic structure in which material with relatively high velocity and low absorption overlies material with low velocity and high absorption.

Major lateral variations in this seismic structure could then be associated with the pattern of plate motions, and indeed, the determination of such variations continues to provide crucial information on many aspects of plate tectonics. For example, the structure beneath continents is found to be considerably different from that beneath oceans to a depth of at least several hundred kilometers, and perhaps more. Beneath the continents, the low-velocity zone may be absent or poorly developed. These studies may significantly affect our concepts of the motions of material in the earth's interior.

Some of the most pronounced lateral variations have been found in zones of lithosphere subduction. At a depth of 100 km, for example, variations of about 10 percent in seismic-wave velocities and of 1 to 2 orders of magnitude in the absorption coefficient are found in going from material inside the descending lithospheric plate to that outside it. Indeed, these remarkable variations and their close association with the planar zones of earthquakes that reach depths of nearly 700 km in the mantle led to the realization that the mantle seismic zones mark slabs of down-going lithosphere. In other areas, where plates are moving apart and hot material rises to shallow depths, anomalously low velocities and high attenuation are found, serving to illuminate the structure and tectonics of those areas.

The success of the plate-tectonics concept has largely been expressed in the description of the motions of the plates. The nature of the forces involved and the nature of convective motions beneath the plates are still subjects located at the frontier of earth science. Again, seismological studies play crucial roles here.

Although most earthquakes occur at plate boundaries, some occur within the plates themselves. Examples are the occasional shocks in the eastern part of North America. Some of these, such as the Charleston earthquake of 1886, are sufficiently large to represent a significant hazard. They are of special concern in the siting of nuclear power plants. The cause, or causes, of such "intraplate" earthquakes remains unknown. If the shocks result from stresses transmitted throughout a lithospheric plate, as some scientists have suggested, further investigation may yield important information about the forces that move the plates.

The most intense seismic activity within plates occurs in the parts that have been subducted and are descending into the mantle. Earthquakes at depths greater than about 70 km occur in these down-going slabs of lithosphere. Study of the mechanisms of these events has supported the idea that the descending slabs act as stress guides. Because these slabs are cooler and therefore denser than the surrounding mantle, they may be sinking under their own weight. If the downward pull of a descending slab is transmitted to the portion of the plate remaining on the surface, it could be an important component of the system of forces controlling the motion of the plate. Recent attempts to model the dynamics of plate motions have included this force.

No earthquakes occur deeper than about 680 km, a limit quite close to the depth at which the material in the mantle changes its crystalline structure into a denser form. Whether this limit represents a barrier to the descent of slabs or merely a cessation of earthquake production within descending slabs is a question with important implications about the pattern of convection within the earth. It is not known, for example, whether convection occurs throughout the entire mantle or is confined to the upper mantle. Another possibility is a dual system of upper and lower mantle convection with little or no interchange of material. These are problems to whose solution seismological studies must contribute crucial information.

The interaction between the development of the concept of plate tectonics and the science of seismology has been of mutual benefit. For example, an important area of seismology invigorated by the ideas of plate tectonics is the study of the occurrence of large, shallow earthquakes. These events pose the most serious hazards to man. The idea that earthquakes that occur along a plate boundary accommodate slippage between the adjacent plates is a conceptual foundation for study of the physical mechanism of the earthquake source. The orientation, geometry, and other properties of the plate boundary become significant constraints in the problem.

In the simplest approach, large earthquakes are viewed as accommodating all slippage between plates, and the zones of slip along a plate boundary associated with earthquake shocks are contiguous and nonoverlapping. In time, a shock occurs in any "gap" left by preceding sequences of shocks along a particular plate boundary. This simple pattern seems to hold along the Kurile and the Alaskan-Aleutian plate boundary, for example. There are interesting exceptions to the pattern, however. One of the main unsolved problems concerns the amount of slippage that may take place slowly and not generate earthquakes. This phenomenon, known as "creep," occurs along portions of the San Andreas fault system in California and, interestingly, is most prominent along that part of the system located between the zones of slippage associated with the largest earthquakes on record. It is not yet known whether creep occurs along boundaries between converging plates, such as the Alaskan-Aleutian zone or western South America, or how important it is in those zones if it does indeed occur.

The development of the concept of plate tectonics during the past 10 years has had a strong and healthy effect on the earth sciences, drawing many fields of earth science together. Seismology has always been close to the mainstream of solid-earth geophysics because it supplies most of the information about the earth's interior and because of the intimate relationship between earthquakes and tectonics. The crucial role of seismology in the further development of the concept of plate tectonics will integrate seismology even more strongly with other branches of geophysics and with geology. This integration of the earth sciences is reflected in the increasing number of interdisciplinary meetings that bring specialists from a number of fields to consider a particular problem, such as the nature of the lithosphere-asthenosphere boundary or the state of stress in the lithosphere.

One of the most effective positive influences in this integration has been the very active U.S. participation in the International Geodynamics Program. This project is an international program of research into the dynamics and dynamic history of the earth, with major emphasis on phenomena that affect the surface and near surface. One of the most significant by-products of the development of the plate-tectonics concept has been the accelerated transition from discipline-oriented studies to multidisciplinary, problem-oriented studies. This flexibility of approach to the research needs of particular problems is a sign of a healthy and vigorous science, one in which seismology has played and will continue to play a leading role.

9 THEORETICAL SEISMOLOGY

It has been customary to divide theoretical seismology into two parts: the theory of seismic sources and the theory of the propagation or transmission of seismic pulses and waves. This division is at least partly arbitrary, especially when one considers the related inverse problems. In recent times, moreover, another aspect of the subject, related to computing, has become important and has led to improved methods for studying both sources and propagation effects.

SEISMIC SOURCES

The nature of the seismic source, whether natural or man-made, must be well known before the observed seismogram can be used to study the structure of the earth's interior. This is a problem common to seismological studies at all scales, from the structure of a sedimentary basin for economic exploration efforts to the structure of the earth's core. The earth's lithosphere is divided into a number of plates, most of which move nearly rigidly with respect to each other. Some plates, such as the Asiatic plate, deform internally in response to peripheral stresses caused by "collision" with neighboring plates. All the relative motions appear to be episodic. Abrupt motions along plate boundaries are earthquakes. Less abrupt motions are lumped together as creep, aseismic behavior, etc. The theoretical study of seismic sources is closely associated

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with the subject of plate tectonics and with studies of the poorly known driving mechanism responsible for the plate motions.

In continuum mechanics, the study of the responses of materials to applied forces is governed by the constitutive relations and the conservation equations. In the former, one seeks a relation between stress, strain, and temperature (or entropy); and in the latter, one studies the conservation of momentum and energy. Combining the constitutive relations and the momentum equations provides the equations of wave propagation. Alternatively, combining the constitutive relations and the energy equations leads to equations of parabolic type, providing the continuum version of thermodynamics.

Thus, the study of seismic sources is fundamentally a study of constitutive relations--the strength of materials. It is also a study of the temporal redistribution of stress, either parabolically (diffusion) or hyperbolically (propagation), that is, whether the stress redistribution is slow or fast.

Most models of seismic sources are kinematic models, such as dislocation mechanisms with prescribed spatial and temporal distributions. The study of such models often leads to singular integral equations. Frequently, these equations cannot be solved in closed form, and one must rely on asymptotic approximations or numerical results. Both have their drawbacks: the asymptotic approximations are not uniform, and the numerical algorithms for singular integral equations are still in the formative stages of development.

Dynamical models of seismic sources have only recently been studied in any detail. Here, the constitutive relations play an important role in studies of the propagation of a stress singularity (a crack) or the "healing" of a ruptured zone. Better dynamical models will come from both laboratory and field studies that provide better constitutive relations, as well as from theoretical and numerical solutions to the dynamical equations.

Whether one uses kinematical models or dynamical models to represent seismic sources, one must face the problems of using observations for making estimates of the parameters and functions in the model. These are *inverse problems,* the best known of which is the estimation of the orientation of a fault plane from the distribution of the first motion of *P* waves.

At high frequencies, almost all earthquake sources can be well approximated as double couples. In the 1930's, a method using the first motion of *P* pulses around the world was developed to find the double couple and led to improved understanding of patterns of stress release. In particular, the horizontal projection of the couple's slip vector was an important datum in the development of plate tectonics. Slip vectors for hundreds of earthquakes clearly showed relative plate motions coherent over hundreds, even thousands, of kilometers.

