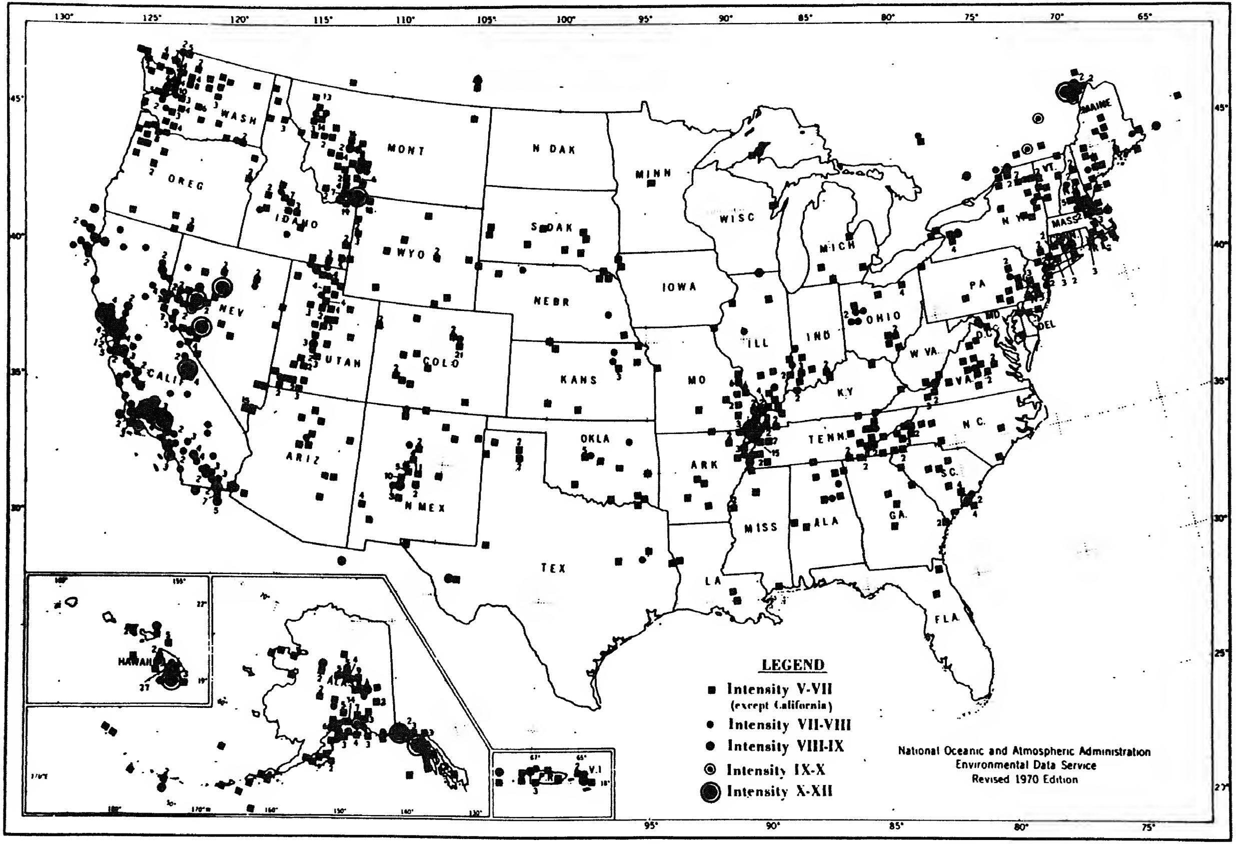
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U.S.EARTHQUAKE OBSERVATORIES:
Recommendations for a New National Network

Panel on National, Regional, and Local
Seismograph Networks
Committee on Seismology
Assembly of Mathematical and Physical Sciences
National Research Council

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*Deceased July 6, 1979.

PREFACE

The study of earthquakes requires observatories that can measure them. Seismology is no different from any of the sciences in that both understanding and ability to respond to society's needs depend on reliable and precise measurements. If seismology is to make an effective contribution to the nation, it must employ the latest technology available to measure earthquakes.

A special feature of seismology is that it not only provides the most detailed information about the structure of the Earth's interior, but it also relates to fundamental problems of economic importance and social well-being. Earthquakes are destructive over wide areas in the United States and, with the growth of industrialization and the spread of population, the consequences of strong ground shaking can be catastrophic. Thus, seismology is called on to provide engineers with risk maps, which are the basis for national building codes, as well as to estimate strong ground motions for the proper design of large critical facilities such as nuclear reactors, hospitals, dams, and bridges.

The first great advance in quantitative seismology in the United States took place at the turn of the century when seismographs were established in various parts of the country. The availability of seismograms showing the actual motion of the ground provided a great impetus to studies of earthquake waves. As the century advanced, the accumulating knowledge from such studies provided a geophysical key that led to an understanding of the structure and tectonics of North America and played a crucial role in the exploration for minerals, oil, and other energy sources.

It is hard to foresee exactly what improvements the observational side of a science will produce. For instance, we can be fairly sure that the scientists who, with imagination and foresight, established the first seismograph networks in the United States could not have predicted the scientific and economic rewards. In the last two decades, for example, seismograph networks have provided vital information to the government in the attempt to obtain a comprehensive nuclear test ban treaty. Catalogs of earthquake locations and size have proved to be essential in the rational siting of the nation's power stations and dams. Other recent examples of large engineering structures where records from seismograph stations provided crucial siting information are large liquid-gas storage facilities, Veterans Administration and other hospitals, and geothermal power stations.

Much of the initiative for the continual improvement and increased number of seismograph stations has come in the United States from the U.S. Geological Survey and from local groups, particularly in universities. Improved observational capabilities were more easily acquired in the early days when equipment cost was relatively low and technical design was relatively simple. The first attempt in modern times to upgrade radically earthquake observatories arose during the nuclear test ban negotiations. A special panel was set up by the President's Special Assistant for Science and Technology to recommend improvement in seismograph networks. The 1959 report of that panel, chaired by L. V. Berkner, had a dramatic effect on the improvement of seismograph measurements. An immediate result was the installation in the early 1960's of the Worldwide Standardized Seismograph Network (WWSSN) to provide calibrated earthquake recordings. The result of this network was a significant advance in research on earthquake mechanisms, global tectonics, and the structure of the earth's interior. No systematic improvement of seismographs or reassessment of station locations across the whole country has occurred at the national level since the blueprint of the Berkner panel, although several abortive attempts have been made.

The charge from the National Research Council's Committee on Seismology to this Panel (see Appendix A) was to examine all aspects of earthquake monitoring in the United States. Such monitoring ranges from the major observatories with seismographs able to record both small and large earthquakes, locally and overseas, to individual strong-motion accelerometers at unattended stations ready to record a large earthquake when it strikes nearby.

This broad task presented a considerable challenge to the Panel. We were asked, in effect, to chart a course, at least for a decade, in observational seismology. Our goal has been to find a plan that would achieve a success comparable with that of the recommendations of the Berkner panel. We had the advantage of excellent advice and information from scientists from many federal, university, and private agencies involved in earthquake monitoring and research. As the discussions proceeded, a pattern emerged that should allow the maintenance of individual initiative, which has been a highlight of U.S. seismology during this century, together with a more stable and cost-effective national seismograph system. Significantly, the success of these proposals will make a major U.S. contribution to the newly approved (by the International Union of Geodesy and Geophysics, the International Union of Geological Sciences, and the International Council of Scientific Unions) international program entitled Dynamics and Evolution of the Lithosphere: The Framework for Earth Resource Systems and Geological Hazards.

Our recommendations make use of the high technology available in the United States and the abilities of many government and private agencies to develop and sustain an earthquake observation program that would meet the national research and application needs. We have dealt with some exciting prospects such as linking of standardized digital earthquake observatories in a nationwide array, the establishment of earthquake observatories on the ocean floor around the continental margins, and the rapid analysis of earthquakes using high-speed computers. It is our hope that the implementation of our recommendations will lead to a major step forward in U.S. seismology.

Bruce A. Bolt, *Chairman*
Panel on National, Regional, and
Local Seismograph Networks

ACKNOWLEDGMENTS

This study was made by the Panel on National, Regional, and Local Seismograph Networks of the Committee on Seismology in the National Research Council's Assembly of Mathematical and Physical Sciences. The Panel wishes to express its appreciation for the interest and support of the following agencies: the Defense Advanced Research Projects Agency, the Division of Problem-Focused Research of the National Science Foundation, the U.S. Geological Survey, the U.S. Air Force Office of Scientific Research, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Division of Earth Sciences of the National Science Foundation, the U.S. Nuclear Regulatory Commission, and the Department of Energy.

On July 6, 1979, the Panel suffered a grievous loss with the death of one of its members, Don Tocher. Members of the Panel wish to place on record his vital help, based on his intimate experiences with all aspects of observational seismology.

Kenneth Whitham, Assistant Deputy Minister, Conservation and Nonpetroleum, of Energy, Mines, and Resources Canada, and Jorge Prince, Subdirector, Instituto de Ingenieria, Ciudad Universitaria, Mexico, discussed various aspects of seismic networks with the Panel and provided the information presented in Appendixes C and D.

Invaluable help was given by many individuals in assembling background information. In particular, Jon Peterson of the U.S. Geological Survey Albuquerque Seismological Laboratory, New Mexico, provided key information on the instrumentation now available for a new seismograph network.

CONTENTS

1 SUMMARY AND RECOMMENDATIONS

1.1 SUMMARY AND MAJOR RECOMMENDATIONS

This report is the first attempt by the seismological community to rationalize and optimize the distribution of earthquake observatories across the United States. The main aim is to increase significantly our knowledge of earthquakes and the earth's dynamics by providing access to scientifically more valuable data. Other objectives are to provide a more efficient and cost-effective system of recording and distributing earthquake data and to make as uniform as possible the recording of earthquakes in all states.

Many problems of major national importance related to earthquakes remain to be solved. Earthquake prediction and the amelioration of earthquake hazards, for example, require uniform, continuous, and standardized earthquake records over the entire country using modern computer-coupled instrumentation. We cannot anticipate all the scientific gains that will accrue from sharply improving the national capability to observe, measure, and study earthquakes, but we can be reasonably sure of many successes. Among the research goals are the quantitative study of sources of earthquakes above magnitude 3.0 up to the greatest earthquakes in the entire United States, a capability never before possible; more reliable understanding and prediction of strong ground shaking; the precise definition of fine structure in the earth's crust and deep interior using high-resolution techniques; and the close mapping of regional tectonics, related to geological hazards, and location of natural resources. In particular, there is a need to monitor and analyze quickly short-term stress variations in active fault zones for earthquake prediction purposes, a high national priority.

Two recent developments make the present appropriate to move ahead by redesigning and consolidating the uncoordinated mixture of local, regional, and national earthquake observatories of which many are becoming obsolescent. The first development is the new technology based on digital sampling of signals. The second development is the decisive advance in theoretical seismology, including powerful computational ability, that has created a need for high-quality observations of seismic waves, with wide dynamic ranges in both frequency and amplitude.

For the fulfillment of the research and applied goals, data analysis, archiving, and retrieval capabilities in the United States need streamlining, and partly centralizing, so that digital tapes, seismograms, and the derived seismicity data from all stations are available in a short time to all users.

In order to bring together these components, the central recommendation of the Panel is that the guiding concept be established of a rationalized and integrated seismograph system consisting of regional seismograph networks run for crucial regional research and monitoring purposes in tandem with a carefully designed, but sparser, nationwide network of technologically advanced observatories. Such a national system must be thought of not only in terms of instrumentation but equally in terms of data storage, computer processing, and record availability.

In order to take advantage of recent technological and theoretical advances, the concept of an integrated United States Seismograph System (USSS) should be adopted in the United States so that enhanced information on earthquake sources, seismic hazards, ground motions, and earth structure is available.

Digital technology is now being applied at earthquake research observatories situated around the world. A plan for the monitoring of global earthquakes by an upgraded worldwide seismograph network, which used this technology, was most effectively argued in 1977 in a companion report of the Committee on Seismology titled *Global Earthquake Monitoring* (Panel on Seismograph Networks, 1977). Some key recommendations of the 1977 report have already been adopted successfully, and the present report builds on these gains toward a modern *domestic* earthquake system.

The now common photographic (analog) recording at U.S. permanent seismograph stations must be supplemented (or replaced at specially chosen stations) by digital recording using magnetic tape or other digital storage media.

The inability to resolve valuable details of seismic wave forms on existing three-component photographic records restricts their usage, particularly for the fine resolution of earthquake source mechanisms, premonitory variations, and tectonic properties. Availability of digital records with their large dynamic range holds the prospect for significant expansion of our understanding of ground motion and earth structure.

The Panel strongly recommends that a network, optimally distributed across the whole country, of high-quality digital seismographs be constructed as soon as possible. These standardized digital stations will provide high-quality continuous data on all U.S. earthquakes down to small size and permit the application of high-resolution rapid analysis techniques.

The core of the proposed United States Seismograph System (USSS) should be a network of permanent stations with three components that will constitute the National Digital Seismograph Network (NDSN). These observatories should be designed to provide broadband records of felt earthquakes in the United States and larger earthquakes elsewhere. Capital funding of at least $15 million should be established for the next 4 years for purchase, installation, and operation of the NDSN.

1.2 OVERALL RECOMMENDATIONS

In order to achieve the specified scientific and social objectives, the Panel makes the following 14 recommendations. Recommendations 1 and 2 repeat the two major recommendations stated in the previous section.

First and foremost, the Panel has been impressed by the need to take greater advantage in seismology of the observational, technical, and data-processing resources of the United States by encouraging new initiatives and development of all types of networks within the general framework of a United States Seismograph System. (For more details, see Chapters 2 and 8 and Sections 5.1, 7.1, and 9.2.)

RECOMMENDATION 1. In order to take advantage of recent technological and theoretical advances, the concept of an integrated United States Seismograph System (USSS) should be adopted so that enhanced information on earthquake sources, seismic hazards, ground motions, and Earth structure is available.

For some time, it has been difficult in the United States to obtain the capital funds necessary to upgrade seismograph stations by taking advantage of available high technology. This is particularly true in the field of digital recording, transmission, storage, and minicomputer and microcomputer processing. This situation gravely compromises our expertise about earthquakes and our development of advanced seismograph technology and related data reduction.

Most existing stations of regional networks in the United States record only a single component of ground motion in earthquakes, with severe limitations in dynamic range. These stations provide information primarily for hypocentral locations of earthquakes. Some of the best current stations in the United States are those equipped in the 1960's as elements of the Worldwide Standardized Seismograph Network (WWSSN). In the last two decades, these have contributed greatly to our knowledge of earthquakes, but the WWSSN stations are not all optimally located for uniform geographical coverage, nor do they have the capability to record seismic waves with anything approaching completeness. A carefully distributed nationwide network of wide-band digital three-component stations is required. Such a network would have the capability of providing observations of earthquake waves with the necessary range of frequency and amplitude. These digital three-component stations, comprising the National Digital Seismograph Network (NDSN), would serve as first-order pivotal earthquake observatories of an integrated national multipurpose seismograph system (USSS). (See Chapters 2 and 3 and Sections 4.1, 5.2, 6.1, 7.1, 8.1, 9.3, and 9.4.)

RECOMMENDATION 2. The core of the proposed United States Seismograph System (USSS) should be a network of permanent stations with three components that will constitute the National Digital Seismograph Network (NDSN). These observatories should be designed to provide broadband records of felt earthquakes in the United States and larger earthquakes elsewhere. New funding of at least $15 million should be established for the next 4 years for purchase, installation, and operation of the NDSN.

The Panel believes that the installation of the National Digital Seismograph Network (NDSN) should proceed with some urgency. A national earthquake observatory system, giving uniform coverage on earthquake monitoring for the whole country, is long overdue. The proposed network, together with the capabilities of regional networks, will provide the detail that has been lacking in earthquake-hazard evaluation, critical-facility location, and work on earthquake prediction in all parts of the country, including the continental shelves. The Panel concludes that the NDSN is vitally necessary to bring observatory instrumentation up to available technology in order to provide a first-rate data base for seismological research. This research is now hampered by lack of standardization of seismographs across the country, restriction in the dynamic range of earthquake recording, and lack of stability in the configuration of a "first-order" observatory network.

The Panel considered a number of NDSN configurations based on the criteria of uniform geographical coverage and significantly increased research capability. These trial configurations were also restricted by the need for a minimum number of stations, consistent with the scientific requirements and with keeping capital and maintenance costs to a minimum. For this reason, in the trials, as many of the NDSN stations as possible were sited at or near existing seismographic facilities, although in a number of cases this did not prove possible. It was found that the minimum number of NDSN stations needed to fulfill requirements was about 30 in the contiguous United States. A geographical distribution for a trial model that was near optimum is shown in Figure 1.1. It is estimated that, with a national network similar to the one shown, any earthquake in the coterminous United States with magnitude between 3.0 and 3.5 would have almost the entire wave train recorded at five stations of the NDSN with about 90 percent confidence.

Regional and hemisphere seismicity are such that elements of the NDSN are also required in Alaska, Hawaii, and Puerto Rico. In Alaska, earthquake activity is high and frequent, with special conditions related to the development of that state. (See Chapter 3 and Sections 4.1, 4.4, 5.2, and 9.1.)

RECOMMENDATION 3. The implementation of a National Digital Seismograph Network (NDSN) should be commenced in the 1981-1982 fiscal year. In the next 4 years, 36 NDSN stations should be established at optimum sites: 29 stations in the contiguous United States, 5 in Alaska, 1 in Hawaii, and 1 in Puerto Rico. This is the minimum number needed to record felt earthquakes uniformly across the United States.

There is a growing demand for information on strong ground motion in earthquakes and distribution of seismicity on and near the continental shelves of the United States. If all stations of the NDSN are land-based, there will be

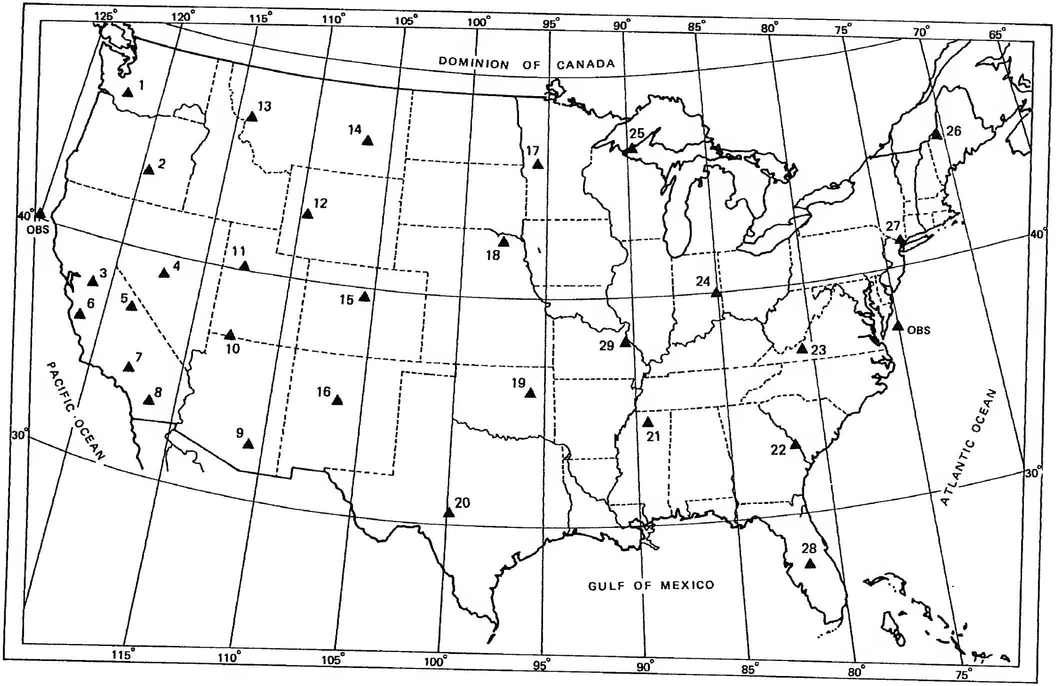

FIGURE 1.1 Proposed locations of 29 continental and 2 ocean-bottom observatories for the National Digital Seismograph Network (NDSN). *Comment*: The following recommended NDSN stations are at or near the given Worldwide Standardized Seismograph Network stations: 1, Longmire; 9, Tucson; 11, Dugway; 13, Missoula; 15, Golden; 16, Albuquerque; 20, Junction; 23, Blacksburg; 27, Ogdensburg; and 29, French Village.

a serious limitation in coverage of U.S. earthquakes, because land stations alone do not provide the coverage necessary to map and analyze the seismicity and tectonic activity in coastal and offshore areas. A major recent development in earthquake recording has been the design of instrument packages that are able to measure, for relatively long intervals, earthquake waves at the bottom of the ocean.

In the related field of tsunami research, one of the major problems is lack of information on the nature of tsunami waves in the open ocean before they are modified by nearshore and coastal features. Ocean-bottom observatories could readily be used to monitor these rarely occurring waves. Because permanent ocean-bottom observatories are still expensive to operate, we recommend a limited but decisive step in starting their deployment around the United States.

An interagency committee, with representatives from the U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Defense Advanced Research Projects Agency (DARPA), Office of Naval Research (ONR), and Department of Energy (DOE), should be established to arrange funding and management responsibilities for this work. (See Sections 3.4, 4.4, 5.2, 6.3, and 7.3.)

RECOMMENDATION 4. Four ocean-bottom observatories should be established offshore of the continental United States as part of the National Digital Seismograph Network (NDSN). At least two of these systems (one off the East Coast and one off the West Coast) should be installed during the initial 4-year establishment period of the NDSN. The ocean-bottom observatories should contain instrumentation as responsive to earthquakes as the land-based seismographs of the NDSN as well as instruments for the measurement of tsunami effects.

Even with the establishment of a national network of digital broadband stations (NDSN), there remains the need for denser networks of simpler telemetered seismographs in the high-seismicity regions of the United States.

Such regional networks have proved their value over decades in California and, more recently, for example, in Alaska, Nevada, Washington, Utah, New England, Montana, and the central Mississippi Valley. They have become essential sources of information to the public, news media, state and local government, engineering operations, and disaster preparedness organizations. Their most immediate use is the rapid cataloging of precise locations and sizes of felt regional earthquakes. Moreover, the recorded waves are used for fundamental geological and geophysical research on regional strain, fault properties, crustal structure, and earthquake-prediction investigations.

Within the concept of a United States Seismograph System (USSS), the establishment of the NDSN provides a fruitful opportunity to re-evaluate the present distribution, instrumentation, calibration, design, and data flow of regional networks. A responsibility of the proposed Working Group on the USSS (Recommendation 6) should be to review the operation of present regional networks in order to integrate them as closely as possible into the USSS and thereby substantiate the need for long-term funding that is both stable and cost-effective. (See Sections 3.1, 3.3, 4.2, 5.3, 6.2, 7.2, 8.2, and 9.4.)

RECOMMENDATION 5. Telemetered seismograph networks with simple instrumentation in earthquake regions remain of central practical and research importance. As part of the United States Seismograph System, federal and state funding agencies should give high priority to maintaining the continuity and the appropriate level of improvements and operation of those regional networks with demonstrated productivity.

The establishment of the NDSN involves a number of interrelated but specialized questions. First, the optimal siting of the stations must be worked out with cooperating institutions, such as universities. It is appropriate, for example, that some of the NDSN stations should be located at low-noise sites where there are currently WWSSN observatories. Some sites will, however, of necessity be new, and some will operate as remote observatories with telemetry to regional centers. Instrumental design for suitable digital seismograph recording is well advanced and, in part, field-tested. Design details, however, must be finalized, including manufacture and standardization of components. Questions also have to be settled on the standardization of magnetic tape formats, data flow, and responsibilities of local operators.

A broader requirement is the integration of the NDSN and established regional networks within the USSS. We believe that all seismograph stations in the United States should be considered part of an integrated network with the NDSN as the core. In this framework, regional seismograph networks that now supply earthquake data for risk and ground-motion analysis must, after justification, be not only sustained and modernized, but ties between the NDSN and regional stations must be developed so that calibrations may be made for earthquake locations, source parameters, and long-term temporal variations of seismicity. At this stage, the Panel believes that it is not practical to recommend specific changes in individual regional networks; these must be worked out as the NDSN becomes established within the USSS. For these reasons, arrangements for continued supervision of the development of the new national system are needed. (See Chapters 2, 4, and 6 and Sections 5.1, 5.4, 8.4, and 9.2.)

RECOMMENDATION 6. A special working group, the Working Group on the USSS, representing the seismological community as a whole, should be created to guide the development of a new integrated United States Seismograph System that includes the National Digital Seismograph Network.

There is at present no central advisory service for the operation, upgrading, and data management of seismograph networks in the United States. There are about 20 largely independent regional seismological laboratories, each with its satellite network of seismograph stations. As well, during the past decade many local seismograph networks of varying size and sophistication have been put into operation to gather earthquake (particularly microearthquake) data related to a specific site or project. Typically, these local networks are found at proposed or existing sites of critical facilities such as dams and nuclear power plants. The regional and local networks are owned and operated by universities, private industry, state agencies, and federal agencies. The data that they collect contain valuable information on both regional and teleseismic earthquakes, localized correlation of earthquakes with geologic structures, source properties, and sometimes reservoir-associated seismicity. It is clearly necessary to encourage those operating them to facilitate data access to all seismologists. Yet, because of the specific aims associated with local networks, in particular, the collected raw data are often discarded after the specific aims have been achieved.

The only overview is a limited one provided by the U.S. Geological Survey (USGS) through its National Earthquake Information Service. The USGS has maintained and extended cooperative agreements with universities and has operated most of the early U.S. Coast and Geodetic Survey seismograph stations, particularly the Albuquerque Seismological Laboratory. An important recent development has been the establishment, within the USGS Branch of Global Seismology, of expanded responsibilities for design, deployment, and maintenance of both the WWSSN and new digitally equipped stations located around the world. It is thus highly appropriate for the USGS to have prime responsibility for the NDSN. The necessary technical basis clearly is within the present expertise of the USGS.

Unlike most other countries where direction and financial responsibility for a national earthquake observatory network is centralized, in the United States the evolution of an USSS relies on individual cooperation. Without interfering with local initiative and independence, the Panel believes that, for both cost and scientific effectiveness, it would be helpful to establish a continuous advisory overview to the United States Seismograph System. The federal agency with prime responsibility for basic earthquake data gathering in the United States is the USGS, and that organization should take the lead in establishing the NDSN and providing guidance for the USSS. (See Chapters 4 and 6 and Sections 5.1 and 9.3.)

RECOMMENDATION 7. Adequate funding should be made available to the U.S. Geological Survey (USGS) for it to assume prime responsibility for the installation, maintenance, quality control, and data flow of the National Digital Seismograph Network. Further, the USGS should develop standards and provide guidelines on record formats and quality control for the overall integrated United States Seismograph System.

Upgrading of observational seismology in the United States by installation of the NDSN must be accompanied by changes in data management. The technologies of data storage and transmission continue to evolve rapidly. Even without the NDSN, the present amount of seismological data would have been unimaginable a few years ago. Digital recording systems, both in the NDSN and regional networks, will produce extremely large quantities of data of entirely different form from present analog records. Without sophisticated data-handling equipment, this mass of digital data will rapidly become unmanageable, yet the quantity is offset by the greater resolution of earthquake recording and direct compatability with high-speed computers. If the reality of the new networks is to meet expectations, there must be an economical system of data gathering that is flexible enough to change as new problems are identified. The data-archiving systems must also be flexible and able to adapt to changing research as well as data and user needs.

Responsibility at the federal level for the management of geophysical data resides with the Environmental Data and Information Service (EDIS) of the National Oceanic and Atmospheric Administration (NOAA). This service currently archives seismograms from the Worldwide Standardized Seismograph Network (WWSSN) and from selected national stations and strong-motion records obtained in the near field of large earthquakes. It distributes these analog data on request and assumes responsibility for their archiving. A similar service is being developed for digital data on magnetic tapes that are starting to flow from the digital stations of the global seismograph network. This new responsibility will mandate more technical resources and the extended provision of facilities for visiting scientists to retrieve data directly. (See Chapters 2 and 8 and Sections 4.7, 5.3, and 6.1.)

RECOMMENDATION 8. The Environmental Data and Information Service (EDIS) should be expanded in order to assume the prime responsibility for archiving and timely dissemination of standardized data from the National Digital Seismograph Network (NDSN) and regional networks. Stable additional funding should be provided to handle these essential services.

The effective use of digital data from the NDSN by the nation's seismologists will place a significant burden on the various centers of seismological research in the United States. The establishment of a modernized United States Seismograph System and the National Digital Seismograph Network envisaged here must not be allowed to result in the weakening of centers where strong programs of research on earthquakes are carried out. Nor must it preclude seismologists at institutions without appropriate computer facilities from taking full advantage of the digital data.

Analysis of large volumes of digital seismic data requires computer hardware and software that are tailored to the job. The most efficient solution is to develop regional seismological research through voluntary commitments by some of the main seismological research centers in the United States. These commitments will require moderate financial subsidies, over and above the usual costs of research, for space and technical upgrading and assurance of stable support for operational costs, telemetry costs, and data management. It is important that funding agencies recognize the additional financial need of these institutions and that grants and contracts be allowed to respond to this need, as long as these expenditures can be shown to be scientifically and economically effective. (See Sections 4.2, 5.3, 6.2, 7.2, 8.2, and 9.4.)

RECOMMENDATION 9. Appropriate support should be made available to regional earthquake research centers, according to the needs of each institution for data acquisition, digital data analysis, capital replacement costs, and management operations. Such needs may include computer operation and supplies, programming support, visiting scientist support, telemetry of data to and from National Digital Seismograph Network stations, and data-distribution costs.

In recent years, numerous seismograph stations and arrays in the United States have been operated for the monitoring of nuclear-weapons testing and treaty verification. Many of these stations were for experimental purposes. The need to monitor weapons testing and to verify treaties has provided the impetus to develop and incorporate advanced technology in seismic instrumentation and processing. Some of the first of these arrays [e.g., Blue Mountain Observatory (BMO), Cumberland Plateau Observatory (CPO), Tonto Forest Observatory (TFO), Unita Basin Observatory (UBO), Wichita Mountain Observatory (WMO), and Large Aperture Seismic Array (LASA)] were semipermanent observatory systems, although most are now closed. Other stations were installed on strictly a temporary basis [e.g., Long Range Seismic Monitoring (LRSM) and Special Data Collection System (SDCS)] for specific seismological experiments.

Access to the data from these stations and arrays by seismologists for research has already proved to be invaluable. Some of the records were archived, but not all data have been saved. Because these stations are designed for a highly specialized purpose and utilize advanced developments in technology for instrumentation, recording, and processing, they are usually expensive to install, operate, and maintain. Yet, even though the stations do not provide a stable long-term operational data base, their existence helps to fill in the gaps of a sparse national network with often extremely crucial data. (See Sections 3.5, 4.1, 5.1, 7.1, and 8.4.)

RECOMMENDATION 10. Data collected from seismograph stations and arrays installed for the monitoring of nuclear-weapons testing and treaty verification should be made available through expanded Environmental Data and Information Service (EDIS) facilities and archived in a format compatible with the National Digital Seismograph Network (NDSN). These special-purpose observatory facilities, *ıpplemental to the NDSN, would provide valuable ạata for seismological research using the NDSN.*

ənt of seismograph instrumentation in the United ɔeen carried out by a wide variety of organiza- ə of the more sophisticated instruments have əars arisen from the specialized needs of the ɔf Defense for the monitoring of underground Losions. Other advanced seismographs (includ- ɔttom seismographs) have been developed mainly .ndustry and by university laboratories. ederal level, the U.S. Geological Survey has seismograph instrument development at a number ratories, including those at Menlo Park and Particularly, the Albuquerque Seismological .s dedicated solely to the development and seismograph instrumentation. Initially re- ɔr the maintenance of the Worldwide Standardized Network, it has now taken responsibility for installation, and maintenance of a substantial current global digital network. The Albuquerque ıl Laboratory has recently developed digital- ismograph equipment described in this report .e of the standardized broadband system to be new National Digital Seismograph Network. The ied out by a small staff with the aim to develop On adoption, these would most likely be manu- private industry. Given the technological eographical extent, and national seismological ems clear that in parallel with more short-term ate industry, government agencies, and univer- should be a stable and continuous federal gov- lvement in development of new standardized instrumentation. (See Sections 4.1, 5.2, 7.5,

ATION 11. Upgrading and long-term maintenance and other elements of the USSS require that the cal Survey (USGS) maintain a strong effort in and related systems. The USGS Albuquerque hould be continued as a federal center for pments, and it should receive adequate funding a high professional level.

re than 20 government, private, and university operate sizable seismograph networks, at least ced in-house projects on instrumentation devel- ssembly. Unfortunately, almost no sustained communication occurs between these groups at the engineering and technical level.

Manufacturers of seismological equipment often have inadequate information from the scientific community on the desired characteristics of instruments. As a result, a diversity of instrumentation is now being developed, which, while partly beneficial, is not always in the interest of a uniform data base. At the same time, geotechnical and geophysical groups in the United States and elsewhere evidence a growing demand for the establishment of seismograph equipment for earthquake monitoring, particularly related to risk and prediction. An effort is now appropriate, concurrent with the establishment of the new national system to provide a mechanism for improving earthquake observational instrumentation. Both reduced costs and improved scientific work should result. (See Chapters 4 and 7 and Sections 5.4, 8.1, and 9.2.)

RECOMMENDATION 12. A special working group on seismic instrumentation should be established consisting of representatives of government, private industry, and universities. This group should examine standards for seismic instrumentation, provide a forum for communication between those using and manufacturing seismograph equipment, and recommend optimum instrumentation development.

Historically, there has been a gulf between the recording of large seismic waves on low-gain instruments near the source of a moderate to large earthquake and the recording of tiny seismic waves from more distant sources on sensitive seismographs. Strong-motion seismographs have been developed by the engineering community largely because of the information that they provided on strong ground shaking and building response. This distinction, however, is an artificial one, and both seismologists and earthquake engineers now realize that near-field and far-field measurements of ground motion are merely parts of a continuum of earthquake vibrations. The measurement of structural response to strong ground shaking remains, of course, a problem of great interest to earthquake engineers.

Earthquake observatories in seismic regions must maintain seismographs capable of measuring high-frequency and low-frequency waves, seismic waves from distant sources as well as strong ground motion from a large nearby earthquake. With the availability of strong-motion accelerograms recorded near earthquake sources, seismologists are more and more using these records to make basic studies of source mechanisms, seismic-wave generation, and propagation near an extended source. It is essential for the growth of this key interaction between seismology and earthquake engineering to integrate the different kinds of instrumentation.

Advanced solid-state strong-motion instrumentation is now available with digital recording on magnetic tape rather than film and with a pretrigger memory. As the number of digital recording devices and their field-tested reliability increase, it is essential that strong-motion records have a standardized and uniform form that can be accessed directly by computers such as those at regional research centers.

Typically, strong-motion instruments are owned and operated by a diversity of organizations with a significant percentage operated by the private sector.

Future planning for a national system of strong-motion instruments of various kinds in all zones of high earthquake risk is too specialized to be treated in this report. Specialized engineering questions of the response of buildings, bridges, and other structures are involved. The Panel stresses, however, the need for measurements of strong ground motion to be part of the United States Seismograph System (USSS). In particular, appropriate NDSN and regional seismograph stations should include strong-motion recorders. Strong-ground-motion digital data should be accessible through regional centers, and strong-motion seismograms and digital tapes should be carefully archived. The optimum instrumentation and location of a special national integrated system of instruments for the measurement of strong ground motion should be the subject of a separate study. (See Sections 3.1, 3.3, 4.5, 5.2, 6.4, 7.4, 8.3, and 9.4.)

RECOMMENDATION 13. Low-gain sensors for recording nearby strong motion of the ground should be incorporated into the instrumental design for the new National Digital Seismograph Network. Adequate funds should be made available to allow the U.S. Geological Survey to maintain a national overview of the distribution and operation of strong-motion seismographs in the United States. Responsibility for comprehensive data storage for all significant records of strong ground motion obtained in the United States and for dissemination to users should be retained by the Environmental Data and Information Service.