Within the past decade, a new measure of the "size" of an earthquake, the moment, was introduced. The moment is the product of rigidity × fault area × average slip and is determined from the amplitudes of long-period surface waves or from field observations. It was soon realized that moment is a second-order tensor quantity when account is taken of the orientation of the fault and the direction of slip. This led to the moment tensor as a function of time--as a measure of the temporal pattern of stress release. The concept of moment can also be used for explosions and allows one to combine earthquakelike and explosionlike (or implosionlike) parts.

The concept of a temporal-spatial stress-release function, the moment tensor or moment density tensor, provides ideas concerning the study of long-term stress patterns and improvement of discrimination between earthquakes and nuclear explosions.

Methods of deconvolution and stacking are currently being developed in the oil industry to recover and eliminate source effects.

PROPAGATION AND TRANSMISSION

Geometrical ray theory is still a useful tool for studying the propagation of seismic pulses. It exists in two forms: the differential form, in which the source point and ray parameters are specified and the ray path and receiver point are then computed, and the integral form, in which both the source point and receiver point are specified and the ray parameters and ray path are computed. Both forms can be used in two or three dimensions, but both are computationally involved and expensive. Recent efforts to use geometrical ray theory to study heterogeneous two-dimensional and three-dimensional structures would benefit greatly from improved theoretical understanding and the resulting computational simplifications.

Dynamical, or generalized, ray theory exists in at least three forms: the Laplace transform method pioneered by

Cagniard and Pekeris, the Fourier transform method of Scholte and many others, and the reflectivity method of Fuchs and Muller. All three methods can yield "exact" synthetic seismograms for one-dimensional structures and approximate synthetic seismograms for different structures beneath source and receiver. All three methods are computationally expensive. Extending them to two- or three-dimensional problems is a difficult challenge.

A bridge between geometrical ray theory and generalized ray theory has recently been developed. This "quantized" ray theory enables one to construct an approximate high-frequency synthetic seismogram from the travel-time curve. The effect of caustics is included. While this method is restricted to high frequencies, it is attractive for its economy. Extending it to two- and three-dimensional problems awaits, among other things, the parallel extension of geometrical ray theory.

One more desideratum of quantized ray theory is an estimate of the lowest frequencies of its applicability. Another is the inclusion of the effect of dissipation.

Rays imply pulses, and pulses imply hyperbolic differential equations. One of the most powerful methods for studying solutions of hyperbolic differential equations is the method of characteristics. This method is especially valuable for studying wavefronts, but it has found only limited favor in seismology.

Dispersive systems of waves and modes are conceptually most easily studied in the frequency domain. Here one uses a standing-wave representation or a traveling-wave representation, as appropriate. The challenging theoretical problems are concerned with both very low and very high frequencies.

At very low frequencies, where the effects of rotation and ellipticity are strong, one can study gravitational oscillations and planetary oscillations, primarily in the fluid core, and attempt to learn more about density stratification. Although this may appear to be somewhat far afield from seismology, it represents a logical, low-frequency extension of studies of the free oscillations of the earth.

Other, logical, low-frequency extensions are the effects of seismic sources, including very long-period creep, on the length of the day and on the Chandler wobble. Intimately related to these is the static deformation associated with the long-time limit of the seismic-moment tensor.

At high frequencies, a study of the solotone effect can lead to new information about the locations of discontinuities. The theory of the solotone effect is complete for toroidal modes but not for spheroidal modes, and here we have an interesting problem in Sturn-Liouville theory.

The effect of weakly heterogeneous media on the free oscillations has been worked out by using perturbation theory. Measuring the small splitting awaits a truly dramatic increase in the quality, as well as the quantity, of the observations. In the meantime, traveling-wave theory may provide a basis for studying lateral variations in structure. Of continuing importance and interest is the transfer function, or matrix, between different elastic waveguides. Can the transfer matrix be constructed from data on transmitted and reflected modes? If so, what constraints does the transfer matrix place on the transitional structure?

In all theoretical and observational studies of propagation and transmission it is often important to take into account the effect of dissipation. Observations are difficult to obtain and interpret, and the dissipative part of the constitutive relation is essentially unknown, since there is more than one dissipative mechanism not rejected by the data. An interesting theoretical problem is to search for classes of mechanisms compatible with the data and to ascertain whether such mechanisms are related to those in laboratory and field studies of seismic sources.

To obtain the mechanical structure from the surface observations is an inverse problem--really a family of inverse problems--toward whose solutions seismologists have made several fundamental contributions. Many of these contributions exploit the nonuniqueness of the solution to most geophysical inverse problems in order to provide methods for constructing solutions and estimating what features of a solution are resolvable by the data. That is, one does not determine structure exactly, but one does determine whether a given data set can resolve certain features of the structure. The concept of the resolving power of the data and the methods for computing the resolving power have been used in low-frequency seismology, work on travel times, exploration seismology, geomagnetism, gravity, lunar magnetism, radio occultation in planetary atmospheres, and marine geophysics.

COMPUTING

Any discussion of theoretical seismology would be incomplete without a statement about the numerical algorithms that accompany the theoretical results.

The direct and inverse problems of dynamical-source theory or of wave propagation often lead to the development of computer programs. Still challenging are questions of the numerical solution of singular integral equations, the application of the method of characteristics, and the solution of homogeneous and inhomogeneous ordinary differential equations. The latter includes the numerical realization of the Rayleigh-Ritz procedure, the organization of finite-difference and finite-element methods, and other problems. To answer these challenging questions the seismologist must become acquainted with the numerical analysis behind the methods rather than accept computer codes "off the shelf."

10 STRUCTURE AND COMPOSITION OF THE EARTH

The study of the crust of the earth is of obvious and immediate benefit to man. It was not until it became necessary to be able to distinguish underground nuclear tests from natural earthquakes that the study of the deep interior became a nationally and internationally important science that was directly involved in setting policy. In order to solve an immediate practical problem it became necessary to attack some of the most fundamental problems in geophysics. Although the nature of the deep interior of the earth is far from completely known, major advances have been made as a result of Project VELA.

The crust of the earth varies in thickness from about 5 km under oceans to 50 km under high plateaus and mountain ranges. The lithosphere, the brittle and mobile outer layer of the earth, varies in thickness from zero at the midoceanic ridges to over 150 km in the older continental shields.

The earth's mantle extends from the base of the crust to the top of the core, at a depth of 2885 km. From seismic data and from the rocks brought to the earth's surface by volcanic and kimberlite eruptions, we know that the main minerals of the mantle are olivine, pyroxene, and garnet. Some minerals of economic importance, notably diamonds, are mantle-derived. Typical uppermost mantle compressional-wave velocities are 7.8 to 8.2 km/sec. An important feature of the upper mantle under oceans and tectonic regions is the low-velocity zone. This zone attenuates seismic waves rapidly and also causes a shadow

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zone for seismic rays at the surface. It is believed to be partially molten and weaker than the crust and other parts of the mantle. It therefore plays an important role in plate tectonics and in studies of the origin of magmas.

For many years, the transition region, 400-850 km in depth, was the most controversial region of the mantle. Seismic velocities in this region are abnormal in that they increase much more rapidly with depth than in other regions of the mantle or than predicted for a homogeneous self-compressed material. There are regions of high-velocity gradient at depths of 400, 500, and 650 km. The interpretation of these in terms of phase changes required input from seismology, petrology, and thermodynamics. Only recently have the predicted high-pressure phases actually been synthesized in the laboratory. The 400-km discontinuity is due to the collapse of olivine to a distorted spinelike phase and to the solid solution of pyroxene into the garnet structure. The 500-km discontinuity or transition region, only discovered in the last few years, is due to the further collapse of olivine to a denser spinel phase; possibly it is also due in part to the decomposition of pyroxene to spinel and stishovite, a high-pressure form of quartz. At 650 km, the pyroxene and garnet decompose to the elementary oxides or to the perovskite structure.

The complexities of the transition region express themselves in complex seismograms at distances between 14° and 30° at the earth's surface. To unravel these seismograms, the establishment of a worldwide network of seismometers was required, along with a considerable advance in theoretical methods of analysis. Theoretical seismograms now are an important tool in understanding natural seismograms.

The transition region may also play a role in plate tectonics, since earthquake activity ceases at about the depth of the 650-km discontinuity. Theoretical calculations show that phase changes in a downgoing, or subducting, slab occur at shallower depths than in the normal mantle, thus creating a negative buoyancy driving force.