The core of the new earthquake observatory system (USSS) for the United States will be provided by the permanent NDSN stations. Many of these stations will be associated with regional seismograph research centers, each with its own local or regional seismograph network. Even, however, with this greatly improved system, there are important problems that could not be tackled because of the fixed distribution of the networks.

Crucial seismological research on the Earth's deep interior and on earthquake-prone areas and active tectonic zones has been performed already by the use of temporary stations. For such studies, mobile stations have been deployed in special profiles and arrays, often under an *ad hoc* committee representing interested parties, including universities, federal agencies, and private industry. Both controlled explosions and natural earthquakes have been used to provide the seismic signals. After the experiment, the mobile seismographs have been retrieved by their owners.

Lack of uniformity in instrumentation, however, often significantly limits the quality of these studies. Significant improvement would accrue from the creation of a basic collection of portable seismographs of standard design. These seismographs would be kept for special studies of the kind outlined above and for rapid deployment after a large earthquake. It should be noted that the Panel on Seismograph Networks (1977) recommended that a set of portable broadband digital seismographs be available for use on a worldwide basis. A specially designed system could serve for both national and overseas deployment. (See Sections 3.2, 4.6, 5.3, and 7.1.)

RECOMMENDATION 14. A portable research array of standardized seismographs should be established for special regional or local studies of earthquakes. The flexibility of this array would augment the strengths of the National Digital Seismograph Network. A consortium should be organized to establish research goals for the array and to seek funds for specific projects using the array.

2 GOALS FOR A NATIONAL SEISMOGRAPH SYSTEM FOR OBSERVATIONS AND RESEARCH ON EARTHQUAKES

A major upgrading of U.S. earthquake observatories would be appropriate now. Recent advances in technology make possible both a more rapid and a more complete analysis of earthquakes than is now achieved. Such abilities are essential if seismology is to help with cost-effective solutions to environmental problems confronting our complex industrial society. Assessments of natural resources and economic vulnerability are continually being made in the light of growing population and industrial activities. New energy and production requirements of the United States must be achieved by facilities that are sited safely with respect to earthquakes and related hazards.

Only by taking a new step forward with earthquake observations and associated research can seismologists describe earthquakes more adequately, better define stable and unstable areas of the North American crust, provide more adequate information on earthquake occurrence and strength of shaking, and monitor earthquakes all around the Earth. We have reached a time of critical transition. Although the technological tools are at hand, they have not yet been efficiently incorporated into seismological practice so that the level of earthquake information and research can be raised.

Since the beginning of the twentieth century, many countries have established national networks of seismographic stations and data-analysis facilities. The motive was the desire to understand the structure, dynamics, and resources of the Earth, as well as the wish to reduce earthquake catastrophies. It was realized that an understanding of the causes and effects of earthquakes would only come by recording seismic waves both near and far from earthquake sources. Most developed countries (and many undeveloped countries) now operate electronic seismographs, and, indeed, a few have earthquake observing facilities that rival and surpass those in the United States.

In the United States, early seismograph stations and networks were established by the University of California, by the California Institute of Technology, and by other groups, notably the Society of Jesus. Later, the U.S. Coast and Geodetic Survey took responsibility for a widely distributed group of stations. A radical improvement in earthquake observations, both in the United States and abroad, occurred in the early 1960's with the establishment (see Figure 2.1) by the United States of the Worldwide Standardized Seismograph Network (WWSSN) as recommended by the Panel on Seismic Improvement (1959). In 1973, the federal responsibilities on earthquake observatory operation and analysis passed from the U.S. Coast and Geodetic Survey in the Department of Commerce to the U.S. Geological Survey in the Department of the Interior.

In recent years, the observational situation has become quite complex. There are now thousands of seismographs recording in the United States, some in the old permanent observatories but most, on a temporary or semipermanent basis, in remote sites with signals telemetered to a central regional observatory (see Chapter 4). There is a great variety of equipment and operating standards. This multiplication of stations has been a direct response to the needs of many federal, state, and private agencies, some mandated by law, to monitor earthquakes around critical facilities. Furthermore, there is a direct U.S. interest in a variety of modern high-quality digital seismographs currently being deployed worldwide (see Section 7.1). Yet at present, the basic system of permanent observatories in the United States uses seismographs that are limited in frequency response and record ground motion on photographic paper or film. The Panel concludes that this system is rapidly becoming obsolescent and is, already, in some critical ways woefully inadequate to meet present demands.

We recognize that our recommendations to remedy the situation expeditiously involve a minimum but not insignificant cost. They must be justified in terms of the scientific and social demands and expectations of seismology for the next decades. Therefore, at the beginning, we set out the principal goals that have guided our recommendations.

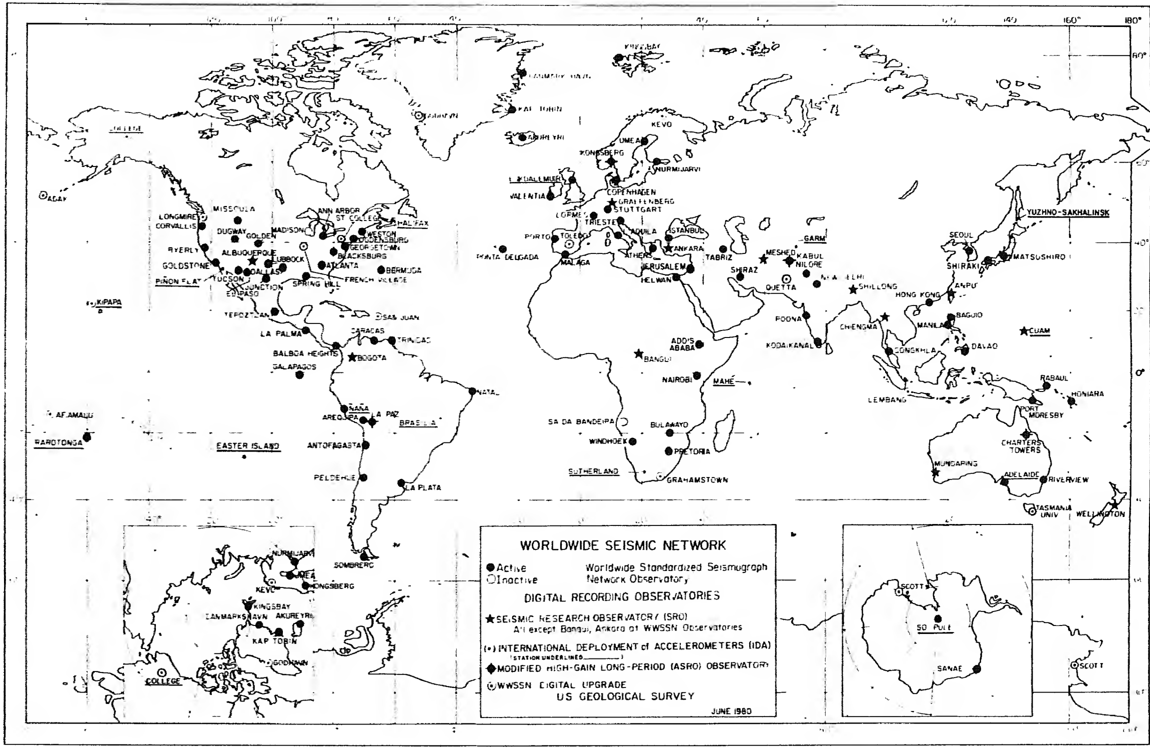

FIGURE 2.1 Locations of the Worldwide Standardized Seismograph Network stations and the Global Digital Seismograph Network.

2.1 ESTABLISHMENT OF UNIFORM EARTHQUAKE MONITORING FOR THE WHOLE COUNTRY

It is clearly not acceptable that measurements of ground shaking from damaging local earthquakes have different emphasis in different parts of the country. Each community now expects rapid availability of earthquake information for emergency preparedness and for the development of maps of shaking hazard.

A recent report of the National Academy of Sciences (Committee on Seismology, 1977) gave, as the primary goal of seismology, the provision of "the knowledge required to reduce loss of life and property resulting from earthquakes." The report points out that one third of the population of the United States lives in places where significant losses from earthquakes are likely (see Frontispiece). Less than one tenth of the citizens can be considered to be free of earthquake hazards. Thus, one of the important functions of a national network is the rapid detection and location of earthquakes greater than about magnitude 3.0 across the whole United States.

It should be remarked that this is currently the goal of the National Earthquake Information Service (NEIS), but, for a number of reasons, mainly the lack of appropriate seismograph station coverage, the goal is not realized (see Section 4.1).

2.2 PROVISION OF A MODERN SEISMOLOGICAL TOOL FOR THE STUDY OF OUTSTANDING GEOPHYSICAL PROBLEMS

There is little need to argue here the importance of fundamental research in seismology (see Section 3.2). Many applications of seismology to mineral exploration, the study of Earth structure, and earthquake engineering have grown out of previous basic research.

The vigor of seismological research in all of its facets, from past experience, is a vital part of the research and technological strength of the United States. It can only be strengthened, and probably even maintained at present levels, if the available financial resources of the nation are used in an optimally designed and careful way.

Such a coordinated effort in seismology involves replacing unfruitful observational and data-processing practices with advanced recording and analysis models. The investment will be returned many times. There will be exciting new results on the structure, composition, and dynamics of our planet and the stimulation of earthquake-related research by geologists, geophysicists, engineers, and physicists.

2.3 THE ESTABLISHMENT OF AN EFFICIENT AND COST-EFFECTIVE UNITED STATES SEISMOGRAPH SYSTEM (USSS)

The developments in the last decade demonstrate that it is inevitable that there will be such great demands for observations on various aspects of earthquakes that considerable funds will be spent in establishing regional and local networks and analyzing earthquake recordings. Without some advice and planning, uncontrolled proliferation of diverse observational and analysis systems may, overall, lead to the wasting of resources of management, administration, and funding.

Like other aspects of the national research effort, the observational side of seismology must be developed in a financially prudent and sound way. Two important issues are involved. The first is the ability to obtain stable funding for modern observatories over a decade. The second, of equal importance, is the optimal structuring of the seismograph system so that waste of the nation's scientific talent does not occur through complications of access and data dissemination.

2.4 AN UPGRADE OF THE AGING EARTHQUAKE OBSERVATORIES IN THE UNITED STATES WITH THE LATEST INSTRUMENTAL TECHNOLOGY

As other sciences, such as nuclear physics and astronomy, are nurtured by the continual incorporation of the latest instrumental developments, so too the vigor and health of seismology depend on incorporating instrumental advances. Already, it is widely accepted that the present network of principal seismograph stations is using what would be regarded in other sciences as antiquated equipment, so that the minimum national objective must be to upgrade seismograph instrumentation to take advantage of available U.S. technology.

In fact, there is now a growing network of seismograph stations with modern equipment in other countries around the world. Some are operated under cooperative agreements with U.S. federal agencies (see Figure 2.1), but many have been established by scientific groups in the particular country itself. In the latter category are national stations of advanced design in the Republic of Germany, Japan, the United Kingdom, Sweden, Canada, France, and the Soviet Union. These advanced global stations make use of digital instrumentation and magnetic-tape storage, which provides much more satisfactory measurements of earthquake waves than the old analog equipment using photographic recordings. The digital samples on tape also allow rapid input to high-speed computers for estimation of earthquake parameters. Another important advantage is the ability to record on-scale large U.S. and overseas earthquakes.

In the United States, initiatives have also begun at a few domestic earthquake observatories to improve facilities using digital instrumentation, although the sources of funds for new equipment and operations for U.S. stations have been limited. A danger with the present slow *ad hoc* procedures is that, unless standardization of digital instrumentation and recordings is achieved quickly, much capital will be spent in saddling the country with a nonstandard mix of seismographs, recording levels, and data formats. There will be no productive way in which these data can be integrated or even accessed by all research workers.

2.5 A NATIONAL SEISMOLOGICAL SERVICE THAT WILL PROVIDE EFFICIENT ACCESS TO ALL TYPES OF EARTHQUAKE RECORDINGS

The underlying concern among seismologists today is that, with the diversification of seismograph networks and equipment and the conversion from photographic recording to digital recording, access to new higher-fidelity data will become difficult and confined to a few people with specialized facilities. A move in this direction would be devastating for seismology since it would dry up interest in the smaller research centers and remove the possibility for ready data exchange that has been a foundation stone of the science since its inception. Our desire is to see earthquake data not just being collected but, rather, used as widely as possible.

The five goals defined above have been addressed much more extensively in recent years in companion reports of the National Academy of Sciences (Committee on Seismology, 1977; Panel on Seismograph Networks, 1977) and elsewhere. In some ways, our recommendations go beyond the charge given to the Panel (Appendix A) in that we found it impossible to concentrate only on the future developments of seismograph networks. We found that the number and type

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uch depend on the overall philosophy that is
seismological research in the United States
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concluded that piecemeal measures are not
, and there is clearly a need for the estab-
an overall flexible plan of development through
al resources can be channeled to achieve the
goals for earthquake study. In short, we con-
the overall goals can be crucially assisted by
ent of a United States Seismograph System (USSS)
re seismological community, both national and
, which makes use of the best equipment and
thods now available in the United States.
this USSS concept voluntarily by all inter-
ogists and agencies in the United States
not only a fruitful research environment but
ensure continued financial support for earth-
. To do less would be to deter seismological
applications for many years and to invite a
in the level of work now being performed.

3 BENEFITS FROM ENHANCED MONITORING AND RESEARCH ON EARTHQUAKES

3.1 REDUCTION OF SOCIAL AND ECONOMIC DAMAGE FROM EARTHQUAKE OCCURRENCE IN THE UNITED STATES

In historical times, many regions of the United States have been hit by earthquakes. In particular, Alaska, California, Hawaii, Idaho, Illinois, Kansas, Missouri, Montana, Nevada, New Mexico, New York, Ohio, Oklahoma, South Carolina, Utah, Washington, and parts of New England are subject to sizable earthquakes. The Pacific Coast, including Alaska, is the most seismically active section in North America. The Aleutian Islands and south Alaska have many earthquakes; specially notable was the 1964 Good Friday earthquake, which did serious damage over more than 20,000 square kilometers, killed 131 people, and caused $300 million worth of damage in Alaska. Industry was dislocated with widespread destruction of harbors, bridges, railway tracks, highways, power facilities, and other structures.

It generated a tsunami (seismic sea wave), which caused 122 fatalities in Alaska, California, and Oregon and did $100 million damage in Alaska, Hawaii, California, Oregon, and Canada.

On the West Coast, although Washington State has suffered from damaging earthquakes during its short period of modern settlement it is California that has historically had the greatest earthquakes. An outstanding earthquake occurred near Point Concepcion in southern California in 1812, and in 1836 and 1838 large earthquakes were centered near San Francisco. Then in 1857 a large earthquake struck central California near Fort Tejon, with surface rupture of the San Andreas fault. In 1872, perhaps the most severe California earthquake of the recorded era occurred in Owens Valley, with extensive fault rupture along 150 km of the valley floor. At least 25 persons died, and shaking was felt east as far as Salt Lake City. In this century, the 1906 San Francisco earthquake dominates the seismic risk concerns of California. This tragic event killed about 700 persons and caused great destruction in San Francisco, Santa Rosa, and other towns along the ruptured San Andreas fault in northern California. Since that time, 8 damaging earthquakes have occurred in the state, with significant loss of life and property and injuries; many others have caused economic loss and public concern. The most destructive recent California earthquake was that in 1971 in the San Fernando Valley near Los Angeles with $500 million direct physical loss, 65 persons killed, and more than 1000 persons injured. Notable moderate earthquakes occurred more recently in the Imperial Valley with an estimated damage of $15 million (Newsletter, Earthquake Engineering Research Institute, November 1979) and in the Livermore Valley with an estimated damage of $12 million (California Geology, April 1980).

The western states of Montana, Nevada, and Utah have also been the sites of energetic earthquakes (see Frontispiece) in historical times, although because of the early sparse populations the economic effects were then small.

East of the Rocky Mountains, the most seismic zone runs from southern Missouri southward along the Mississippi River. In the fall and winter of 1811-1812, three principal earthquakes and numerous aftershocks occurred near the town of New Madrid. These earthquakes were notable for the extended distances where they were felt, with chimneys down in Cincinnati and Richmond and reports of being felt as far away as Washington, D.C., and New England. Many earthquakes have shaken the New England states during their relatively long period of settlement. Particularly violent shaking has been felt in the neighborhood of the St. Lawrence River. A 1663 report is of a large earthquake centered near or in the valley of the St. Lawrence River with damage in Canada and south of Massachusetts Bay. A more recent damaging earthquake occurred near the Grand Banks off the coast of Newfoundland in 1929 with persons killed because of a seismic sea wave (tsunami). Further south along the Atlantic Coast, an earthquake occurred in 1886 to the west of Charleston, South Carolina, the geological cause of which remains controversial. It did significant damage to parts of that city of 55,000, and about 50 persons were killed. Outside the contiguous United States and Alaska, earthquakes have also caused casualties and significant damage in the Hawaiian Islands, Puerto Rico, and American Samoa, and they present an ever-present hazard to the populace.

As well as the historical record, knowledge of earthquake occurrence depends mainly on the more recent instrumental records from seismograph stations. For over 70 years, such stations have kept track of earthquakes, both great and small, in at least some parts of North America. It is clear that in order to make predictions on future seismic risk with any confidence, the active zones in the Earth's crust must be mapped by a variety of geophysical, geological, and geodetic methods, especially the use of local networks of seismographs. The distribution of stations and their sensitivity, however, have been such that the resulting earthquake catalogs of location and magnitudes do not yield uniform statistics in either geographical region or in time and therefore provide an uneven basis for reliable statistical treatment of earthquake frequency. Indeed, it has often been demonstrated that more intensive surveillance by sensitive seismographs in areas previously monitored only by distant stations detects appreciably more earthquakes than before.

Experience has shown that anything but a stable and continuous data base of the locations and sizes of earthquakes greatly weakens the value of the observations. The value not only involves earthquake-hazard evaluation, land use, and emergency planning but also the observational basis needed for research. Such research does not proceed only as current earthquakes occur, but new theoretical techniques and algorithms can be applied to past earthquakes if the recording is of sufficient quality. An important example of the need for a uniform earthquake catalog comes from studies that attempt to *predict* the time and place of significant earthquakes using the time sequence of past earthquakes in a region. Unfortunately, in few parts of the United States are earthquake catalogs sufficiently complete and uniform to permit the application of robust prediction schemes and their checking against past occurrences. Current ideas regarding the state of preparation for large earthquakes in the Earth's crust suggest that significant stress variations may occur along a fault zone, and the comparatively rapid time variations of stress at localized zones may precede the main rupture. Such stress variations should be observable in the signatures of earthquakes occurring in the high-stress zones provided high-quality recordings are available for analysis. Thus, data from the upgraded stations of the United States Seismograph System (USSS) will play an important role in evaluating various techniques and models for earthquake prediction, a high national priority.

Some problems on local tectonics and hazard evaluation can, of course, be treated from data gathered by regional networks of seismographs, although even here modern demands for more detail [often related to siting, for example, large dams and nuclear reactors (see Section 3.3)] on recorded earthquake mechanisms and wave propagation require greater resolution than usually available. The primary difficulties are the present lack of recording uniformity of regional networks and their inadequate areal coverage across the United States (see Appendix B).

The Panel is convinced that the establishment of a sparse but optimally located national network of digital seismograph stations (the NDSN) with broadband instruments having a large dynamic range is necessary to provide the coverage of U.S. earthquakes required for risk studies on land and on the continental shelves. The regional networks need to be tied to this network of modern "first-order" observatories to achieve a monitoring threshold of earthquakes above magnitude 3.0.

The expanse of Alaska and its continental shelves, coupled with its low population, make an initial detection threshold of earthquakes of magnitude 3.0 or 3.5 an unreasonable goal. The vast natural resources, both renewable and nonrenewable, and the high level of seismic activity over the state (especially along the Aleutians and southern Alaska) require that special attention be paid to instrumentation for this state. An extra effort will eventually have to be made to monitor all significant earthquakes in Alaska if we are to benefit optimally from both its resources and the scientific opportunity afforded by the high level of seismic activity.

3.2 BASIC RESEARCH ON THE STRUCTURE AND DYNAMICS OF THE EARTH, SEISMIC WAVES, EARTHQUAKE MECHANISMS, AND PREDICTION

From their beginnings, U.S. seismological observatories have enabled geophysicists in the United States to make important and incisive contributions to the knowledge of the structure and dynamics of the interior of the Earth. As the sensitivity and resolving power of seismographs at U.S. observatories have improved, along with parallel developments in other countries, one can trace the steps forward in our knowledge of the planet Earth (see, e.g., Figure 3.1).

Several examples of decisive U.S. instrumental contributions can be made. The first was the development by

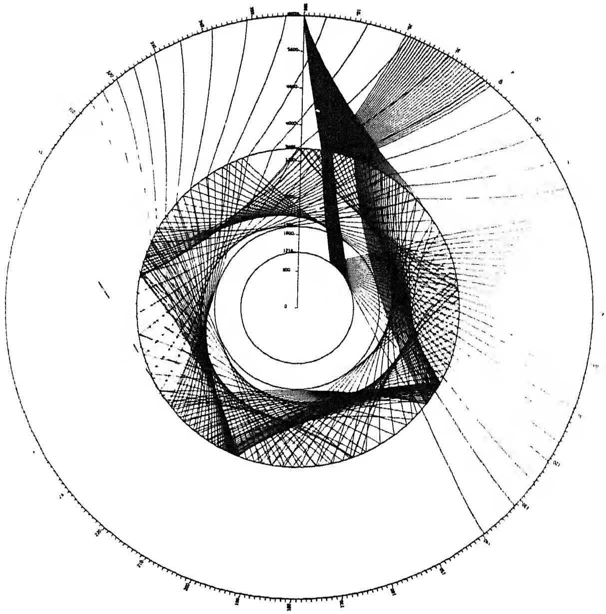

FIGURE 3.1 Paths of seismic waves through the Earth. Boundaries that are shown in the Earth are crust-mantle, mantle-core, outer-inner core, and boundary within the inner core. (Courtesy of Christopher H. Chapman.)

Hugo Benioff at the California Institute of Technology of a sensitive short-period seismograph in the 1930's. This instrument, when placed at worldwide observatories, greatly increased the precision of seismic travel-time tables and thereby allowed much more precise location of earthquake hypocenters around the world. Another advance (see Section 4.1) was the decision to use three-component long-period seismographs of the kind developed by F. Press and M. Ewing at Lamont Geological Observatory in the Worldwide Standardized Seismograph Network (WWSSN). This network, among other things, dramatically improved the knowledge of earthquake mechanism and seismicity patterns around the world and thus contributed in a fundamental way to the theory of global plate tectonics. The third example is the spectral measurements of the free oscillations of the entire Earth, which are instigated by great earthquakes. Measurements and analyses of these oscillations reveal much about the interior properties of the Earth. The first unequivocal spectra were resolved after the 1960 Chilean earthquake, and the majority of these measurements were made on long-period seismographs developed in the United States. Unfortunately, today, only in a few U.S. seismograph stations can one find ultra-long-period seismographs that can record with high fidelity both the spheroidal and torsional modes of the Earth and long-period mantle waves. Fortunately, the *global* distribution of such stations is better with, for example, the digitally recording Seismic Research Observatory (SRO), Abbreviated Seismic Research Observatory (ASRO) [modified High-Gain, Long-Period (HGLP) system], and International Deployment of Accelerographs (IDA) world networks (see Figure 2.1). These networks have, however, at present only four of their stations in the coterminous United States.

We cannot, of course, be content with past accomplishments. Instrumentation is available at reasonable costs, which would raise the resolution of U.S. and overseas earthquakes by an order of magnitude and open doors to new and important lines of research on earthquake-hazard mitigation, source mechanisms, Earth structure, earthquake prediction, the distribution of mineral resources, and related energy matters, such as the study of geothermal regions and sites for nuclear-waste disposal.

What are some of the basic research problems that need enhanced observations for their solutions? An illustration is the study of surface waves from earthquakes in the United States. The broadband characteristics of a modern digital network such as the proposed National Digital Seismograph Network (NDSN) would allow use of wave forms from earthquakes as small as $M_L = 3$ to determine source mechanism, depth, and source spectrum. The current network of stations does not have this capability (see Appendix B). These studies would provide important information regarding regional tectonics, the state of stress in the Earth's crust, and the nature of strong ground motions.

Second, greater resolution could be obtained for studies of the Earth's mantle and core by the use of seismic-wave amplitudes, arrival times, and wave forms from teleseismic events. Recent theoretical progress, particularly with synthetic seismograms, allows seismologists to determine detailed structure within the Earth by measuring changes in wave form across a seismic array of continental dimensions. The NDSN network supplemented by the Canadian and Mexican networks (see Appendixes C and D), would provide key data for such studies; at present, no network of this capability is contemplated elsewhere. There are a number of source areas, such as Novaya Zemlya, Kazakhstan, Mid-American trench, South American trench, the Solomon Islands, and Japan, that are well located relative to the NDSN to provide data at crucial epicentral ranges and depths. Arrival times and amplitudes of both *P* and *S* waves measured by an integrated system of the NDSN and (upgraded) regional networks would also be valuable for the determination of the three-dimensional structure of seismic velocity and attenuation in the crust lithosphere and mantle beneath the United States.

In order to infer detailed upper-mantle structure using seismic surface waves, analysis of overtones as well as fundamental modes is crucial, but such multimode analysis requires a regularly spaced network of three-component broadband seismographs. The measurements that will be provided by the NDSN should resolve these and other outstanding problems, such as the regional variation of the low-velocity zone and the frequency dependence of the attenuation parameter *Q* for both *P* and *S* waves that travel through the Earth. It is hard to see how convincing solutions to such problems can be obtained without high-quality broadband data.

A basic problem in seismology is the parameterization of the earthquake source. The first questions asked about an earthquake concern the origin time and location and depth of the focus. Next, some quantification of earthquake size is required, such as the traditional parameters of earthquake magnitude, duration of shaking, and spectra of various seismic phases. This particular parameterization is essentially the offspring of the limited instrumentation available in the past. Modern advances in pattern recognition of complicated wave forms provide opportunities of much more efficient parameterization of complex earthquake properties. Broadband digital stations, both in the basic NDSN and also in improved regional networks, will permit experimentation with pattern recognition methods in which the whole seismogram rather than small portions of it is used to specify properties of a particular earthquake.

Within the context of advanced scientific research, there is little question that many regional networks will not reach their full potential until they are also converted to digital data acquisition. The Panel foresees that such conversion will make possible a reduction in the number of remote network telemetered stations with perhaps a consequent saving in dollars. Adoption of new technology will make it feasible to obtain earthquake parameters using a few three-component digitally recording stations, rather than a great many stations equipped with limited instrumentation. In the words of the U.S. Geodynamics Committee (1980), "modernization of scientific instrumentation and facilities should be given high priority in planning in geodynamics in the 1980's."

3.3 RISK REDUCTION FOR CRITICAL ENGINEERED STRUCTURES

The growth of population and industrial regions in the United States in the last few decades has increased markedly the risk from earthquakes. This demographic and industrial change has been accompanied by a technological one in which engineers have constructed larger and more complex facilities, such as long bridges, high dams, high-rise buildings, nuclear reactors, and offshore oil-drilling platforms. Structures of this kind involve capital investment, and often many staff personnel and high surrounding population density, so that failure of any one of them could be a major catastrophe (Panel on Earthquake Problems Related to the Siting of Critical Facilities, 1980). Thus, it is accepted that the seismic response of these structures must be examined in great detail. Such analysis must be based on the most reliable seismological estimation of ground motions.

These industrial changes, which are also occurring in other earthquake-prone countries such as Japan, the People's Republic of China, Mexico, and the Soviet Union, have been accompanied in the United States by strict laws requiring environmental impact statements. These statements must take into account the occurrence of earthquakes, tectonic activity, and crustal movements in the vicinity of major structures and urban and industrial development. In response to these demands, many geotechnical companies have grown up in the private sector, each with a staff of scientists, often including seismologists. These professionals have made exhaustive demands on seismicity catalogs and seismograms compiled during the operation of seismograph stations in the United States over the past 80 years. From the catalogs, recurrence relations for earthquakes of various sizes have been calculated; strong-motion accelerograms have been used to determine attenuation of shaking with distance from sources; mechanisms from earthquakes have been worked out and forecasts made concerning the likely amplitude, intensity, and spectral properties of the seismic waves at the developmental sites. Regulatory agencies (such as the Nuclear Regulatory Commission and the California Energy Commission) have been charged with overview of these activities and often carry out their own earthquake-related analysis. Thus, the seismological record, much of it built up when the main interest was purely scientific, has become an essential ingredient in the activities of perhaps tens of thousands of professional people across the United States.

As well, seismologists have been engaged to monitor earthquakes around critical facilities such as large dams (see Figure 3.2) and nuclear reactors. One type of surveillance involves a local network of sensitive seismographs that enables the location of nearby hypocenters and their mapping in relation to geological faults. Another type of monitoring involves strong-motion seismographs installed near the facilities so that checks can be made of the dynamic response of the structures in strong earthquakes.

With this sharply increased demand for seismological information has come a realization that the past unplanned distribution of seismographs around the country has left many gaps and unnecessary uncertainties in the ability to answer seismological questions asked by engineers and city and county planners. The outcome has been uneven, frustrating, and often uninformative responses of risk assessment. Lack of uniformity makes statistical and risk analyses difficult. The cost of evaluations is undoubtedly higher than would be the case if a permanent network of seismographs were operating without the necessity of special installations, staffing, and start-up and close-down agreements.

The National Research Council's Panel on Earthquake Problems Related to the Siting of Critical Facilities (1980) has addressed the question of critical facilities in a special report. This report stresses the risk from earthquakes to many of these structures and the helpful role that seismology can play to reduce the hazard, given adequate observations.

3.4 TSUNAMI WARNING AND SEISMIC-HAZARD REDUCTION ON THE CONTINENTAL SHELF

When large fault motions occur along the floors of the oceans, they produce not only earthquake waves but also energetic water waves that travel across the oceans and run up on the coastlines. Between 500,000 and 1 million residents along the coastlines of Hawaii, California, Oregon, Washington, Alaska, and the U.S. Pacific Territories

FIGURE 3.2 The lower Van Norman Dam, which was severely damaged by the February 9, 1971, San Fernando earthquake. 80,000 people living in the valley below the dam were evacuated because complete failure appeared imminent. (Photograph supplied by Bruce Bolt.)

are endangered by these infrequent but devastating tsunami (see Figure 3.3). For this reason, an international service has been set up in the Pacific called the Pacific Tsunami Warning Center, with headquarters in Hawaii. Seismological information from observatories around the Pacific is sent from the United States, Canada, Japan, the Philippines, and the Soviet Union.

A number of permanent U.S. seismograph stations are involved in this work on a cooperative basis. In Alaska, some 20 stations are monitored by the Tsunami Warning Network centered in Palmer, including stations at Shemya, Adak, Kodiak, and Sitka.

The Tsunami Early Warning System (TEWS) is the only warning service in the world designed specifically to reduce the loss of life and property damage caused by tsunami in participating nations around an oceanic region. Approximately 40 earthquakes per year are reported as being likely to generate tsunami. Without the observations of seismic waves from the participating U.S. seismograph stations, it would be impossible to locate the earthquakes and determine their magnitudes with sufficient accuracy and timeliness to provide prompt and reliable warnings. Many other seismographic stations, although not official participants in the TEWS, transmit their data promptly to the National Earthquake Information Service in Golden, Colorado. This service routinely provides rapid information on major earthquakes worldwide and assists the TEWS in providing a precise determination of the location, depth, and magnitude of the tsunamigenic earthquakes.

Obviously, to reduce loss of life from tsunami, particularly in Alaska, California, and Hawaii, it is important that the TEWS response be as quick as possible and that the information on earthquake parameters such as location, magnitude, and moment be specific. An improvement of the present capabilities can be satisfied by modern recording technology and computer technology and points to real-time telemetry from the proposed NDSN stations in Alaska, Hawaii, and other states along the Pacific Ocean and the Caribbean, and from the recommended seismographs on the ocean bottom (see Recommendations 3 and 4).

Major problems exist in identifying which earthquakes may cause tsunami and, if a tsunami has been generated, in predicting the potential wave height at a distant shore. At present, all large coastal earthquakes are considered as potential tsunami generators, and tsunami watches are issued when such earthquakes are detected. Confirmation that a tsunami has been generated must wait until an actual water

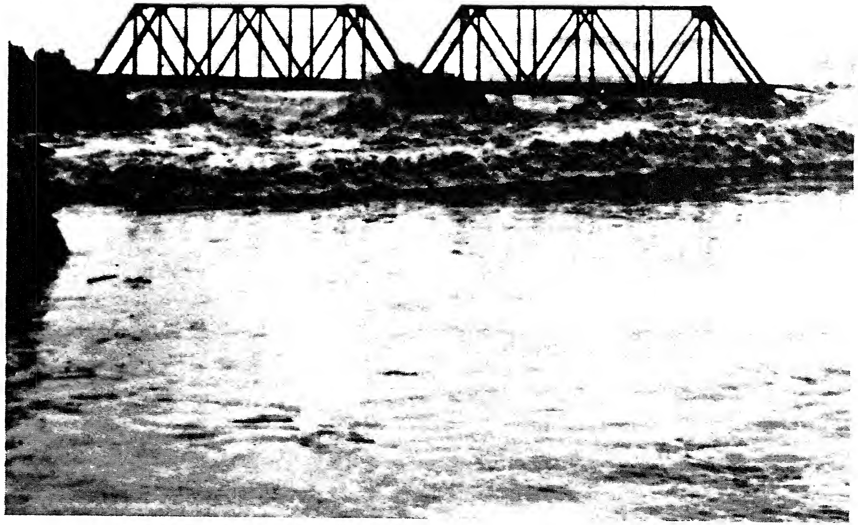

FIGURE 3.3 Tsunami, Hawaii, April 1, 1946. Bore advancing past the railroad bridge at the mouth of the Wailuku River, Hilo. A previous wave had removed one span of the bridge. Note the steep front and the turbulence of the water behind the bore. (Photographer: Shigeru Ushijima.) Reprinted from *Pacific Science* by permission of The University Press of Hawaii (formerly University of Hawaii Press). G. A. Macdonald, F. P. Shepard, and D. C. Cox (1947), "The Tsunami of April 1, 1946, in the Hawaiian Islands," *Pacific Science*, 1(1), plate 8, pp. 21-37.

wave has been observed at the nearest participating tide station. This may delay the issuance of a warning by several critical hours. Once a warning has been issued, emergency procedures are begun that include moving ships clear of the harbors. Since it is not possible to predict the height of the wave and since most tsunamis are small, many precautionary measures are needlessly taken. It is hoped that research using high-quality digital seismic data can lead to the identification of a tsunamigenic earthquake from its seismic signal alone and to yield estimates of the amount of energy transferred to the ocean as a tsunami. If this can be realized, the speed and efficiency of the tsunamic warning system would be greatly improved to the benefit of coastal dwellers and ships at port.

3.5 SURVEILLANCE OF OVERSEAS EARTHQUAKES AND NUCLEAR EXPLOSIONS

Each year there are approximately 10,000 earthquakes above magnitude 4.0 around the globe. The estimated locations and sizes of these earthquakes have provided information of the most profound importance to our knowledge of the dynamics and physical processes in the Earth. Travel times and damping of the waves from globally distributed earthquakes have given geophysicists a simplified x-ray picture of the Earth's interior, and at present the effort is to map anomalous interior zones more precisely.