The lower mantle is relatively homogeneous to about 300 km above the core-mantle boundary. The minerals in the lower mantle exist in phases that are about 20 percent denser than the phases in the upper mantle. It is still a matter of controversy whether the lower mantle is of the same composition as the upper mantle or is enriched in iron. This has bearing on the overall composition and origin of the earth.

The lowermost mantle is another anomalous region of the earth; here, the increase of velocity with depth is abnormally slow and the scattering of seismic energy becomes more pronounced.

Although the core is denser than the mantle, it is seismically slower. From shock-wave data we can infer that the core is 90 percent nickel-iron and 10 percent sulfur or some other light element or compound. The anomalous features of the lowermost mantle may be due to the trapping of primitive material from the core or to heat flow from the core. The core is molten and is the source of the earth's magnetic field.

The inner core of the earth, about the size of the moon, is solid. It appears also to be mainly iron and nickel.

Few of these facts could have been learned by a seismologist studying earthquakes in his own country or even studying his own seismograms. Seismology is a global science that requires international cooperation and a global network of instruments.

The study of the structure of the earth's interior is now fairly advanced, but there are still many directions for future research.

Broadband digital seismic systems are just now being installed on a global basis. The free-oscillation data set is primarily based on analog recordings of a few major earthquakes. The next giant earthquake of the Chilean or Alaskan class will add considerably to the quality and quantity of free-oscillation data. This, in turn, will improve our models of the earth's interior and our understanding of lateral variations. The free oscillations of a laterally inhomogeneous earth provide an outstanding theoretical problem.

The use of synthetic seismograms is a new development in seismology. The ability to match pulse shapes has opened up a new area with a high-resolving-power potential. The use of amplitudes will permit more detail to be resolved and will contribute to studies of the earth's anelasticity.

11 EXPLORATION SEISMOLOGY

Exploration seismology has seen dramatic changes since its beginnings in the 1920's. In the 1960's, a new era in reflection seismology was begun with the introduction of digital recording and processing. The use of digital recording equipment has made it possible to preserve accurately information on the relative amplitudes of seismic-wave motions. Amplitude and phase information no longer need be distorted as a result of transmission to the recording unit over conventional cables.

Improvements in recording techniques have permitted the use of higher frequencies and have therefore improved resolution of seismic data. Substantial advances have been made with seismic sources both offshore, where air guns are used extensively, and onshore, where vibrator sources are coming into common use. Advances also have been made in geophone design and in design of offshore seismic streamers. All of this has provided data from field operations that is much superior to that available 15, 10, and even 5 years ago.

At the same time that recording of seismic data has improved, seismic data processing has also improved dramatically, partly because of the improved quality of the field data and partly because of the availability of the data-processing capability of modern computers. At the same time, the advent of high-speed arithmetic units, or programmable "array processers," for use with large mainframe computers or with stand-alone minicomputers, has

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reduced the cost of processing large volumes of seismic data.

The new computer hardware and software systems have been utilized for application of various concepts to improve the interpretation of seismic data. For example, automatic determination of "static connections" for variations in thickness of the low-velocity, weathered layer has come into widespread use. Seismic velocities in the subsurface can be determined with increased accuracy from determination of the curvature and arrival times of the seismic waves reflected back to the earth's surface from below. Analysis, or "migration," procedures have been developed to utilize the seismic velocity information to reconstruct automatically the spatial coordinates of seismic reflectors from the time sections normally recorded. Removal of the effect of reverberations within water layers in offshore areas has become possible. Also, the adverse effects of source oscillation and of multiple reflections within the earth can be minimized through "deconvolution" procedures. We hope eventually to be able to determine reflection coefficients in the subsurface directly from seismic data.

The exploration industry has developed methods of assisting the interpretation of seismic data through application of the computer to construction of subsurface models. Seismic waves in the earth are simulated using ray-tracing methods, application of the wave equation, or the Kirchhoff integral equation. Also, the propagation of both compressional and shear waves is simulated using the elastic-wave equation. Interpretation is aided further by study and measurement of rock samples in the laboratory. Mineralogy, porosity, fluid content, and seismic compressional and shear-wave velocities are determined at given overburden and hydrostatic pressures and at various temperatures.

The display of seismic data has been improved remarkably in recent years. High-resolution seismic-data plotters have become available for display of seismic data in wiggle-trace, variable-area, or variable-density format. The use of color has been introduced so that a third dimension can be added to denote amplitude, velocity, or other parameters of interest.

In seismic recording, efforts will be made to continue work at higher and higher frequencies in order to maximize resolution. Recent advances in digital recording and in transmission of digitized data to the recording vehicle have largely removed the engineering limitations. The geophysical limitations to recording at high frequencies can be attacked by increasing further the number of recording channels so that the physical size and spacing of the groups of recording geophones can be reduced further without sacrifice of the overall length of the recording arrays. This will prevent "aliasing" at the higher frequencies, provide improved "statics" corrections, and permit improved measurement of seismic velocity for both shallow and deep reflectors.

Also, in seismic recording, the present trend toward large areal arrays, to permit seismic illumination of the subsurface in a true three-dimensional sense, will be expanded into additional areas. This is needed to obtain an accurate three-dimensional map of the subsurface rather than a "cross section." Efforts to date have been limited by the limited number of recording channels.

In seismic-data processing, restrictions imposed by computers are being relaxed rapidly by advances in computer technology. This will make practical the computational procedures needed to resolve severe problems posed by "interfering" sets of multiple and primary reflections having nearly the same dip but different velocity. This problem has been troublesome both offshore and on land. Also, it probably will become practical to attack the analysis of complex sets of seismic events by subtracting sets of events one at a time from the record section and re-examining the residual events for significant data. This process would be repeated until the residue consisted only of random noise.

Extensive efforts will be made to construct mathematical models of the subsurface in two or three dimensions and to compute the corresponding "synthetic seismograms." These can be compared with field data, and then adjustments can be made in the mathematical model to improve agreement. This approach should improve the ability of the exploration seismologist to identify and map "stratigraphic traps" containing large hydrocarbon reserves. In the past, this kind of structure has not been found with much success by the seismic method.

The problem areas in exploration seismology occur in translating or converting the subsurface maps of seismic reflectors into geologic structure and lithologic units. Our improving ability to record relative amplitudes of seismic reflections and to compute seismic velocities over smaller spatial intervals permits one to speculate whether the seismic-reflection method may eventually be utilized to construct detailed maps of reflection coefficients, or "stickograms," and, hence, of subsurface velocity and density. It may even become possible to identify the type of fluid present in the pore spaces of the rock. To do this, we must improve our ability to identify and remove seismic-source and receiver waveforms, to relate compressional and shear-wave velocities to rocks and fluids in the subsurface, and to understand better the factors involved in the attenuation of seismic waves at various frequencies.

12 SEISMIC EXPLORATION FOR MINERALS

Mineral environmental rocks are generally consolidated and usually have undergone weak to intermediate metamorphism (modification by temperature and pressure). Their longitudinal velocities are in the 12,000-20,000 ft/sec range and their specific gravities in the 2.6-3.0 range. Sulfides, which are frequently sought minerals, if massive, have *in situ* longitudinal velocities of about 8000 ft/sec and a specific gravity of about 3.5. Mineralized boundaries are not infrequently somewhat diffused or transitional. Ore bodies may be lenticular or irregular. Within the rock medium, attenuation is lower, but scattering from fractures and other phenomena is more severe. A higher frequency-content, of the order of 100-1000 cycles, is therefore possible.

Possibilities for the use of seismology in the exploration for minerals, underground and at the surface, are discussed below:

1. Underground exploration can be conducted from either drill holes of approximately 2 3/8" diameter or from underground drifts, crosscuts, and other openings. Essentially holographic reproduction techniques may be possible (with contrasting physical property) to outline the diffracting surface of interest. Controlled-source waveforms can be applied from a series of points either along a drill hole or from mine openings; reception can be made at a series of points either along the drill hole

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or within openings; and the appropriate analytical mixing function, or functions, applied and the diffracting surface developed. Some work that has been done in this direction is referenced at the end of this chapter.