Each day seismographs at U.S. observatories record many dozens of earthquakes. Some are from local areas, some from other parts of the United States, but most are from overseas. The readings of the seismic phases of these earthquakes are listed and sent by Telex, telephone, or mail to the National Earthquake Information Service (NEIS) of the U.S. Geological Survey. Some readings are also sent to other data centers such as the International Seismological Centre in Newbury, England. Some regional centers in the United States prepare their own lists of provisional locations and magnitudes of some of the major earthquakes. However, the NEIS in Golden routinely calculates and publishes in a relatively short time extensive lists of earthquake locations both in North America and overseas. These are published in standard bulletins, which are disseminated worldwide. The services are inexpensive, and information is freely available to scientists in any country. Each year the NEIS publishes earthquake data reports that include as many as 7000 events. After one or two years, the Catalog of the International Seismological Centre is published, containing over 20,000 events. Many global, national, and regional catalogs are now stored on magnetic tape, and these are available, for example, through the Environmental Data and Information Service (EDIS) of the National Oceanic and Atmospheric Administration, at minimal cost to government and private users throughout the world.

The United States has played and continues to play an important role in the international distribution of such earthquake data. No assessment of the contribution of this work to the standing of the United States in international science has been made, but experience suggests that the scientific posture of the United States internationally is greatly enhanced by this global-earthquake-monitoring activity. There is considerable advantage to U.S. scientists in international data exchange. Much of the research done in seismology requires global coverage, which can only be obtained by exchange. Other countries also make a substantial contribution in operating these stations largely on their own resources. The Panel suggests that this important service should be considered as an essential component of the United States Seismograph System.

The major expansion in seismological activity initiated by the United States in 1959 to solve problems revealed during negotiations for a treaty banning nuclear-weapons testing has already been mentioned in Chapter 2. As a result of the 1959 recommendations of the Berkner panel, the Defense Advanced Research Projects Agency (DARPA) was assigned the mission of devising improved means for seismic discrimination. The ensuing observational and research program, named Vela Uniform, commenced with funds of $7.5 million in fiscal year 1960 and increased to $31 million in fiscal year 1961.

The research program recommended by the Berkner panel for solving problems associated with the detection and identification of nuclear explosions dealt with all aspects of seismology from theory to instrumentation. The Worldwide Seismograph Station Network (WWSSN) was established with standard calibrated seismometers, analog recording, reliable recorders, and accurate timing systems; some 120 stations were operating by 1968. Overall, the Berkner panel believed that the program would "result in dramatic advances in our knowledge of the Earth's interior, of the mechanism of earthquakes, and of elastic wave propagation." In the last two decades this prediction has been strongly confirmed, and, in retrospect, the specially installed global seismographs, then the best available, played a dominant role.

However, in the last decade there has been an instrumental revolution, using digital seismic recording systems. In the oil industry, such technology has proved its versatility and superiority in seismic exploration when associated with computer analyses, and it has already been successfully incorporated into a few earthquake observatories. For example, DARPA has supported the upgrading of a set of about 15 of the old WWSSN stations, all except two at overseas observatories, with digital recording. The digital WWSSN (DWWSSN) stations will have low-gain, intermediate-period recording as well as short- and long-period recording. In addition, a new *global* network of 13 SRO and 7 ASRO stations (see Figure 9 of Peterson and Orsini, 1976) has been installed to supply the high dynamic range of earthquake recording now regarded as essential for discrimination between underground explosions and natural earthquakes.

In the Vela Uniform program, seismic-array technology was also exploited for the first time to better record distant seismic sources. The United States built a number of seismic arrays within its borders and made funding available for the construction of arrays elsewhere. As well as their specific test-ban role, these arrays led to the extension of worldwide seismicity studies to lower magnitudes than in the past, and they led to the discovery of new seismic phases and fine detail of the deep interior. Unfortunately, all such arrays in the United States except the Alaskan Long Period Array (ALPA) have now ceased operating, and their data are not uniformly available (see Section 4.6).

At present, testing continues above and below ground (or is a possibility) in a number of countries (see Figure 3.4). Negotiations, however, for a comprehensive test-ban treaty between the United States, the Soviet Union, and the United Kingdom have progressed to almost a final stage. The parties have agreed on the need for exchange of earthquake parameters and wave forms on a global scale. It is anticipated that this exchange will be achieved by the establishment of international data centers. These centers would rely on special seismograph stations with the most sophisticated recording seismographs (undoubtedly digital broadband systems), which would be located in the Soviet Union, the United States, and elsewhere. According to evidence before the Panel, the interrelation between such international data centers and international networks designed to monitor a comprehensive test ban treaty and the proposed U.S. Seismograph System (USSS) and the National

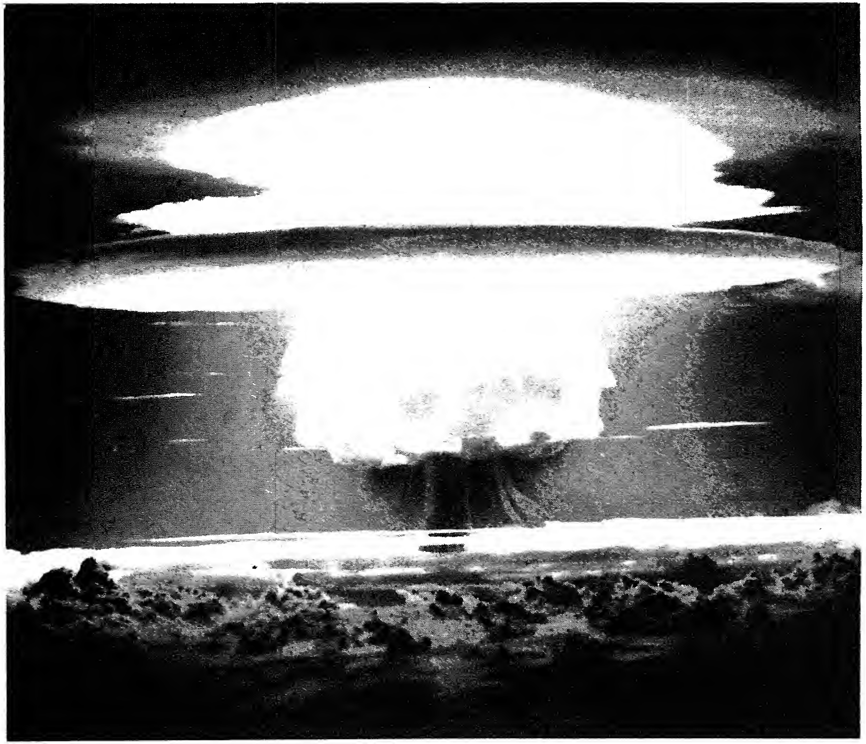

FIGURE 3.4 Thermonuclear weapon test. A thermonuclear detonation in the Pacific Test area on February 28, 1954. (Credit: Lookout Mountain Air Force Station.)

Earthquake Information Service (NEIS) is not yet clear. It is also not clear that such a specially dedicated network could provide the long-term (decades) stability of operation required for studies of earthquake processes. It is likely, however, that any special monitoring network will need backup from national networks, and the confidence in such a treaty would be improved by the existence of an open U.S. network such as the NDSN (see Recommendation 10).

4 STRENGTHENING THE PRESENT U.S. EARTHQUAKE MONITORING SYSTEM

4.1 NATIONAL NETWORK

The prime expectation of the proposed U.S. Seismograph System (USSS) is to provide continuous monitoring of all earthquakes of the United States on the continent and continental shelf down to magnitudes of at least 3.5 and perhaps 3.0. For U.S. earthquakes, monitoring capability must provide for prompt location and determination of their essential parameters (such as magnitude and seismic moment) and the rapid distribution of such information (Recommendation 1). A valuable scientific bonus is that such a system can, if properly designed, provide a continental-size seismic array with high resolution of world seismicity and the interior structure of the Earth. These goals are now only partially achieved through limited but critical coordination with some regional networks by the National Earthquake Information Service (NEIS).

The budgets of both university- and government-supported stations have been subject to significant fluctuation, and in the last few years the number of first-order stations has fallen. For example, many seismograph stations that operated in the early part of the century on a continuous basis have ceased operation (e.g., Marquette, Fordham), and even some Worldwide Standardized Seismograph Network (WWSSN) stations in the United States have been closed for lack of local interest or support (Oxford, Madison, Minneapolis, and Rapid City).

In order to make clear the extent of the observational problem, consider the present telemetered network of seismograph stations in the United States used for rapid location by the NEIS (see Figure 4.1). The map shows that stations are clustered in the more highly seismic regions (e.g., California, Washington, Nevada, and Utah), while,

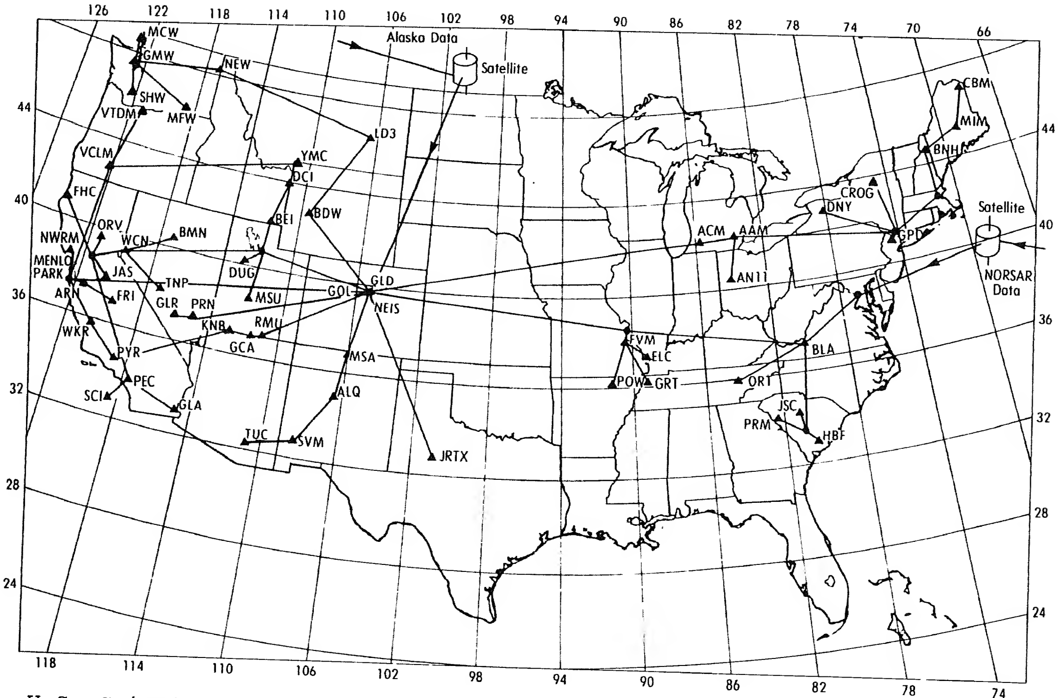

FIGURE 4.1 U.S. Seismic Network, June 1980. The map shows the seismic stations that contrib-
ute data in real time to form the basis of the U.S. Seismic Network. Data are telemetered
continuously from all locations shown and recorded at the National Earthquake Information Ser-
vice office in Golden, Colorado. At present, 65 channels of short-period seismic data and 9
channels of long-period data are being recorded on film and heat-sensitive paper in Golden.

for example, within 350 km of Charleston, South Carolina, the site of the damaging 1886 earthquake, there are only three stations in the link to the NEIS.

Second, it must be stressed that the stations shown in Figure 4.1 are by no means all of the same quality (see Appendix B). The earthquake signals sent to NEIS at Golden by telephone lines are almost all from vertical-component, short-period seismographs. Only a few of the stations shown operate three-component, short-period and long-period instruments, even of the analog type. In the whole contiguous United States there are only about 15 such "first-order" stations, of which 10 are stations of the WWSSN (see Figure 6.1). It is generally agreed that some stations in Figure 4.1 are situated on seismologically noisy areas and have instrumentation that produces indifferent seismograms, so that records are of only limited research use. The overall result is considerable variation in data quality and an unreliable flow of measurements.

On the other hand, some upgrading of a few permanent U.S. seismograph stations with digital equipment has taken place in recent years (see Figure 2.1). There are three stations of the International Deployment of Accelerometer (IDA) network (vertical component only) (Fairbanks, Alaska; Pinon Flat, California; and Ogdensburg, New Jersey), and there are High-Gain Long-Period seismographs (HGLP) at Ogdensburg and a Seismic Research Observaotry (SRO) at Albuquerque, New Mexico (see Figure 4.2). In the 1980-1981 fiscal year, digital broadband seismographs of the Digital Worldwide Standardized Seismograph Network (DWWSSN) type have been funded and installation begun at four sites in the United States by the U.S. Geological Survey. These stations go only a little way toward beginning the proposed National Digital Seismograph Network (NDSN) (see Recommendation 2). Some observatories at universities have also operated broadband equipment for a number of years. For example, in the University of California at Berkeley (UCB) network there has been broadband three-component analog recording on magnetic tape since 1964. Digital broadband recording commenced in 1979 from the Byerly vault. At the same time, single-component broadband analog recorders have operated at the Jamestown station and the Whiskeytown station since 1974 and 1975, respectively. All of these stations are integrated into the UCB regional network and serve not only to monitor large distant earthquakes but also help to determine parameters over a wide frequency range of earthquakes in California.

Finally, if earthquake prediction is to become a national service of practical importance, then the national

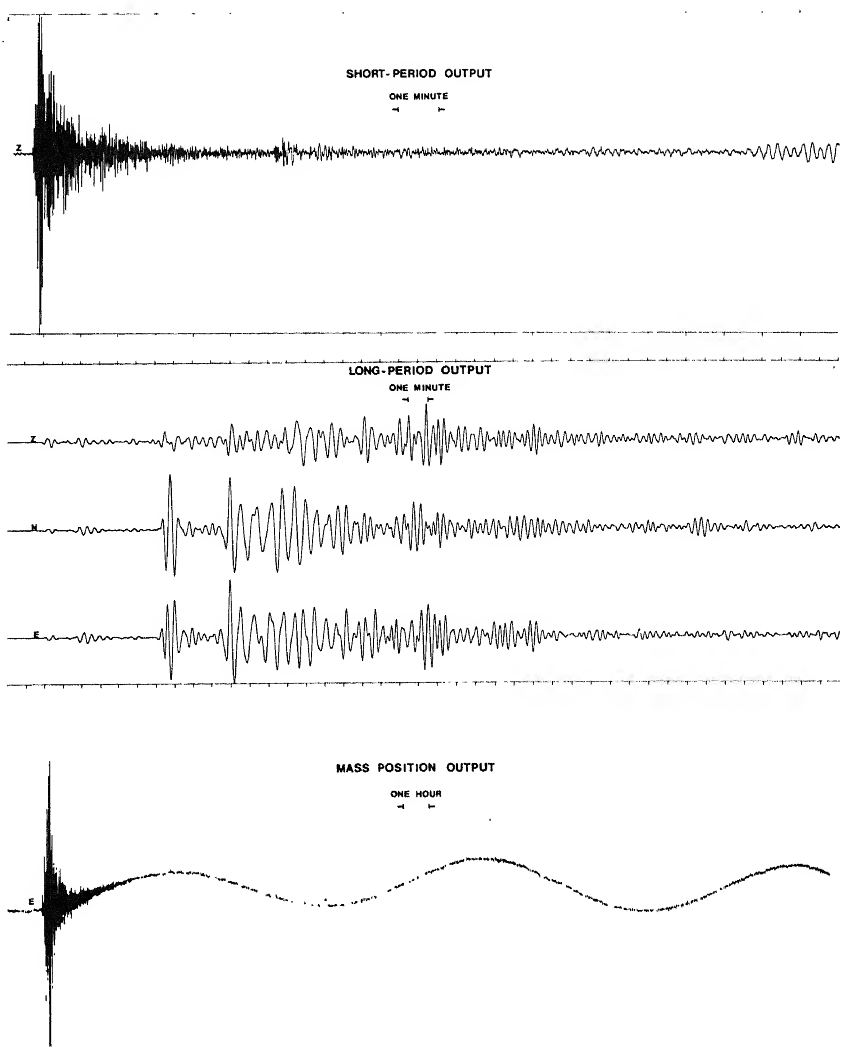

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FIGURE 4.2 Digital plots showing short-, long-, and very-long-period signals recorded on the Albuquerque SRO. The very-long-period signals are not normally recorded at the SRO stations at present. (From J. Peterson, H. M. Butler, L. G. Holcomb, and C. R. Hutt, *Bull. Seismol. Soc. Am. 66*, 2049-2068, 1976.)

seismograph network must be capable of supplying rapid information concerning small variations in earthquake patterns and seismic-wave properties. It is unlikely that special networks for earthquake prediction can ever be placed in all areas of the country where damaging earthquakes are likely. In the long term, therefore, the NDSN and upgraded regional networks of the USSS must be used to monitor the physical fields involved in earthquake prediction. Already, it is known that the sensitivity of present recording on photographic paper or film is not sufficiently precise and does not cover a wide enough frequency band to resolve the variations needed for earthquake prediction. Once again, one is led to the modern technology of digital recording, which provides far greater dynamic range and analysis capabilities in real time.

4.2 REGIONAL NETWORKS AND ARRAYS

At present, regional networks dominate the funding, manpower, and interest (both technical and scientific) in observational seismology in the United States (Appendix B). One of the largest such regional networks is in southern California (see Figure 4.3).

As has been pointed out elsewhere in this report, advances in technology now make it possible to update sharply the quality of data gathered by the regional networks; further, advances in understanding regional seismic processes make it desirable to do so. The Panel believes that the groups operating regional networks are convinced of the need to improve data quality. Advantage should be taken of the resources and interest of these groups by closely involving them in the implementation of the USSS. It is of the utmost importance that regional networks that are responsible for essential earthquake monitoring be sustained at a stable level and be tied, through the USSS, to the NDSN stations. Such a link would allow crucial calibration of earthquake parameters and the long-term variations of seismicity.

Because regional networks, by their nature, vary in number of stations and geographic distribution, it is not possible to recommend specific configurations or locations. (Optimum design theory is now available, however, that permits more-efficient regional network configurations with resultant saving in expense. The Panel suggests that this theory be used more often.) The Panel does recommend, however, that major regional networks be augmented with at

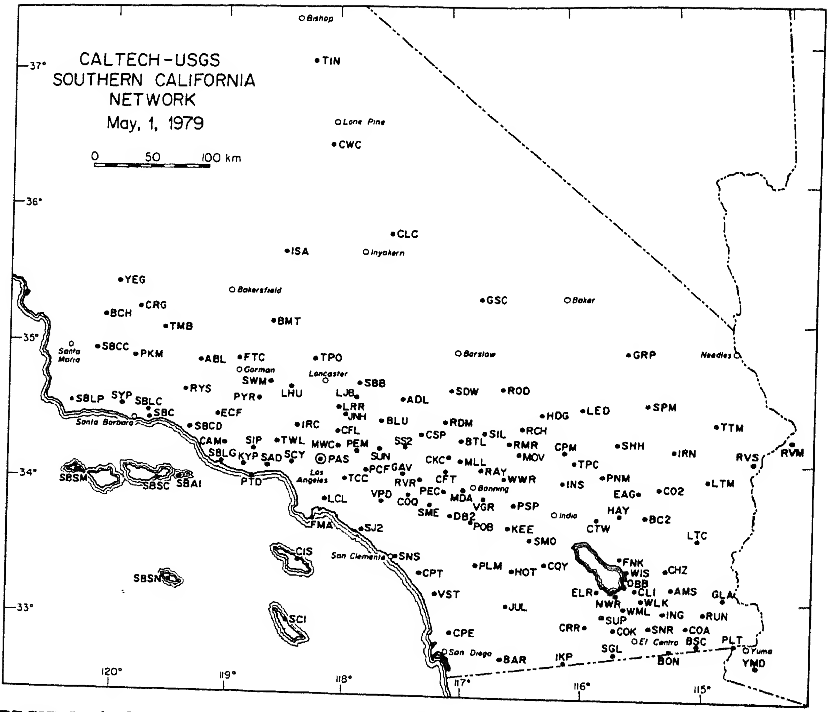

FIGURE 4.3 Stations of the cooperative Caltech-USGS regional network of sensitive seismographs in southern California.

least one of the NDSN stations and that the NDSN station signals be available to the regional network (Recommendation 5).

Additional regional stations might also be upgraded with digital recording. Such upgrading and integration would close the gap between the NDSN and regional observatories and provide a sound starting point for an eventually integrated and optimal USSS.

The emphasis in this report should not give the mistaken impression that seismology can make headway by concentrating solely on earthquakes in or adjacent to the United States. It has always been the case that the study of earthquakes around the world has played an important part in the growth of seismological knowledge. The Panel spent some time reviewing the history of the United States seismic arrays that were specifically designed to give high signal-to-noise ratios for distant earthquakes (see Section 3.5). It has already been mentioned that all such arrays in the contiguous United States have now been closed. In Alaska, a long-period instrument array (ALPA) began recording in October 1970 and continues in operation. It consists of 19 remote sites, each of which has a three-component set of long-period seismometers installed in 15-m boreholes. Data from each site are amplified, digitized at one sample per second, and transmitted to a maintenance center at Pedro Dome. The linear dimension of the array is approximately 75 km, so that it provides a valuable and unique set of long-period records for specialized seismological research (see Recommendation 10).

Many discoveries of the fine structure of the Earth's interior in the last decade have come from the analysis of array recordings of seismic waves from earthquakes and underground nuclear explosions. In particular, important information on the structure of the Earth's core was obtained from the Large-Aperture Seismic Array (LASA) in Montana. Certainly it would be advantageous to seismology to continue to have large permanent arrays of this kind, but, after consideration of advantages and disadvantages, the Panel agreed not to recommend the installation of new arrays at this time. The overwhelming reasons are cost of installation, data transmission, and maintenance. Large arrays such as LASA require dedicated computer facilities and a highly qualified staff for even routine maintenance, signal analysis, and data retrieval. The preferred alternative is the assembling of portable digital seismographs, which would be able to be used as a mobile array for specific research purposes (see Section 4.6).

4.3 LOCAL NETWORKS

There are, at present, on the order of 100 local seismograph networks operating in the United States. In contrast to regional networks, which are operated by government agencies and universities, these networks are often, but not always, operated by private companies. In general, they do not have dimensions greater than several tens of kilometers nor operating lives greater than several years, and their instrumentation is often progressively changed. For these reasons, there is no complete listing of their locations or specifications. Their purposes are mainly aimed at specialized research and monitoring, such as the detection of seismicity associated with reservoirs or microearthquakes near power-generation facilities. Larger local networks are also used to monitor volcanoes and geothermal areas (Figure 4.4).

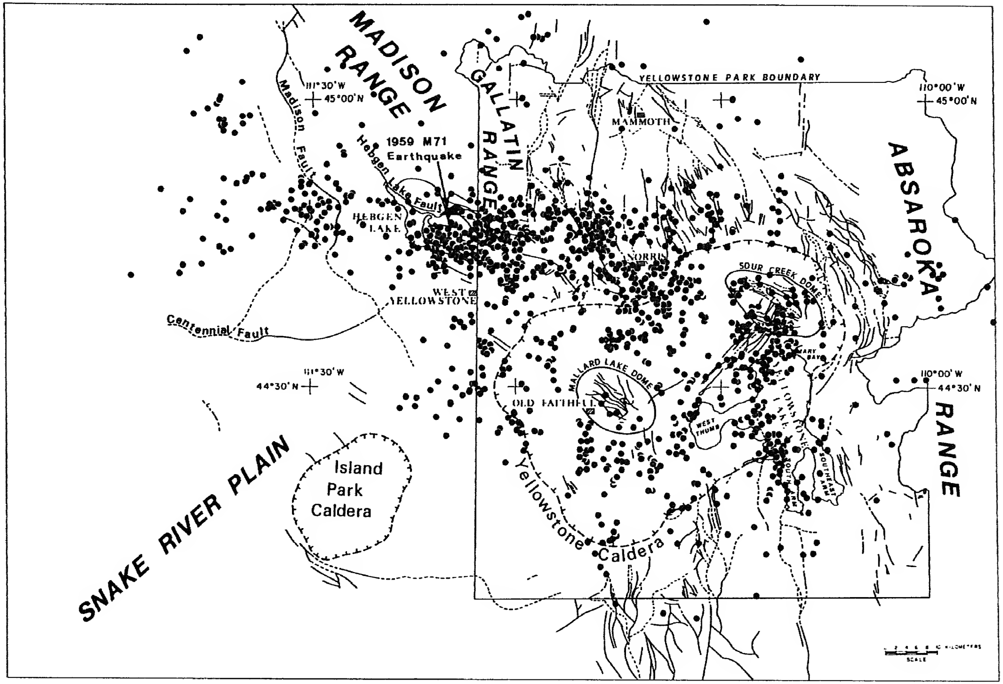

FIGURE 4.4 Map of epicenters (black dots) of more than 1500 earthquakes with magnitudes on the Richter scale of between 1 and 6 comes from measurements made on seismographs of the U.S. Geological Survey and the University of Utah. The peak focal depth was 16 km. (From R. B. Smith and R. L. Christiansen, Yellowstone *Park as a Window on the Earth's Interior, Scientific*

In its consideration of the scope and utility of these networks, the Panel concluded that it was not advantageous to try to standardize them. However, in the broad sense, they are part of the USSS, and efforts should be made by the seismological community to incorporate them more effectively into a nationwide system of earthquake surveillance in the United States. Regional research centers and data-acquisition centers should be encouraged to provide storage for significant recordings from local networks. Once the immediate objectives of the local network have been met, the aim of the regional research centers might be to transfer "high-level" data (such as hypocenter locations) to the national data centers.

Because local networks are operated by diverse groups, there are large differences in instrumentation and reporting procedures. In order to improve the present situation, the U.S. Geological Survey (USGS) should consider providing some guidance on local networks. For example, recommendations of standards for instrumentation, configuration, and operation would be useful (Recommendation 7). Such standards would allow the better attainment of specific goals and integration of recordings into the regional networks and the USSS.

4.4 OCEAN-BOTTOM SEISMOGRAPHS

Many of the earthquakes that are of major interest to society from both a hazard and development point of view occur offshore from the United States and its territories. Moreover, seismic gaps which may be associated with future great earthquakes occur off the Aleutian Islands and the Puerto Rico-Virgin Island areas. To monitor offshore earthquakes adequately with a national network, siesmographs located on the seaward side of the earthquake activity in water covered areas and on the seaward side of the seismic gaps are necessary.

In the past few years, the technology used in building ocean-bottom seismograph (OBS) systems has developed to the point where it is now entirely feasible to consider free-standing OBS units capable of operating "permanently" on the sea bottom. These systems can be powered using energy stored in conventional form on the bottom (batteries), from replaceable surface power packages (including solar panels), or from power drawn from the ocean itself. Amplified sensor outputs can be transmitted by wire or acoustically for reception at the surface. The signals can then be retransmitted for satellite transmission to a land-based recording station, or, alternatively, signals can be stored at the surface for pick up by a service vessel at routine intervals.

As an alternative to free-standing units, the technology to build, deploy, and maintain OBS at distances up to 200 km offshore and bring signals to land via hard wire has existed since the mid-1960's. This was demonstrated by the highly successful installation of an ocean-bottom observatory (OBO) off Port Arena, California, that functioned for more than 5 years, beginning in 1966.

It is difficult to separate national and regional concepts when considering proposed locations for OBS stations. Single stations provide a wealth of data, but in highly active areas as, for example, in the Aleutians and off Northern California, Oregon, and Washington, additional stations are essential to define the seismic source and propagation properties adequately. Since a start must be made, the Panel concluded (Recommendation 4) that at least four OBO should be placed off the contiguous United States as part of the NDSN.

The use of OBS capability in local networks has not been considered here. It is possible that local network requirements for offshore work can be met using "pop-up" OBS systems for the next several years.

One problem lies in those offshore areas of the continental United States that are considered to be of low seismicity, such as off the East Coast. Many of the questions in these areas relating to causal mechanisms of intraplate earthquakes and the long-term seismic risk to offshore engineered structures could be answered if activity were monitored along offshore portions of fracture-zone extensions. Clearly, OBS stations are essential for this purpose. Moreover, the occurrence of a magnitude 6.1 earthquake southwest of Bermuda on March 24, 1978, with several aftershocks of magnitudes 3 and 4, raises vital questions regarding short-term seismic hazard associated with offshore development in broader offshore areas. On the other hand, OBO off the East Coast might operate for years and only record a minimum of seismic activity.

The Panel's conclusion on incorporating OBO into the USSS (Recommendation 4) goes some way to respond to the earlier submission on OBS in Recommendation 4 of the 1977 companion report (Panel on Seismograph Networks, 1977, Recommendation 4) that "A comprehensive effort should be made to determine the feasibility of an extensive, long-term program in ocean-bottom seismology."

4.5 STRONG-MOTION NETWORKS

Progress in predicting strong ground motion and the seismic response of engineering structures critically depends on more measurements of seismic waves near the source of great earthquakes. These needs arise for two main reasons: First, only such basic observations can provide full understanding of the generation of seismic waves from the moving dislocation along the fault and the effect of the intervening geology on the waves. Second, spatio-temporal variations of ground motions are essential for engineering design for large structures.

The basic observational data are obtained by strong-motion accelerometers emplaced in areas that are likely to be strongly shaken. The first network of strong-motion accelerometers was commenced by the United States Coast and Geodetic Survey about 50 years ago. Accelerograms obtained in the Long Beach, California, earthquake of 1933 provided the first quantitative measure of the amplitude and frequency content of strong ground shaking and constitute a milestone in strong-motion seismology and earthquake engineering.

After a slow beginning, there has recently been progress in the extension of the networks for strong-motion accelerometers across the United States. The present status is shown in Figure 4.5. By far the greatest number of instruments are placed in California, where building code provisions require payment of a building fee into a central fund that is used to purchase and install strong-motion accelerographs in buildings and other structures and in the free field away from buildings. As Figure 4.5 shows, the extension of the strong-motion seismograph network in states other than California is still unsatisfactory.

It should be stressed that most stations shown in Figure 4.5 have only a *single* three-component accelerograph. The great majority of these are triggered instruments that remain passive until the onset of an earthquake wave above a certain amplitude threshold. A recording is then made on photographic paper or film. The most recent generation of these field instruments has proven reliable in practice, and successful recordings were made in the Imperial Valley earthquake of October 15, 1979. Strong-motion accelerograms were obtained at 19 stations at distances from within 1 km of the Imperial Fault rupture to 22 km from the fault. Thirteen of these stations formed a linear array that crossed the ruptured fault at right angles. Many of the stations provided radio time signals on the records, so

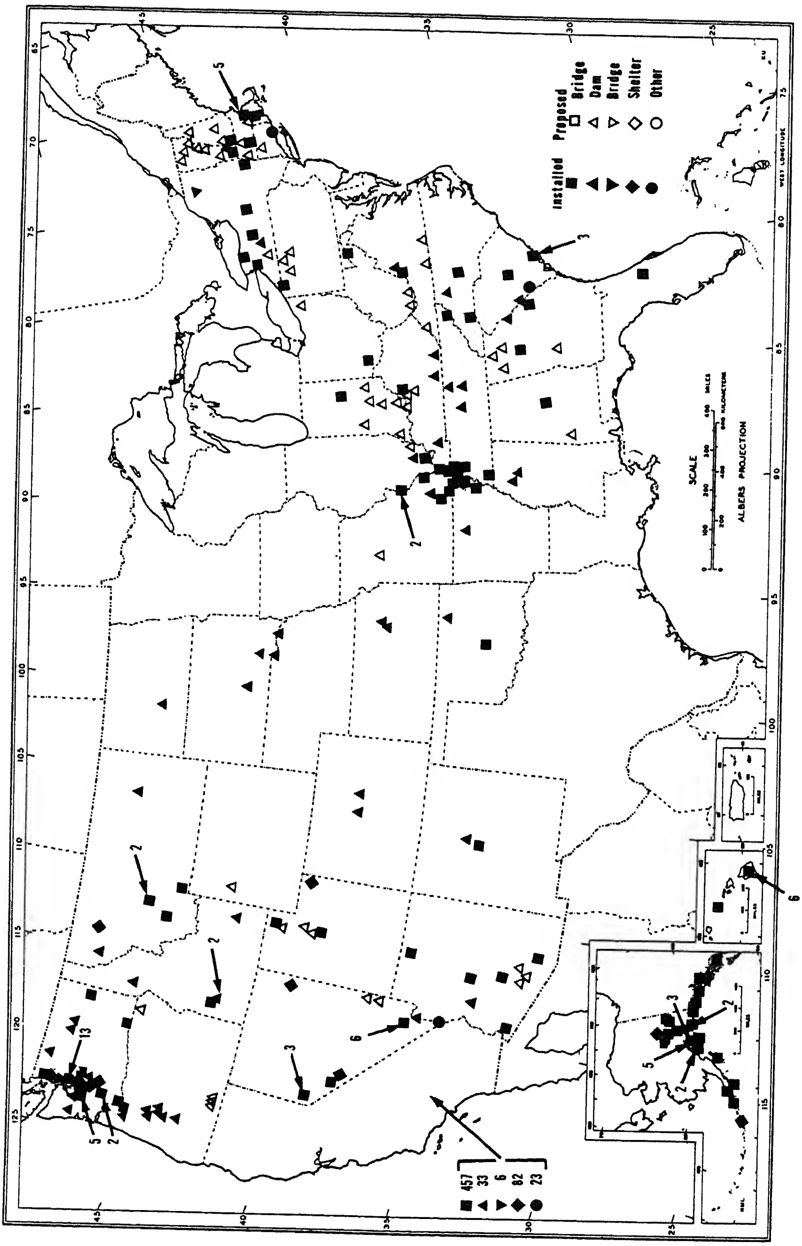

FIGURE 4.5 Strong-motion accelerographs in the United States, 1978.

that this set of accelerographs constitutes the first on-scale accurately timed seismograms from a strong-motion array obtained near a significant earthquake. Analysis of these records will provide information of great importance to earthquake engineers.

The Panel was asked to consider the design of new instruments for strong-motion recording and the incorporation of special low-gain channels in regular seismographic equipment (Appendix A). Because the ramifications of strong-motion networks are great, the Panel considered mainly two aspects of this problem. The first was related to integration of strong-motion recording program with NDSN stations and the second with the data management of strong-motion records.

In the judgment of the Panel, it is important to link strong-motion seismology, a vigorous part of modern seismological activities, intimately with the USSS. In the past, strong-motion recording has been, unfortunately, regarded largely as a separate part of seismology. To a large extent, because of tradition and their direct interest in strong shaking and structural response, the responsibility of strong-motion recording has been carried by the engineering community. At only a few seismograph stations in the country have strong-motion instruments been installed as part of the observational equipment at present.

The Panel proposes that wherever stations of the National Digital Network are located in seismic areas, the instrumental systems should be designed to include strong-motion channels recording from strong-motion accelerometers (Recommendation 13). The recording from these strong-motion channels should be in digital form and should form part of the integrated data-processing facilities of the USSS. These provisions will close the gap between the permanent earthquake observatories with their standard sensitive recording devices and free-field strong-motion accelerometers. The timing of Recommendation 13 is propitious, because new types of strong-motion accelerometers with digital recording and prememories are now commercially available and being installed in the field. Thus, the inclusive design of NDSN stations will provide an integrated link with the network of strong-motion accelerometers that has begun in the country.

4.6 PORTABLE RESEARCH ARRAY

The Panel wishes to argue strongly for the provision in USSS of a set of portable digital recording seismographs that would constitute a flexible research array for planned regional or local studies (Recommendation 14). The benefits of portable instruments in addition to networks of permanent stations have already been stressed in the report *Global Earthquake Monitoring* (Panel on Seismograph Networks, 1977). That report recommends, "that portable broadband, digital instruments be obtained for a variety of fundamental investigations for which high-density instrumental coverage is necessary for a limited time." From the point of view of *global* earthquake monitoring, the portable instruments would be brought together for special studies overseas. There is, of course, no reason why such an array of portable instruments could not also be installed *within* the boundaries of the United States.

The Panel looked into the history and present status of seismic arrays in the United States and concluded that, given their cost, an extended modern seismic array of the dimensions of ALPA or LASA would be too expensive to recommend as a permanent part of the USSS. It appeared to the Panel that a more cost-effective procedure would be to use standardized portable broadband digital instruments as a special configuration for a specific project. In this light, we see a portable research array providing an important spatial enhancement to the national digital seismograph network.