The main problems, particularly in holes, are from boundary waves; and, if water-filled, from tube and water waves. Systems developed would not be simple but would most likely require spatial arrays and, certainly, computer processing. Development costs are estimated by Christansen (see Referenced Work) at about $1 million over a 4-5 year period. The objective of such efforts is essentially the detection of ore bodies in the lateral rock areas. Another possibility would be the mapping of intrusive contacts and rolls (frequent ore loci) laterally from deep vertical holes, to determine whether a massive ore-replacement body might be present at such contacts.

2. The second application that could be developed is in the search for strata-bound sulfide deposits, whether in a volcanic or a sedimentary environment. In such deposits, sulfides constitute 80 percent by volume in volcanic rocks and 20 percent by volume in sedimentary rocks. These types combined are the world's greatest occurrences, and the sedimentary environmental types are frequently square miles in area, e.g., Sullivan, B.C.; Gamsberg, South Africa; Broken Hill, Australia. They may well occur down dip or under later cover.

Rock physical chemistry, trace-element analysis, and reconstruction of the stratigraphic environment are reaching a point where recognition of potential conditions from removed outcrop study are possible. The problem then is to trace stratiform rocks down dip under cover and later formations and to recognize the existence and inception of a necessary possible ore condition, e.g., volcanogenic occurrences are frequently at a fragmental-rhyolite or shaly tuff-fragmental rhyolitic contact. Sedimentary stratabound deposits frequently occur with banded iron formations or ironrich quartzites. The problem then is more than conventional "formation chasing." It is to recognize within the formations the existence and incidence of such preferred conditions. This is akin to the petroleum seismic problem of determining whether the formation is oil-bearing, a problem on which considerable progress has been made.

The mineral problem is a little more complex, however. Strata are less continuous, frequently pinching, alternating, and fingering, as at volcanic slopes and shore margins. Folding can be severe and steep. Metamorphism may be present and therewith nonsharp boundary transitions. This second problem is therefore not unique but requires some good basic rock-physical-property evaluations and then the application and perhaps extension of known techniques. But it is necessary to be wary, since mineral environments, although providing geological contrast with their surroundings, seldom have the clearer-cut physical property differences encountered in oil work.

Development work here, although direct, could run to a few million dollars, if tuffs, fragmentals, sulfides, and iron formation are to be recognized.

The above are the two main areas of seismic development that are considered to be of major importance and that could have the greatest eventual exploration economic potential.

The following applications are accessory and are listed although they will not be discussed.

Detection of nearby faults or veins underground at higher frequencies (order 100,000 cps);

Depth of cover and gravel in deep basin-and-range valleys;

Continuity of lower or higher velocity formations, etc.;

Conventional at-hole seismic logging.

REFERENCED WORK

Newmont Exploration Limited, in two years of experimentation in the Magma Mine, Arizona, with J. Kuo, Columbia University.
G. L. Fitzpatrick of the U.S. Bureau of Mines, Denver.
Jon Claerbout of the School of Earth Sciences, Stanford University, theoretical work on seismic diffraction.
Holosonics of Richland, Washington
John Christansen, Director of the C.B.C. Laboratories, Stamford, Connecticut

13 EARTHQUAKE SOURCE MECHANISM STUDIES

During the last decade, seismologists began to explain observed seismograms absolutely quantitatively in terms of theoretical models of earthquakes. There are three reasons for this new development. The Worldwide Standardized Seismograph Network supplied the necessary data. Large-scale computers made possible the use of the tremendous amount of calculations involved in data analysis and theoretical predictions based on the model. And, finally, the fault model adopted by most seismologists was apparently a good one, giving rewarding results that encouraged further work.

At the simplest level, a point source can explain seismic waves with wavelengths much greater than the source dimension. The physical character of a point source is specified completely by the seismic moment, which is equal to the final slip integrated over the fault surface and multiplied by the rigidity of the medium surrounding the fault. Seismic moment has been measured for a large number of earthquakes. Empirical relations between the moment and the earthquake magnitude have been obtained and have been used in estimating the seismic slip-rate at various plate boundaries and the seismic strain-rate in some intraplate crustal volumes. It has also been used to estimate the excitation of Chandler wobble by earthquakes.

At the point-source level, the fault-slip may be assumed to be a step function in time. This assumption has

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been extensively used in the "single-station method" of measuring phase velocities of long-period Love and Rayleigh waves. The results are sometimes more satisfactory than the "two-station method," because the advantage of canceling the source effect provided by the latter method can be undermined by greater scattering and multipathing interference because of the longer wave paths involved. Another impressive example of benefits in the study of the earth's structure given by the point-source model is the unambiguous high-resolution identification of spectral peaks of the earth's free oscillation that it provides by stacking complex spectra at many stations with proper sign determined for a particular mode and given source mechanism.

The fault area is a source parameter that may be estimated by various methods, although greater uncertainties are involved in its estimation than in that for the seismic moment. The shape of the seismic spectrum, the extent of aftershock area, and the area of tsunami source have been used for this purpose. In some cases, the fault area of a deep-focus earthquake is determined not only from the spectral shape but also from the area covered by multiple events associated with the earthquake. Evidences from the spatial distribution of multiple events favor the view that fault-slip along a surface rather than phase change or shear-collapse in a volume is the source of deep earthquakes. Once the seismic moment and the fault area are known, an average stress-drop may be evaluated. It is now well established that the stress drop in large, shallow earthquakes ($M > 6$) is in the range of 10 to 100 bars independent of magnitude.

In order to explain observations associated with short-period waves, it is necessary to specify the detail of the rupture process, its nucleation, spreading, and stopping. Surprisingly, a simple kinematic model, in which steplike slip with a finite rise-time propagates with a uniform rupture velocity, was able to simulate reasonably well the actual records of strong-motion seismographs located close to the fault breaks during the Parkfield earthquake of 1966 and the San Fernando earthquake of 1971. The rupture velocity was lower than the Rayleigh-wave speed in both earthquakes, and the slip velocity was about 1 m/sec. These preliminary results encourage ambitious attempts at predicting strong motions near a potential earthquake fault on the basis of the physical properties of the fault zone and the existing tectonic stress. The dynamic problems of rupture propagation under various conditions of stress, cohesion, friction, and fracture criterion have been studied using analytical, numerical, and model-experimental methods. A major conclusion emerging from these works is that the specific surface energy needed to produce a unit area of fracture surface may be many orders of magnitude greater for natural earthquakes than for small rock samples.

The nucleation of rupture at a point produces the ω^{-3} frequency dependence in the high-frequency asymptote of the far-field displacement spectrum beyond the corner frequency. If this nucleation phase dominates the high-frequency spectrum, we expect that the absolute level of high-frequency excitation is roughly common to all earthquakes independent of magnitude. This clearly contradicts observations of the high-frequency part of the source spectrum, obtained from absolute measurements of P and S waves of individual events, and relative measurements on coda waves of many events show, in most cases, ω^{-2} dependence. These observations can be explained if the stopping phase dominates the high-frequency part of the source spectrum.

In the area of seismic source mechanism, unresolved outstanding problems include the understanding of high-frequency motion near a large earthquake and large, slow processes at an earthquake source, such as implosive precursors or creep following or preceding earthquakes. The theoretical basis of some powerful discriminants between earthquakes and explosions is still controversial. The success of the M_s-m_b discriminant for small events cannot be attributed to the difference in source dimension because, for $M < 5$, both are essentially point sources when looked at through the teleseismic window. The discriminant works, probably because of the combined effects of (1) nodes of P waves present in earthquakes and absent in explosions, (2) overshoots in source time-function for explosions, and (3) lower impedance of source medium for explosions. The study of anomalous earthquakes that fall close to explosions in the M_s-m_b diagram may throw some light on this important problem.

14 ENGINEERING SEISMOLOGY

Earthquakes constitute one of the most severe of natural hazards to the works of man, and civil engineers long have recognized the need to consider seismic effects in planning construction projects. The field of engineering seismology was created through the interaction of seismologists and engineers dealing with the earthquake hazard. The fundamental objectives of engineering seismology are to identify sources of potentially damaging earthquakes and the regions that they may affect, to estimate the intensity and recurrence intervals of the earthquakes, and to predict the dynamic characteristics of the ground motions that may occur at a given site, including faulting, landslides, and tsunami effects.

In the earliest stage of its development, engineering seismology was based entirely on observation of earthquake effects, such as damage to structures, fault ruptures, and landslides. Attempts to standardize and quantify such observations led to the formulation of earthquake-intensity scales, such as the modified Mercalli scale in current use in the United States. Intensity scales made possible the construction of isoseismal maps after damaging earthquakes, and these maps have provided structural engineers with valuable qualitative information on which to arrive at

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estimates of the earthquake forces to which their structures might be subjected.