It should also be noted that many available digital seismographs can be attached either to sensitive seismometers or force-balance accelerometers. In the latter mode, the instruments would make up a mobile, strong-motion array for the recording of strong motions near the source of a great earthquake. Recently, a resolution was approved unanimously by delegates to the International Workshop on Strong-Motion Instrument Arrays in May 1978 (Iwan, 1978). The resolution stated, "A mobile strong-motion instrument array capable of making source mechanism, wave propagation and local effects measurements be established and maintained for deployment immediately following the occurrence of a major earthquake for the recording of aftershocks." Such a strong-motion array could well be fashioned from a dual-purpose system of portable instruments.

The Panel recommends that the instrumentation of the portable research array should consist of approximately 16 units and that it should complement the instrumentation of the NDSN and be adaptable for studies such as high-resolution surface-wave analysis, attenuation measurements, and the resolution of crustal heterogeneities. A consortium for funding, managing, and establishing research goals for the portable research array should be established.

4.7 DATA MANAGEMENT

At present, few seismograms generated by local, regional, or national U.S. networks are archived by the Environmental Data and Information Service (EDIS) of NOAA. Only the original seismograms from the station operated by the Coast and Geodetic Survey through 1972 are archived by EDIS. The others are kept by the USGS and by universities. Copies of seismograms from some other U.S. stations are available as part of the Worldwide Standardized Seismograph Network (WWSSN), International Deployment of Accelerographs (IDA), International Data Exchange (IDE), and Seismic Research Observatory (SRO) international networks. Epicenter data from Berkeley, Cal Tech, the Hawaii Volcano Observatory (HVO), the USGS, Menlo Park, New England, Lamont, Alaskan Geophysical Institute, and Outer Continental Shelf Environmental Assessment Program (OCSEAP) networks are available as part of the Earthquake Data File and are reasonably current. Phase data are available for few networks publishing bulletins.

There is a marked growth of interest in seismology related to local and regional questions such as prediction, site evaluation, and local and regional tectonics. The EDIS services have been geared in the past to serve primarily the need for global data from relatively permanent observatories. While the need for these data will continue, an effective apparatus must be constructed to deal with domestic data.

A prime EDIS task is to provide data gathered at observatories to other and future users in raw or processed form. Because it takes resources to access and store data, an important consideration is the *likelihood* that the data will be wanted by others now or in the future. It is not clear what types of observations or data products may be wanted from local and regional networks because the expansion of these networks is relatively new. Local networks tend to be temporary and are designed to answer specific questions, but in total the volume of their data is substantial and the formats diverse. On the other hand, data from the NDSN may be useful in the long run to a larger number of users of whom many will be concerned with fundamental problems. A careful trade-off of resources must be worked out.

The acquisition and archiving of data require immediate resources. Because the majority of users are in the future, the practice has been to attempt to have the data collector pay for the cost of getting the data into the archive. This involves the cost of reformatting, inventorying, purchase of storage equipment, and other operations. Users are normally asked to pay only the extra costs associated with retrieval and copying. All of these dilemmas and alternative procedures must be reworked by the EDIS in the context of the USSS. It seems clear, however, that additional funds will be needed (Recommendation 8).

5 DESIGN OF A NEW NATIONAL SYSTEM FOR STUDYING EARTHQUAKES

5.1 MODEL FOR THE UNITED STATES SEISMOGRAPH SYSTEM (USSS)

With expanding population, changing life-styles, construction of critical facilities, and the need for resources required to support a healthy nation, the United States needs to know more about how earthquakes affect all aspects of our society. As we have argued already, seismology is now at a point where improved measurements of earthquakes are crucial and could be quickly assimilated into both theory and application. At the same time, technology can supply superior seismograph equipment at reasonable cost.

The Panel, therefore, concludes that there is both an urgent need and a splendid opportunity in the United States to improve monitoring, research, and information flow on earthquakes. The central recommendation (Recommendation 1) is to establish as rapidly as possible an integrated earthquake observatory and data-handling system for the whole country with a new digital seismograph network as the core. The traditional freedom of choice and independence and flexibility among scientists in the United States has naturally led to a rather complex system of seismograph instruments and stations. The question is how to take the best of what is now available and model a superior system that opens new vistas for the 1980's by using the technological improvements of the last decade. The restructuring of the present system must be done without causing dislocations in the crucial continuity of recording of earthquakes and associated research and yet provide funds to support a new nationwide system. Clearly, we must have the thoroughgoing cooperation of all operators of seismograph stations and the seismological research community, as well as the myriad of users of earthquake data at all levels across the country.

The Panel believes that a vigorous step forward would be the adoption by funding agencies and the seismological community of the concept of a United States Seismograph System (USSS). The system would endeavor to integrate all aspects of observational seismology, ranging from the long-established permanent observatories (Appendix B), through the important regional networks, to the portable arrays and specialized recording systems for particular research projects. Because the system must now accommodate a greater diversity of recording modes than in the past, the instrumentation and recording must be balanced by an equal emphasis on the way that the mass of seismological data is stored, processed, and analyzed. Because processing and analysis of the data produce a large amount of reduced data and preliminary results, it is of equal importance to include in the structure of the national system a well-constructed method of short- and long-term storage, data retrieval, data presentation, and cataloging.

The Panel envisages development of the USSS along the following lines. First, there would be a general discussion of and, it is hoped, adherence to the concept within all parts of the seismological community. The Committee on Seismology of the National Research Council would take a lead in informing seismologists and agencies of this concept. The various funding agencies would be asked to consider national support of seismology in the light of an overall USSS structure. The scheme should prove attractive, because, not only does it give a direction, albeit flexible, but it should conserve financial resources and prevent unnecessary redundancy in capital expenditures. Second, various key agencies, such as those mentioned in Chapter 9, would commence to work toward the recommended goals laid out in Chapters 1 and 2 of this report. Thus, a working group on the USSS would be set up (Recommendation 6) and would help to stimulate the program by scheduling a series of workshops. Details of instrumentation for the National Digital Seismograph Network (NDSN) (see Section 5.2) would be decided (Recommendations 4 and 11) and the U.S. Geological Survey (USGS) through the Branch of Global Seismology (with intended responsibility for both national and global matters) would begin to develop resources and procedures at the national level for the integration and overview of the USSS (Recommendation 7).

The program of installation under the general direction of the USGS of NDSN stations would commence with the aim to complete the minimum network of 36 stations within the next 4 years. At least one of these stations might be established within each of the major regional networks and at Golden and Albuquerque. To speed the process of implementation, it would be possible in a number of cases to use existing Worldwide Standardized Seismograph Network (WWSSN) sites and to begin with existing components (seismometers and amplifiers, for example), first adding digital data transmission and recording and later upgrading to newer equipment. Next, NDSN stations would be established at other sites to provide the more optimum coverage discussed in this report (see Figure 1.1). These may be additional stations within the larger regional networks or at more remote sites where regional networks do not exist. Later, selected stations of the regional networks themselves might be upgraded to "first-order" regional stations (i.e., the addition of broadband recording with three components). All developments of this kind would be regarded as part of the USSS. By these methods, the upgraded program should capture the interest of both USGS and regional network operators and forge links between studies of regional seismicity and studies of teleseisms. It should also demonstrate the scope of high-quality broadband data and provide a rapid and efficient means for moving ahead with the upgraded national network of earthquake observatories.

At the same time, as the installation of equipment at NDSN stations begins, through additional funding and program restructuring, the USGS would incorporate the new measurements into the digital data processing and national earthquake monitoring that they now perform in the Branch of Global Seismology using mainly analog signals from a restricted network of stations (see Figure 4.1).

5.2 ESTABLISHMENT OF A NATIONAL DIGITAL SEISMOGRAPH NETWORK (NDSN)

The backbone of observational seismology in the United States in the next decade should be a small nationwide network of broadband three-component seismographs, established to provide optimum spatial coverage of earthquakes in the United States and its continental shelves. The data should be recorded and transmitted digitally in order to preserve the wide dynamic range. The necessity for such a network has already been pointed out in Chapters 3 and 4. The Panel recommends that this network be called the National Digital Seismograph Network (NDSN) and that in the next four years a minimum of 36 such stations be established in the United States. There would be 29 in the contiguous United States, 5 in Alaska, 1 in Hawaii, and 1 in Puerto Rico. Extensive modeling has indicated that this is about the minimum number that is needed to give uniform coverage of earthquakes across the country (see Figure 1.1).

The advantages of an NDSN can be characterized by standardization, uninterrupted long-term operation, wide dynamic range in amplitude and frequency, and inherent flexibility of recording and analysis. According to calculations of sensitivity of the threshold of detection of earthquakes, carried out for trial configurations of station locations across the United States, the recommended minimum number of stations would provide coverage of location and recorded waveforms down to about magnitude 3.0 for a large part of the United States and about magnitude 3.25 in the western states.

This network of stations is not technically unrealistic nor financially extravagant. Indeed, stations of this kind have now been established in a number of countries around the world, some with the support of the United States but others as a natural consequence of technological developments in countries such as Japan and West Germany. Based on estimates made available to the Panel by the Albuquerque Seismological Laboratory, where prototype digital instrumentation is being developed, the total installation, maintenance, and data-handling costs for the NDSN for the next 4 years would reach some $15 million. This cost is not an unreasonable one for the establishment of a major national scientific resource (see Recommendation 2 and Section 9.4).

As outlined in Section 5.1, the NDSN would be an essential part of the USSS. Many of the stations would be not only a part of an integrated national system supplying information directly to the National Earthquake Information Service, for example, but also a part of the regional seismograph network in which it was geographically located. The Panel predicates the establishment of the NDSN on the premise that it will be funded and operated independently but in close coordination with existing seismograph networks. In this way not inconsiderable funds may well be found by a reassessment of recording practices at many existing observatories. The NDSN installation, maintenance, recording, and data distribution should be under a single management group. The Panel recommends that this group be within the USGS. We have not considered in detail the necessary intercommunication links between NDSN stations, regional research centers, and the national centers at the USGS and other groups that are interested in securing data. It is clear, however, that a critical portion of the digital seismic signals should be transmitted to central laboratories via telephone, so that rapid access, using microprocessors or other computing facilities, can be obtained. Figure 5.1 shows the transmission of seismic data between Palmer, Alaska, and Golden, Colorado, via geostationary communication satellites.

The distribution of NDSN stations in Alaska presents a special problem. The rapidity of the development of certain areas of Alaska, such as the oil fields of the North Slope, the TransAlaska Pipeline, and terminal facilities in the Gulf of Alaska, clearly indicates the importance of improving the present earthquake-monitoring system. In the next few years, proposals should be adopted for an upgraded Alaska regional network that would be compatible with the NDSN and the Canadian observatories (see Appendix C). In Figure 5.2, a summary is given of the current seismograph network in Alaska as well as an extension of this network proposed by participants of a workshop on Alaskan seismology. This number coincides with the recommendation of the Panel for 5 NDSN stations in Alaska as a start.

5.3 REGIONAL RESEARCH CENTERS

There are at present about 15 major regional networks of seismograph stations in the United States (see Appendix B). These provide rapid determinations of earthquake locations and sizes down to quite small magnitudes. The major networks are associated with a central research facility, usually a university seismology research unit. The oldest of these regional centers are the seismographic stations at the University of California at Berkeley, which has been responsible for earthquake recording in northern California since the early part of the twentieth century, and the Seismological Laboratory at the California Institute of Technology, which has been similarly responsible for recording earthquakes in southern California.

The Panel has urged in this report that fruitful regional networks be adequately sustained and that the projected NDSN be incorporated within the regional networks wherever possible. The implementation plan for an integrated national seismograph system envisages the establishment of at least one NDSN station within each of the major networks and at Golden and Albuquerque. This step would provide an initial core of about 15 NDSN stations, each of which is integrated within a regional network. The plan also makes possible the use of a number of WWSSN sites and facilities. Such

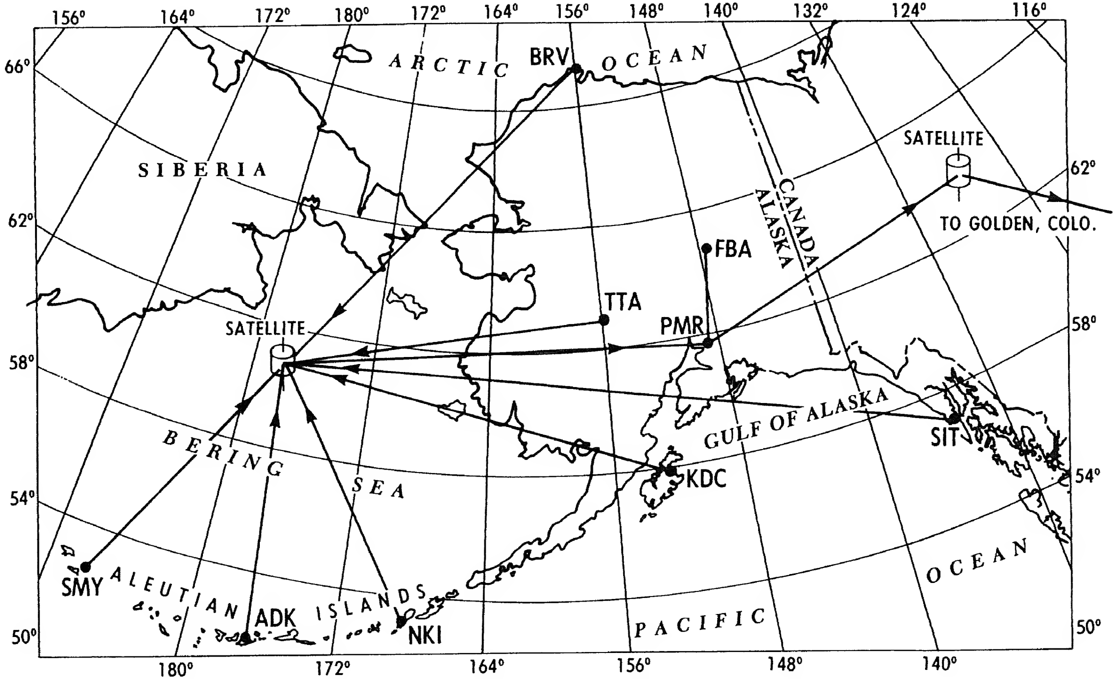

FIGURE 5.1 Alaska stations, U.S. seismic network, June 1980, as part of a seismic data-exchange agreement between the Alaska Tsunami Warning Center, Palmer, Alaska, and the National Earthquake Information Service, Golden, Colorado, in real time via geostationary communication satellites. Digital data are relayed by satellites via Palmer, Alaska, to Golden, Colorado. *Note*: Satellites are geostationary and located over equator.

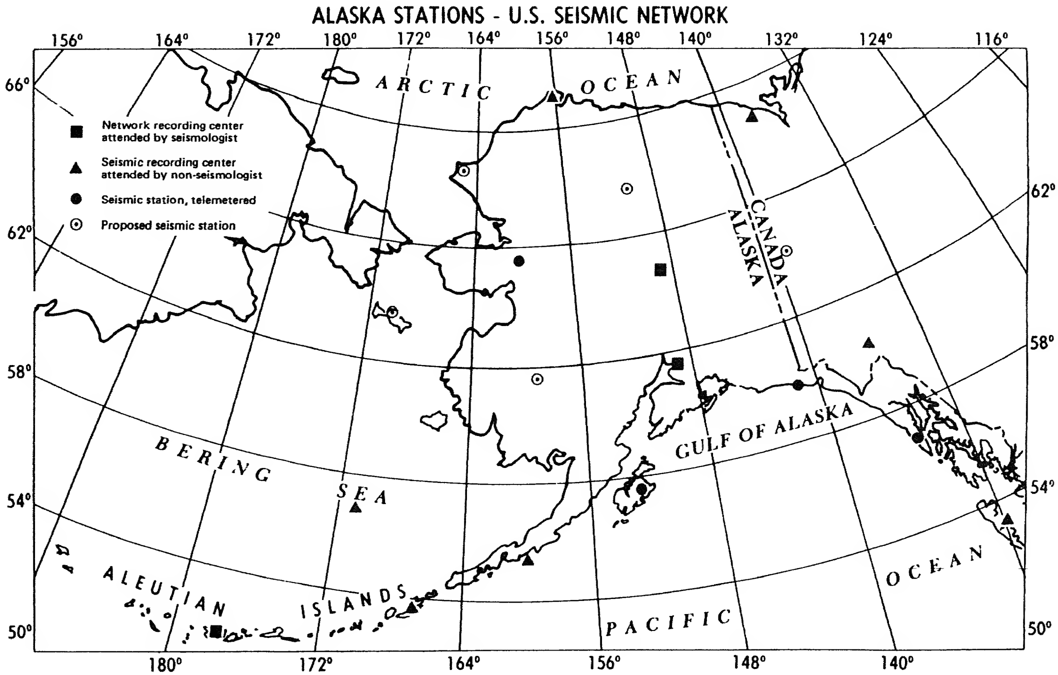

FIGURE 5.2 Possible Alaska network. Current status of existing stations and proposed additions. A workshop of Alaskan seismology proposed this general configuration as a goal for first-order stations for Alaska. Note that it includes one new and four existing Canadian stations. (For more details contact John N. Davies, co-chairman of the workshop, at Lamont-Doherty Geological Observatory, Palisades, New York.)

usage has not only considerable practical advantage but allows uninterrupted recording of earthquakes at the same locations. It is highly likely that within some of the regional networks there will be a parallel upgrading of key regional stations with modern digital equipment of the broadband three-component type. The end result should be upgraded regional networks with both digital and analog data being recorded at a central observatory. This central facility is generally the hub of seismological research. The Panel wishes to take advantage of the resources and research interests of these seismological centers and involve them explicitly and closely in the development of the USSS. Thus, the Panel recommends (Recommendation 9) that a certain number of the seismological research centers designate part of their facilities under voluntary and cooperative arrangements to be part of the USSS. Such centers would be called Regional Research Centers.

Regional Research Centers would be not only local repositories of regional earthquake observations, but they would provide a way to allow seismologists to take full advantage of the new digital data (see Section 6.2). Indeed, it seems likely that the success of an upgraded observatory system for earthquakes in the United States depends considerably on the willingness of regional seismological research centers, particularly those committed to independent research, at universities to participate in the USSS so that the burden of the earthquake monitoring and data analysis is not too great for any single government institution to handle effectively.