However, significant advances in techniques of structural design could not be derived from such qualitative data; major improvements depended on obtaining detailed quantitative measurements of ground motions in the epicentral regions of strong earthquakes. Thus, the development and installation in the early 1930's, by the U.S. Coast and Geodetic Survey (USCGS), of the world's first strong-motion seismographs was the most important event in the history of engineering seismology. These low-sensitivity instruments were designed to record damaging levels of ground acceleration, and records obtained during the 1933 Long Beach earthquake were the first quantitative evidence of the intensity and dynamic characteristics of such motions. Other important earthquake records obtained by that original network included those for the El Centro, California (1934 and 1940), Helena, Montana (1935), Olympia, Washington (1949), and Taft, California (1952) earthquakes. Studies made of these early records included integration to obtain velocity and displacement histories and analysis of the acceleration or velocity response spectra used in structural analysis and design.

During its early years of operation, the USCGS strong-motion measurement program was greatly hampered by the small number of the instruments installed in the field, so that many earthquakes were not recorded at all, and the records obtained did not provide adequate information on the influence of local factors such as geology, topography, and surficial soil properties. Continuing pressure by the structural engineering profession led to gradual increases in the number of instruments deployed and to improvements in their operational characteristics. The most important increase in the number of strong-motion instruments resulted from the Los Angeles Building Code provision adopted in the late 1960's, which requires that three strong-motion seismographs be installed in each new high-rise building, located in the foundation, at midheight, and at the top. As a consequence of this regulation, the number of instruments within range to be triggered by the 1971 San Fernando earthquake exceeded 270.

This single earthquake doubled the number of available strong-motion records and made possible for the first time the study of the effects of various topographic and soil conditions, as well as distance attenuation effects, on the ground-motion characteristics. It also provided a graphic demonstration of the immense effort required to digitize, analyze, and make available to the design profession the records resulting from a major urban earthquake. These records will continue to serve structural engineers as a major research resource for many years; in addition, seismologists are finding them a valuable tool in the study of seismic source mechanisms.

Strong-motion records serve to define only one aspect of the potential earthquake hazard for a given site: the dynamic characteristics of the potential input motions. During recent years, the planning of a number of major construction projects has demonstrated the need for more comprehensive estimates of the seismic hazard to which they might be subjected, or which they might induce, and a methodology has now evolved for providing such estimates. This involves identification of fault zones that are potential sources of major events, prediction of the magnitude and recurrence intervals of the events, and evaluation of the attenuation and modification of the ground motions expected between the source and the site. Based on these estimates, and taking account of local soil influences, seismic design criteria are adopted for the structures, frequently in the form of design-response spectra. Examples of major projects that required detailed consideration of earthquake effects in design are the Bay Area Rapid Transit, where the tube under San Francisco Bay crosses a potentially active fault; the Trans-Alaska pipeline, which traverses a seismically active region and crosses several fault zones; and all nuclear-power generating stations in the United States.

Design criteria for less monumental structures generally are established in terms of seismic zoning maps, which define expected levels of earthquake intensity in various regions of the country, and building codes, which specify the seismic input for each zone as a function of the dynamic properties of the structure. Codes and zoning maps in current use are based on the best information available when they were formulated, but intensive efforts are under way to improve both the zoning maps and the code criteria, taking advantage of the most recent seismic data and technical advances.

From the foregoing summary it is apparent that a large part of engineering design and construction is heavily dependent upon continuing input from the field of engineering seismology.

15 STRONG GROUND MOTION AND RELATED EARTHQUAKE HAZARDS

Since the dawn of civilization, loss of life and property due to earthquake-related phenomena has adversely affected the human condition. There is general agreement that earthquakes pose the most serious and, at the present time, most unpredictable natural threat to the social and structural works of man and that, with increasing urbanization and economic interdependence, the potential threat is correspondingly increasing. The principal earthquake hazard has been, and still is, damage to and failure of man-made structures and the attendant loss in human life and material investment. The principal agent of this damage and destruction is the primary passage of large-amplitude seismic radiation at the earth's surface. This strong ground motion, which has its origin in the rapid and extensive release of elastic strain energy in the course of a major earthquake, imparts dynamic forces to human dwellings--forces that must be resisted by prudent structural design. The loss of life consequent to ground-motion-induced failure of man-made structures can be awesome; more than 800,000 people perished in the Huahsien (Shensi), China, earthquake of 1556 when widespread collapse of inadequately constructed family dwellings occurred.

Ground-motion-induced failure of surficial geological systems and engineering structures other than those designed for human occupancy can lead to loss of life and

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property that, if less direct, is no less important in terms of its potential and actual impact. Earthquake faulting; landslides, liquefaction, and other forms of soil failure; tsunamis and avalanches; and fires and flooding due to failure of engineering systems have led or can lead to significant losses in a major earthquake. Of the nearly 100,000 people who perished in the 1923 Japanese earthquake, 38,000 died in an uncontrolled fire that ravaged Tokyo. Approximately 20,000 people lost their lives when the town of Yungay, Peru, was obliterated by a landslide triggered by a major shock beneath the coast of Peru in 1970.

The effective mitigation of earthquake hazards plainly requires a broad and deep fund of basic scientific knowledge; sound principles and practices of building analysis, design, and construction; and rational assessment of the costs and benefits of government programs intended to protect the public from earthquake hazards. Nevertheless, it has been recognized for several decades that the principal scientific obstacle to this goal has been the uncertainty in accurately estimating the ground motion in the immediate vicinity of damaging and destructive earthquakes.

The first significant steps to develop the needed understanding were taken by the United States Coast and Geodetic Survey about 45 years ago with the emplacement of the first strong-motion accelerographs. The accelerograms written by the Long Beach, California, earthquake of 1933 provided the first quantitative measure of the amplitude and frequency content of strong ground motion; they mark an important milestone in earthquake seismology and earthquake engineering. Strong-motion accelerograms were obtained for several damaging and locally destructive earthquakes in the succeeding three decades, perhaps most importantly for the Imperial Valley earthquake of 1940 ($M = 7.1$) and the Kern County earthquake of 1952 ($M = 7.7$). Nevertheless, the program to deploy strong-motion accelerographs grew very slowly, and in 1965--more than three decades after the Long Beach earthquake--there were still less than 100 such instruments in the entire western United States.

In the middle 1960's, a Los Angeles Building Code provision requiring that three strong-motion accelerographs be located in each new high-rise building affected programs to deploy strong-motion seismographs in two significant ways. First, it led to a dramatic, almost immediate increase in the number of such instruments deployed in the

Los Angeles area. Second, because this code provision, in effect, legislated a commercially viable market for these instruments, an intensive effort was undertaken, principally by industry, to modernize and improve them and to lower their cost significantly.

The benefits of the greatly increased number of strong-motion accelerographs in the Los Angeles area were realized in 1971 when 105 free-field or ground-level strong-motion accelerograms were written by the San Fernando earthquake; this was another important milestone. The development of modern, rugged, and inexpensive strong-motion accelerographs, together with the more recent capability of writing the station WWVB radio time code directly on the recording film, has led to new programs to record strong ground motion in the immediate epicentral regions of causative earthquakes. Strong-motion accelerographs are now deployed along many active faults in Southern California, many in fully external field sites using solar power. Eight positively identified strong-motion accelerograms were recently obtained for an $M = 4.9$ earthquake on the San Jacinto fault, all at hypocentral distances of less than 30 km. A more recent development in recording strong ground motion is the rapid deployment of these highly portable instruments in the aftershock zones of major earthquakes. In the three months following the Oroville earthquake of August 1, 1975 ($M = 5.7$), 313 strong-motion accelerograms were obtained for 86 different aftershocks, with magnitudes as small as 1.8 and as large as 5.2.

While advances in the recording of strong ground motion have been of considerable value to both the seismological and engineering communities, our present understanding of the processes causally responsible for strong ground motion is derived from a base of theoretical and observational seismological knowledge far broader than that of the existing collection of strong-motion accelerograms. Intensive investigations of the physical processes that govern naturally occurring faulting processes and of the wave-propagation effects that modify both the amplitude and frequency content of the elastic radiation emanating from the source region began in the late 1950's, largely stimulated by the VELA Uniform program directed to the discrimination of earthquakes from underground nuclear explosions. National and international seismological networks were expanded dramatically in the early 1960's, both in the number of recording sites and in the quality of the recording systems, to provide the basic ground-motion data. Advances in the theoretical formulation of the source mechanism, both for earthquakes and explosions, and in the theoretical calculation of synthetic ground motion generated by tectonic or explosive sources embedded in realistic earth models were exercised on ground-motion observations at both local and teleseismic distances to provide sophisticated discrimination capabilities.

The potential value of these capabilities in the deterministic appraisal and estimation of strong ground motion for engineering purposes is plain enough, but the actual application of these capabilities in this context occurred only infrequently prior to the San Fernando earthquake. Two reasons for this can be identified. First, the development of the theoretical techniques, together with their detailed evaluation in terms of modeling conventional seismological data, extended into the early 1970's; to a very real extent, the development of this seismological methodology continues at the present. Second, prior to the San Fernando earthquake, there were simply too few strong-motion records of too few earthquakes to place much confidence in the results of a detailed analysis of them. Ground-motion recordings of the San Fernando earthquake, however, suggested that conventional methods of estimating strong ground motion were unsatisfactory for much of the frequency band of engineering interest and that a more fully seismological understanding of strong ground motion was not only desirable but urgently needed.

Because of this, the pace of seismological analysis of strong ground motion has quickened considerably in the past five years, with special emphasis on making these results useful and accessible to the engineering community. It is now known that the average spectral amplitudes of the strong ground motion of the San Fernando earthquake through the entire frequency band of engineering interest can be related to a very few parameters of the source mechanism and source-station propagation path, determined without reference to the set of strong-motion accelerograms. Elementary aspects of the earthquake source mechanism, together with strong-motion accelerograms recently obtained for intermediate and small-magnitude earthquakes, have led to a more physical understanding of peak acceleration data, widely used as an aseismic design parameter. Time-domain modeling of long-period strong ground motion has produced synthetic waveforms that match strong-motion displacement data with often remarkable precision (Figure 15.1).

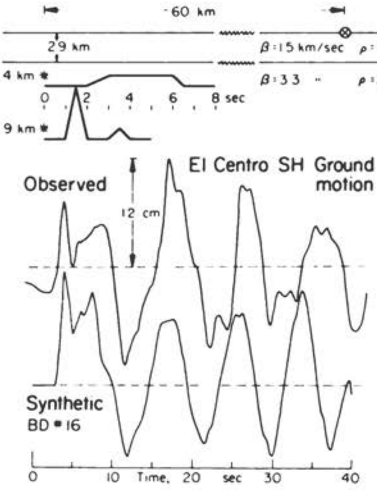

FIGURE 15.1 Comparison of the observed strong ground motion (transverse component) of the Borrego Mountain earthquake (April 9, 1968; $M_L = 6.4$) at El Centro, California, with ground motion computed on the basis of the simple source model schematically illustrated in the upper left embedded in the crustal structure parameterized in the upper right. (Thomas H. Heaton and Donald V. Helmberger, California Institute of Technology, 1976.)

In the near future, the value of these seismological capabilities in the accurate and deterministic estimation of strong ground motion appears even more promising. A high degree of redundancy of strong-motion data now exists for many earthquakes in the magnitude range 3 to 5, and there is no doubt that such data redundancy can be obtained for larger magnitude earthquakes of damaging intensity by properly instrumenting the aftershock zones of great earthquakes. Similarly, the rapid developments of the past several years in understanding the earthquake mechanism and in calculating synthetic ground motion will almost certainly lead to more sophisticated capabilities in strong ground-motion estimation in the next several years. It is well that this is the case. In the absence of any systematic capability of preventing or predicting earthquakes at the present time, our only alternative is to develop a more complete understanding of the causes and consequences of earthquakes. Although an accurate and deterministic capability to estimate strong ground motion will not entirely avert earthquake-related tragedies, it will certainly be of considerable value in reducing their scope.

16 VOLCANOES

Catastrophic volcanic eruptions are among the most spectacular of natural phenomena. They have claimed hundreds, and thousands, of lives, caused large property losses, and rendered harbors and airports unusable for some time (in Alaska, for example). Scientists through the ages have tried to understand the inner workings of volcanoes in order to attempt to forecast these enormous events and alleviate the suffering. Twentieth-century technology has contributed considerably toward that goal. In particular, elastic waves can penetrate deeply into the earth and yield information about its structure and about the dynamic processes that lead to earthquakes and eruptions. These dynamic processes depend on the properties and physical state of the materials in the earth's interior. The increasing need for mineral and energy resources and the new concept of plate tectonics direct our attention toward the chemical composition and processes in the crust and upper mantle, which increasingly explain the existence of large mineral deposits in a global framework. Volcanic eruptions are central to these processes. Seismology plays a key role in answering many questions about the internal structure and the dynamics of volcanoes and their eruptions, but the truly interdisciplinary approach taken over the past 10 to 15 years has resulted in the greatest advances.

Under the concept of plate tectonics, volcanoes are generally located in rift zones, over subduction zones,

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and progressing along opening cracks or hot spots. The intensity with which they have been studied can be related either to their historical or potential danger to the local population or to the general interest in the new global tectonic framework. The continuously increasing capability of equipment and data collection, processing, and communication have permitted research in rather inaccessible areas.

Both active and passive seismic experiments, together with other geophysical measurements, have contributed to a better understanding of the earth's internal structure to considerable depth. Gorshkov was the first to use the idea of *S*-wave absorption by liquids to determine the depth and extent of the magma chamber under the Klyuchevskaya Volcano. This basically simple idea had considerable impact and led to further and refined studies in Kamchatka, Japan, and the United States using earthquake-generated waves. In Kamchatka, the screening of shear waves was observed in the upper mantle under several volcanic complexes to a depth of some 150 km and with a lateral extent of 25 km. In Katmai, Alaska, several shallow chambers are directly associated with separate volcanoes, whereas deeper ones are more diffused. In Kamchatka, other partially molten zones were determined later and the roof of intense fractional melting was found at a depth of 50 to 60 km; the principal magma generation is located at depths between 120 and 200-350 km and connected with the "Pacific focal layer" (of the down-dipping Benioff zone). *S*-wave screening also was found under the Yellowstone caldera complex.

High-density short-period seismic networks led to the inversion of local and teleseismic *p*-wave residuals to determine structure under volcanoes in Hawaii, showing good correlation with Bouguer gravity anomalies, as well as under some volcanoes in the Cascade Mountains.

In addition to gravity, magnetics, and earthquake seismic observations, active refraction seismic shooting has contributed to our knowledge of the structure of the volcanic edifice and its surroundings. In the United States, such work has included studies of the crustal structure and the ash flow deposits at Katmai; crustal structure on the island of Hawaii and the determination of the shape of the buried Koolau plug on Oahu; and, more recently, the northwestern United States and geothermal areas.

Forecasting of volcanic eruptions, and their violence, can draw on the knowledge and methods of many scientific disciplines. The rise of magma to the surface increases stress along its way, generating earthquakes when fracture stress is reached, and therefore can be traced if a sufficient number of sensitive seismometers are used. Nearly every eruption or increase in volcanic activity is preceded by swarms of shallow earthquakes in island arcs and in rift zones and propagating cracks or by hot spots. Other questions related to eruptive magnitude are studied by specialists in other fields (chemical compositon, water content of magma, inflation of the volcanic edifice, high-altitude or satellite infrared observations, compositional changes in fumerolic gases, magnetic-field variations, and others).

The cumulative seismic-strain release prior to eruptions for some andesitic Kamchatka volcanoes shows an exponential increase with time and a sharp stop just prior to the eruption, whereas the number of forerunners of the 1958 eruption of Nymuragira-Kitzimbanyi (in the African rift) follow some different exponential law.

Through study of the upward migration pattern and velocities (1 to 1.5 km/day) of earthquakes from depth to the volcanic eruptions in island arcs along the Benioff zone, 18 of 23 eruptions could be predicted between 1970 and 1974 at volcanoes in the New Hebrides. An independent study also found, by using the upward migration velocity window of 1.15 to 1.35 km/day, that 70 percent of all deep-focus earthquakes in the New Hebrides between 1933 and 1966 could be explained as "source" earthquakes within these velocity limits for 50 percent of all the volcanic eruptions in that region and time interval. Theories also have been developed to account for such migrations associated with the magma transport.

Concentrations of earthquakes, 70-100 km deep, were recognized in association with seven of eight active Central American volcanoes and their eruptions during the interval 1961 to 1972, but spatial-temporal progressions relating specific intermediate-depth earthquakes with specific eruptions could not be substantiated.

Although the violent eruptions of island-arc volcanoes pose a difficult and controversial prediction problem, the prediction of basaltic eruptions has been generally successful in Hawaii, where the volcanoes are well instrumented.

Very little work has been published on global relations between seismicity and volcanic-energy release. In 1972, Latter established a magnitude scale for eruptions. A large data file on eruptions in this century has been assembled, and the data strongly indicate a grouping, or clustering, in time of worldwide major earthquakes correlated with similar clustering of volcanic eruptions. This may indicate either a triggering phenomenon (by randomly occurring large events) over hemisphere-size areas or that extensive areas of the earth's crust and upper mantle respond more or less together to variations in some major process of strain accumulation. It also was found that large, intermediate-focus quakes are followed more frequently than chance would allow by large-magnitude eruptions of volcanoes in the same tectonic structure. Coupling of seismic-strain release (and slip) found to occur between the rising and sinking edges of the Nazca plate, with indications of a 3½-year variation, seems to relate to the migration of volcanic activity from Central to South America.

The past decade witnessed a vast increase in the acquisition and accumulation of data on volcanoes and volcanic eruptions and made possible surveillance of hitherto inaccessible eruptions. Perhaps the most striking results are the ERTS satellite pictures of a recent Kamchatka eruption (Tolbachik Volcano), recordings of submarine eruptions in the Pacific by underwater listening devices, and volcano surveillance via satellite in general. A new impetus to volcanic research was generated by the increased interest in geothermal energy. However, there is a growing feeling that present observational data have outgrown available theory and hypothesis and that new hypotheses are needed that can be tested. Theoretical models are needed to clarify the relationships, origins, and interactions with stress of the volcanoes in particular plate-tectonic settings, i.e., in rift zones (on land and in the oceans) or at diverging plate margins, over subduction zones or at converging plate margins, over hot spots (opening cracks?) or at intraplate locations, and along sliding plate boundaries. A little-used tool, thus far, is the ERTS imagery. Other areas in which seismology is able to test new theory (or at least parts of it) are the mechanics of magma intrusion and eruption and the geometry of magma bodies. The latter is important in geothermal research, and refinements to the older approaches discussed in the earlier part of this chapter seem to be needed.

In summary, there is need and opportunity for more basic theoretical work and data interrogation related to volcano research on three scales: global relations of the volcanic-eruption mechanism to plate dynamics; regional understanding of particular volcano habits that are useful in forecasting eruptions, especially those located in island arcs; and, finally, refinement of old techniques or application of new ones to provide higher resolution of the internal structural elements of particular volcanoes.

17 TSUNAMI

Large submarine earth movements generate sea-waves known as tsunami, their Japanese name. Tsunami are induced by major destructive earthquakes and by volcanic eruptions and propagate to large distances with speeds in excess of 600 miles per hour across the deep, open ocean. Most tsunami are devastating not only in coastal areas near their source but carry their full destructive power to faraway islands and continental shores, where they can cause enormous damage and loss of lives as their waves build up to heights sometimes as great as 100 feet. In the Great Alaska Earthquake on Friday, March 29, 1964, almost all of the lives lost were claimed by the resulting sea-waves, some as far away as Crescent City, California. The islands of Hawaii have suffered from many of these waves, generated in the circum-Pacific belt around which the world's most severe earth tremors occur, as well as from locally generated tsunami such as one in November 1975. Some 180 tsunami have been recorded in the Pacific Ocean since the turn of the century; 35 of these caused damage and destruction near the source, and 9 carried their devastation to distant shores.

If an earthquake can be recognized as a potential generator of tsunami, some lead time for public warning and precautionary measures will be available. The seismic waves recorded at the international Tsunami Warning Center in Honolulu, Hawaii (and at the Regional Center in Palmer, Alaska), from an array of telemetered seismographs now

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permit determinations of magnitude, epicenter, and time of occurrence of the tremor. If the quake is of sufficient magnitude and is located near a coastal area, a potential tsunami threat exists and approximate arrival times in remote areas can be determined. However, the question of whether a tsunami has been generated by any particular earthquake can only be answered after the waves have reached the nearest wave-recording tidal instrument or observation point that is linked in one way or another with the warning centers. At present, such tidal stations are distributed only along shorelines of the continents and islands of the Pacific. But large gaps prevail and reliability is low along the Pacific coast from Baja, California, through Central America to Chile, where devastating seismic sea-waves have been generated in the past. Some critically located gauges along the Aleutian, Alaskan, and Hawaiian coasts are directly telemetered to the warning centers. No such instruments have been installed as yet in deep water despite the fact that these measuring devices could give us a good idea of the tsunami height to be expected and would permit stringent tests of existing theories and computer calculations of propagation across the Pacific. Gauges have been developed over the last decade and could be deployed independently or together with other oceanographic programs. In the event of a potential tsunami-generating earthquake, data could be telemetered to the Warning Centers on demand, with a very high priority.

Over the past 15 years, with the advent of much improved communications and computers, the number of unnecessary warnings has steadily decreased. The linear-propagation theory of these seismic sea-waves is well understood. However, their nonlinear behavior during run-up and breaking is much less well understood. It is this part of the wave's life span that, together with the focusing effect of the underwater bottom topography, contributes most to the destruction in vulnerable harbors like Hilo, Hawaii.

It appears that the only hope for developing adequate warning in near-source coastal areas comes from earthquake prediction, since in these areas the waves are often generated locally by landslides and underwater slumps within seconds or minutes after the first felt ground motions. During the 1964 Alaska earthquake, about one third of the population of the small fishing village of Chenega, in Prince William Sound, was wiped out despite an oral tradition of such sea-waves and the fact that everyone started running to high ground at the signs of heavy shaking.

At present, the two Warning Centers in Honolulu, Hawaii, and Palmer, Alaska, operated by NOAA, seem to function adequately, enjoying good international cooperation from almost all countries around the Pacific. However, there is no adequate capability to predict run-up heights at present. The installation of the deep-sea gauges, therefore, should be implemented not only for warning purposes but also for further research.

The tsunami research effort in the United States seems disproportionately small compared with the efforts in areas that pose considerably less hazard to lives and property. Only a few scientists are concerned with tsunami, and very little attention is generated except for a short time after some considerable disaster. There is an urgent need, and an opportunity, for more work on the tsunami source mechanism and on nonlinear run-ups using both physical and theoretical models.

18 PLANETARY SEISMOLOGY

Since the first Apollo landing on the moon, in 1969, seismic instruments have been operating on a planetary body other than the earth. At present, there is on the moon a seismic network with five stations. Since 1969, this network has detected a large number of moonquakes, meteoroid impacts, nine artificial impacts (ascent stage of the lunar module and Saturn third-stage booster rocket) of known energies, impact times, and locations. Seismic data from all of these sources have been analyzed to determine lunar seismicity and internal structure.

This pioneering effort in the direct seismological exploration of an extraterrestrial planetary body has provided detailed information about the lunar interior. From the seismic data, it was determined that the moon has a layered crust (about 60 km thick on the side facing the earth) and a thick (600 km) lithosphere. Below about 700 km, the lunar interior may be hot enough to have rheological properties similar to those of the earth's asthenosphere.

The moon may have a small iron-rich core, but confirmation of this will require additional seismic observations.

The lunar seismicity has been a major surprise. The moon is very aseismic as compared with the earth. The seismic energy release in the moon is about 10^{15} erg/year--more than 10 orders of magnitude less than that of the earth. In addition, all observed moonquakes are very small, with magnitudes less than 2, and most moonquakes

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are very deep, with focal depths of 600 to 1000 km. There are some relatively shallow moonquakes, but these are infrequent. The deep moonquakes occur periodically and are triggered by the tidal stresses in the moon. None of these seismic properties of the moon were predicted before the actual acquisition and interpretation of the seismograms from the lunar stations.

Seismic investigations of Mars are part of the Viking Project. At present, there is one three-component short-period seismometer operating on the surface of Mars as part of the Viking science package. This seismometer will provide data on the seismicity of Mars, on the level of tectonic activity, and, possibly, on the internal structure of the planet.

19 INTERNATIONAL ASPECTS OF SEISMOLOGY

Seismology has prospered from its earliest days under a tradition of international cooperation in the gathering of data and of active collaboration among individuals and groups of scientists. International good will is a characteristic of all the natural sciences, but the geophysical sciences, including seismology, are totally dependent on the free exchange of data acquired with global coverage for progress in many of their major problems. Even in times of strained international relations, the self-interest of nations has usually kept open the lines of data interchange. Sometimes, and especially in the present era of highly advanced military technology, certain types of geophysical data are identified by political leaders as sensitive in terms of national security. A sensible recognition of the reality of this situation and a prudent choice of the data requested usually produce satisfactory results, although individual researchers may at times be frustrated.

International cooperation in seismology is carried on either through formal organizational pathways or through interactions between friends and colleagues in different nations. For exchange of seismological information, the most important international organization is the International Association of Seismology and Physics of the Earth's Interior (IASPEI), one of the seven associations that together comprise the International Union of Geodesy and Geophysics (IUGG). Seventy-six member nations adhere to

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IUGG, which, in turn, is a member Union of the International Council of Scientific Unions (ICSU). A U.S. National Committee for the IUGG is appointed by the National Research Council, and an analogous U.S. National Committee acts within each of the associations, including IASPEI.*

The IASPEI holds general assemblies every two years, with alternate assemblies held in association with the quadrennial assemblies of the IUGG. Recent assemblies have been held in Zurich, Madrid, Moscow, Lima, and Grenoble. In addition to convening these assemblies, IASPEI plays an important role in the oversight of the International Seismological Centre, Edinburgh, and in the support of the Bureau Central International de Seismologie, in Strassbourg. The Bureau Central will come under a new arrangement in 1976. The European Seismological Commission of IASPEI serves an important function in facilitating international interactions across the national boundaries of Europe. Some of the other IASPEI commissions are Practice (sets standards, formats, and procedures for the operation of seismic observatories); Magnitudes; Earthquake Prediction; Explosion Seismology; and Heat Flow.

The IASPEI joins with other IUGG Associations in work on topics that cross disciplinary lines. An IUGG Committee on the Standard Earth Model has been at work for several years. The IUGG Committee on Tsunami is another inter-association effort.

The IUGG also joins with other major scientific unions--for example, those devoted to the geological sciences, astronomy, and the radio sciences--for the development of international programs of mutual interest. A good example of such multidisciplinary cooperation that is of interest to seismologists is the International Geodynamics Commission, which is responsible for the guidance of the International Geodynamics Program. Another ICSU activity that has become significant for seismology only recently is the system of World Data Centers (WDC's). Created during the International Geophysical Year, these centers provide a smoothly running mechanism, under internationally accepted guidelines, for the exchange of geophysical data.

Although these centers have been important to some of the geophysical sciences, they were not charged with the task of gathering original data of value to seismologists until 1973. Since then, the WDC's have been acquiring and distributing copies of seismograms of important

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*The present USNC/IASPEI consists of Leon Knopoff, Chairman; Frank Press; and Carl Kisslinger.

earthquakes and thereby supplementing in a valuable way the data available from various national centers. The distinction between the U.S. National Geophysical and Solar-Terrestrial Data Center and WDC-A for Solid-Earth Data, both located in the Environmental Data Service in Boulder, Colorado, may seem trivial to the American user of their products, but this is, in fact, a necessary and useful arrangement for acquiring the data needed. Seismology has progressed a long way from the days before 1960 when a major research project based on worldwide data required the mailing of requests directly to dozens of station operators and then waiting patiently as the seismograms, of uneven and unpredictable quality, dribbled in during the following months. The direct, personal contacts between cooperating scientists truly had value, but few would bemoan the passing of that mode of operation.

In addition to the formal, multinational organizations, the United States has joined in cooperative efforts on a bilateral basis with many countries interested in seismology. One of the oldest and most cordial of these interchanges has been with Japan, through the U.S.-Japan Science Cooperation Program. Sponsored on the U.S. side by the National Science Foundation, this program has expedited the exchange of individual Japanese and American scientists and has supported four successful seminars in earthquake-prediction research. The splendid relations between U.S. and Japanese seismologists is truly a model of outstanding international interactions.

Another, much newer program that shows every promise of being equally successful is the U.S.-U.S.S.R. program in earthquake-prediction research. Called for specifically in the agreements on environmental research signed by Mr. Brezhnev and Mr. Nixon in 1972, this program has already resulted in widely expanded contacts between some of the most productive young workers in the subject from both countries, including the opportunity to spend time actively engaged in research in the other country.

A joint French-American effort that has produced important results is Project FAMOUS, a program of observations of the Mid-Atlantic Ridge. The key element in the program has been the direct observation, from French and American submersibles, of the floor and walls of the rift at the center of the Ridge. Although this program is not primarily seismological, the results have important implications for all solid-earth geophysicists concerned with ocean-floor spreading and plate tectonics.

Closer to home, we find that arrangements with colleagues and institutions in Canada, Mexico, and the countries of Central and South America are often arranged directly and simply by individual U.S. scientists or research organizations. Examples are the long-standing cooperation between the Carnegie Institution of Washington and several South American countries and the smaller-scale but very effective cooperative program being carried out by the University of California at San Diego and the National University in Mexico City. In a similar spirit of cooperation, the Government of Canada makes available the output of its excellent national seismographic network for distribution through the U.S. National Geophysical Data Center.

The Worldwide Standardized Seismograph Network, discussed elsewhere in this report, is an outstanding example of successful cooperation between the United States and many other countries.

Scientific societies play an important part in the development of friendship and active cooperation between U.S. and foreign seismologists. The American Geophysical Union, the Seismological Society of America, the Society of Exploration Geophysicists, and the Geological Society of America are all international with regard to their membership and enjoy the contributions of their foreign members both at their meetings and in their publications. It is noteworthy that a number of the important medals awarded by the American Geophysical Union in recognition of outstanding achievement in research have gone to foreign members of the Union.

International cooperation in research will be especially important in the near future as seismologists seek ways to predict earthquakes. Opportunities to acquire data and experience related to the prediction of major earthquakes, which are rare events at any one location, are essential to progress. By preparing cooperatively to make observations related to occurrences of strong earthquakes in many parts of the world, the international seismological community can optimize its chances of being in the right place, with the right instrumentation, at the right time, for the benefit of all nations afflicted by earthquake disasters.

GLOSSARY

ACDA - Arms Control and Disarmament Agency
AFCRL - Air Force Cambridge Research Laboratories
AFGL - Air Force Geophysical Laboratory
AFOSR - Air Force Office of Scientific Research
AFTAC - Air Force Technical Applications Center
ARIES - Astronomical Radio Interferometer Earth Survey
BLM - Bureau of Land Management
BuM - Bureau of Mines
BuR - Bureau of Reclamation
COE - U.S. Army Corps of Engineers
DARPA - Defense Advanced Research Projects Agency
DOD - Department of Defense
DOT - Department of Transportation
EDS - Environmental Data Service
EPA - Environmental Protection Agency
ERDA - Energy Research and Development Administration
GAO - Government Accounting Office
HGLP - High-Gain Long-Period (network)
HUD - Department of Housing and Urban Development
IASPEI - International Association of Seismology and Physics of the Earth's Interior
ICSU - International Council of Scientific Unions
IGDG - Interagency Geophysics Discussion Group
IGP - International Geodynamics Program
IGY - International Geophysical Year
ISS - International Seismological Summary
IUGG - International Union of Geodesy and Geophysics
NASA - National Aeronautics and Space Administration
NBS - National Bureau of Standards
NOAA - National Oceanic and Atmospheric Administration
NRC - National Research Council
NSF - National Science Foundation
OBS - Ocean-bottom seismometers

OMB - Office of Management and Budget
ONR - Office of Naval Research
PDE - Preliminary Determination of Epicenters
RANN - Research Applied to National Needs (a program of NSF's Directorate for Research Applications)
SAFE - San Andreas Fault Experiment
SRO - Seismological Research Observatories
UBC - Uniform Building Code
UMP - Upper Mantle Project
USCGS - U.S. Coast and Geodetic Survey
USGS - U.S. Geological Survey
USNRC - U.S. Nuclear Regulatory Commission
VA - Veterans Administration
VLBI - Very-long-baseline interferometry
VLP - Very long period
WDC - World Data Center
WWSSN - Worldwide Standardized Seismograph Network (or Worldwide Network of Standardized Seismograph Stations)