The concept of Regional Research Centers, as discussed here, is in line with the evolution of seismographic research in the United States in the last few years. Already, for example, specially dedicated minicomputer systems have been installed at a number of major seismological research centers. In 1972, funds were provided by the National Science Foundation for an interactive seismographic data acquisition system based on a Modular Computer Systems (MODCOMP) computer at the seismographic stations at the University of California at Berkeley. In 1976, funds were made available by the USGS for computer installations for on-line processing of data (see Appendix F) at the University of Washington, University of Utah, St. Louis University, Cooperative Institute for Research in Environmental Sciences (CIRES) in Boulder, California Institute of Technology, and Lamont-Doherty Geological Observatory. All of these centers would be likely candidates for Regional Research Centers.

The details of this program of Regional Research Centers need to be worked out over the next few years during the establishment of the NDSN. For this reason, the Panel suggests that the working group on the USSS (Recommendation 6) take up with the directors of the various seismological research centers the proposals put forward here and in *Global Earthquake Monitoring* (Panel on Seismograph Networks, 1977). It would appear advisable for the USGS to hold a special meeting with the directors of possible earthquake research centers to discuss the ramifications of this proposal within the next year or so.

The Panel realizes that there would be a need for additional specific funds in the various seismological support budgets of the federal and state agencies, as well as further industry and private support, to cover the additional work and responsibilities undertaken by the Regional Research Centers.

5.4 COOPERATION WITH CANADIAN AND MEXICAN SEISMOGRAPH NETWORKS

Earthquake waves know no national boundaries, and the knowledge that flows from seismological research is universally applicable. For these reasons, in North America, close ties have grown between seismologists in Canada, Mexico, and the United States. Exchange of seismograms and earthquake data of all kinds is common. Tragic earthquakes have occurred and will again along the common boundaries that require mutual study and assistance. We hardly need to be reminded of the large earthquakes along the St. Lawrence River, in the Puget Sound-Vancouver Island region, and, to the south, the destructive earthquakes in 1940 and 1979 in the Imperial Valley (see Figure 5.3).

The Panel was fortunate enough to have presentations on plans for the development of the Canadian networks by Kenneth Whitham, Director General of the Earth Physics Branch of the Canadian Department of Energy and Mine Resources, Ottawa (see Appendix C). A similar helpful presentation on the status of seismograph stations in Mexico was made to the Panel by Jorge Prince, Sub-Director of the Instituto de Ingenieria, Universitaria Nacional, Mexico (Appendix D). As these presentations confirmed, there seems no reason why the modernization and integration of the U.S. seismograph network through the USSS and NDSN programs cannot be carried out in close cooperation with our geographical neighbors.

FIGURE 5.3 Collapsed masonry wall on a theater on Main Street in Brawley, California, from the October 15, 1979, Imperial Valley earthquake. (Photo by R. A. Hansen, Seismograph Station, University of California at Berkeley.)

The establishment of cooperative programs in seismology and close discussions on the installation of compatible high-quality digital instrumentation in the United States, Canada, and Mexico should be strongly encouraged. Joint programs aimed at satisfying common seismological objectives will require the exchange of scientists, establishment of cooperative research programs, and data exchanges. Many of the objectives of the USSS can be much enhanced by unrestricted exchange of data and even telemetered signals between observatories and earthquake research centers in Canada, Mexico, and the United States and funding of joint research in instrumental programs.

6 OPTIMUM LOCATIONS OF COMPONENTS OF THE PROPOSED UNITED STATES SEISMOGRAPH SYSTEM

6.1 THE NATIONAL DIGITAL SEISMOGRAPH NETWORK (NDSN)

The permanent broadband seismographs of the proposed NDSN should be distributed so as to provide recording of all significant regional and global seismicity and to permit uniform areal coverage of the United States and its surrounding continental shelves. A minimum magnitude threshold for location should be $M_L = 3.5$ earthquakes in the United States, except in California, where the minimum locatable limit of $M_L = 3.25$ is recommended for the NDSN alone. (The regional networks of the University of California at Berkeley, California Institute of Technology, and the U.S. Geological Survey will permit a lower threshold in practice.) Seismic surveillance of the continental shelves and along the coastal areas should be upgraded by use of ocean-bottom seismographs (OBS).

Figure 1.1 shows a map of possible station sites in the coterminous United States (not shown are sites in Hawaii, Alaska, and Puerto Rico). This particular configuration represents one viable option out of a number of possibilities for the NDSN station configuration based on existing long-period installations and quantitative calculations made for the Panel. As an illustration of one calculation, the USGS NETWORTH computer program was used to determine the detection threshold contours drawn in Figure 6.1. These contours indicate the body-wave magnitude threshold at which at least 5 stations of NDSN record the entire wave train of a U.S. earthquake with 90 percent confidence. Based on this analysis, and several other studies of this kind, the recommended distribution of the NDSN is given in Table 6.1.

At this stage, final site selection should be left flexible because varying factors influence the selection of each site of permanent NDSN stations. These include

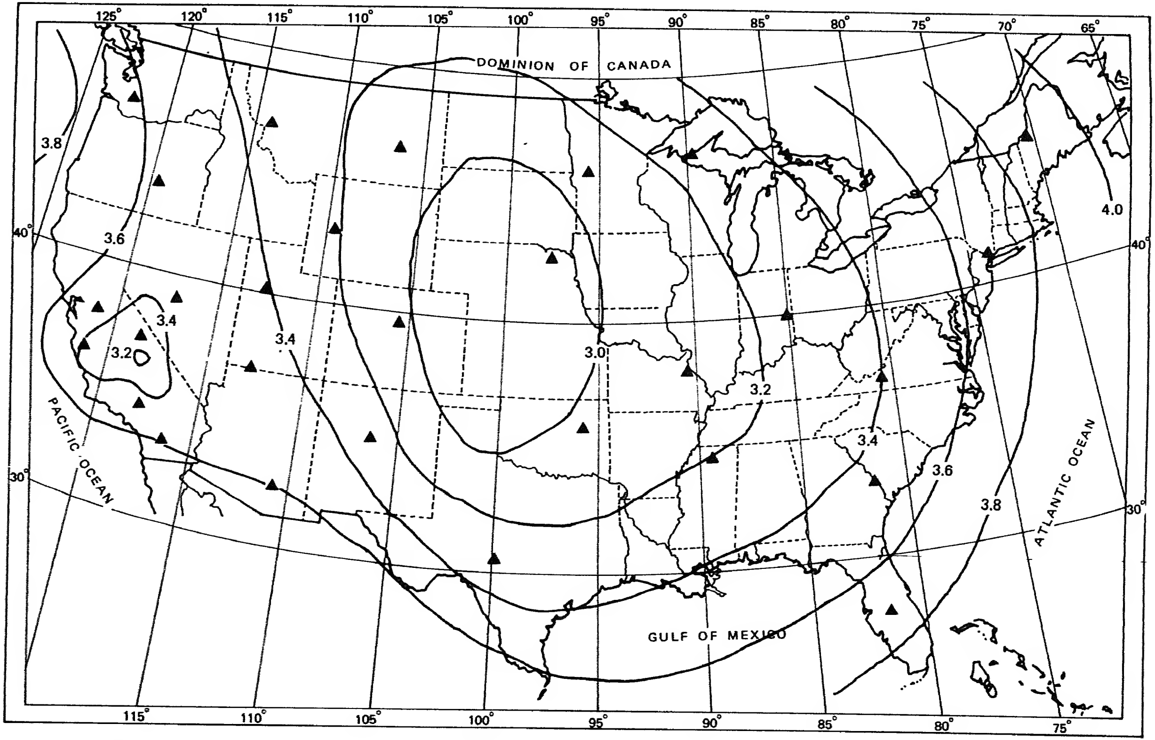

FIGURE 6.1 Calculated detection threshold for 29 possible NDSN stations in the coterminous United States. The contours indicate the body-wave magnitude threshold at which at least 5 stations record the entire wave train of a U.S. earthquake.

TABLE 6.1 Recommended Numbers of Stations for National Digital Seismograph Network

	Coterminous U.S.	Alaska	Hawaii	Puerto Rico	Total
Land	29	5	1	1	36
OBS	4	0	0	0	4
TOTAL	33	5	1	1	40

scientific objectives, areal coverage, cost/benefit ratio, availability of power and communication links, existing facility or vaults, and nearness of a regional research center or user group such as a university. In its analysis, the Panel considered for test selection of NDSN station sites the following factors:

1. Areal and azimuthal coverage of known seismically active areas and otherwise recently tectonically active areas.
2. Station locations at existing facilities and where ground noise is minimum.
3. Uniform azimuthal coverage for unbiased hypocenter determinations.
4. Minimum detectable thresholds of $M_L = 3.0$ for western United States and $M_L = 3.5$ for eastern United States well within overall network capability.

In the implementation program, factors for selection of sites must also include reliability of station power, all-year accessibility, and feasibility of an economic communication link. Recording and transmitting facilities must be in weatherproof and secure buildings.

It would seem advisable and perhaps most cost-effective to locate new NDSN sites at existing WWSSN stations, existing long-period stations, and existing university-government observatories wherever such sites lie close to locations required for a configuration that meets criteria 1-4 above (see, e.g., Figure 6.2). Existing WWSSN, high-gain, long-period (HGLP), and Seismic Research Observatory (SRO) stations will provide additional coverage, and seismic data from these sources should be merged with that from the new network. It is assumed that existing research observatories and network centers will be provided with data links to the new network data whenever these are justified.

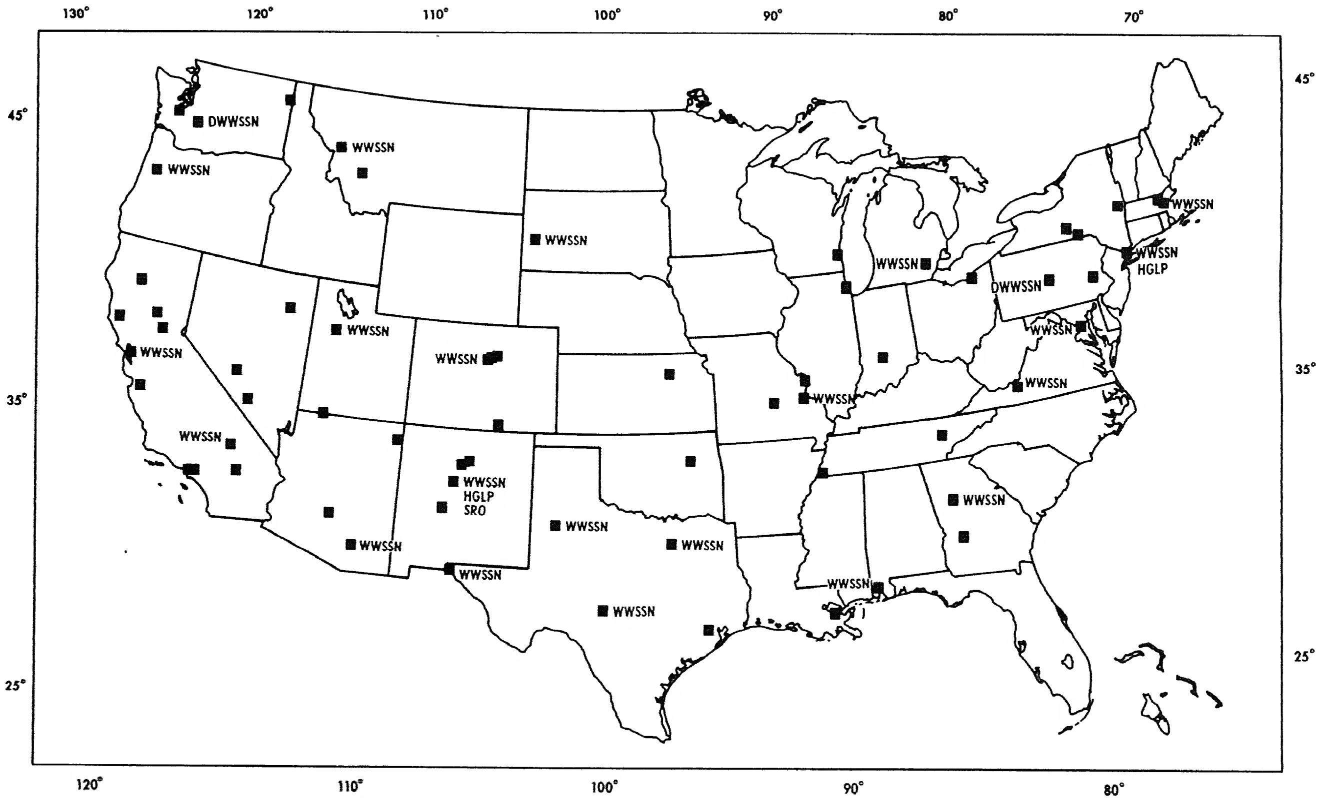

FIGURE 6.2 Seismograph stations with long-period instruments, May 1978.

6.2 DATA-ACQUISITION CENTERS

The importance and future role of the regional networks in the USSS has been discussed in Section 5.3. In particular, the concept of Regional Research Centers was defined. As has been stressed in other places in the report, the Panel is concerned that in the development of the USSS with its more sophisticated systems, relying mainly on computer access to digital data on magnetic tape, the seismological community be assured that seismograph data are readily available. It would be dangerous to move in a way that would tend to exclude individual seismologists and other interested scientists and engineers from the basic data base. If the present recommendations are followed, a great deal of the first-order digital data, particularly that from the NDSN, would be channeled through the USGS digital analysis facilities in Albuquerque and Golden. Access to earthquake recordings, perhaps in the form of "day tapes," can be expected from these facilities on a short-term basis. In the longer term, raw data on selected earthquakes and sequences can be expected to be provided by the Environmental Data Information Service (EDIS).

While these national centers will fill much of the demand, it does not seem practical to channel all requests through them. The Panel, therefore, recommends that direct but limited data acquisition be arranged at the regional centers. There, seismologists should be able to obtain digital recordings and associated network recordings on a timely basis. Such a service by the Regional Research Centers requires a capability to handle the high volume of digital data from the NDSN station (or stations) associated with that particular regional network, together with the network digital data. In addition, there must be a willingness to make available access facilities so that these data are obtainable at reasonable cost by visiting scientists.

A nonexclusive list of candidate data-acquisition centers, based on the present major regional networks of the country, would contain Fairbanks, Alaska; the University of Washington; the University of California at Berkeley; USGS at Menlo Park; California Institute of Technology; the University of Nevada; the University of Utah, Salt Lake City; USGS at Golden (NEIS); Albuquerque (USGS); St. Louis; Lamont-Doherty Geological Observatory; Weston Observatory, the University of South Carolina; and Georgia Institute of Technology. Detail on the use of these regional acquisition centers and the scope of their storage should be settled by the working group on the USSS (Recommendation 6).

Sponsors of current and future seismograph stations and networks will need to address problems of data management at the time of inception of their research programs so that the multiple use of their data through the Regional Research Centers and the EDIS can be performed efficiently. Planning must include facilities for long-term safe storage of data at the regional data-acquisition centers and criteria for deciding which records will become part of the USSS.

An advantage of digital data is that they are quite fluid in passing between institutions that are equipped to handle them. It is thus possible to make part of the national seismograph data base, accumulated at EDIS, available at those regional data centers that request it. In this way, the Regional Research Centers will develop special expertise in retrieval techniques and spread the use of digital seismic data to all those that cannot handle the new technology with their own facilities.

6.3 OCEAN-BOTTOM SEISMOGRAPH DEPLOYMENT

The need for ocean-bottom seismographs to augment the USSS and to monitor more closely earthquakes on the nation's continental shelves has already been presented in Section 4.4. In the report, *Global Earthquake Monitoring* (Panel on Seismograph Networks, 1977, p. 37), it was recommended that "a comprehensive research effort should be made to determine the feasibility of an extensive, long-term program in ocean-bottom seismology. Such a program might include portable arrays of several broadband OBS instruments and a few permanent installations." This Panel has concentrated on the somewhat narrower but central question of the use of ocean-bottom seismographs as it relates to the overall monitoring of earthquakes in the whole country. In this light, we considered what would represent a more or less complete network of ocean-bottom observatories (OBO), if funds were available for such an enterprise.

At first sight, such an OBO network would seem relatively ambitious. The Panel believes, however, that a modest but extremely valuable network in the next decade is a realistic goal, although no detailed costing has been made. One reason is the provision of observatories for the prediction of destructive earthquakes in the seismic areas off the coast of Alaska, Hawaii, and the northwest of the United States. Indeed, a working OBS system (or OBO) is already operational in Japan for this purpose. There, a semipermanent seismograph system was placed on the seafloor off the Pacific

Coast of central Honshu using a cable. It has operated since August 16, 1978, and it is expected to run for more than 10 years. The cable extends to a distance of 40 km across the Japan trench with a terminal OBS and three intermediate OBS's. The total cost of this OBS system in Japan, including design and installation, was about $8 million. It should be remarked that the salaries of the scientists who developed the system are not included in this cost.

For the sake of estimating the scope of a comprehensive U.S. network of permanent ocean-bottom observatories (OBO) as part of the NDSN, the following locations were considered:

Alaska

8 stations
- 1 off Adak
- 1 off Unalaska Island
- 1 off Sanak Islands
- 1 off Shumagin Islands
- 1 off Trinity Island
- 1 off Kayak Island in East Gulf
- 1 off Yakutat
- 1 Cross Sound

3 of these in NDSN

Hawaii

4 stations throughout the islands
1 of these in NDSN

Puerto Rico and Virgin Islands

3 stations north and east of Puerto Rico, west of Anegada
1 of these in NDSN

California

3 stations along the Mendocino Escarpment
3 stations off South California
1 of each group of 3 in NDSN (one recommended in first 4 years)

Oregon

3 stations off Oregon
1 of these in NDSN

East Coast

1 off Charleston
1 off Cape Ann
Both in NDSN (one recommended in first 4 years)

This comprehensive model network has a total of 26 stations, at least 9 of which should be in the NDSN.

In order to make at least a start, the Panel recommends the installation of two of the OBO listed above (one on the East Coast and one on the West) during the four-year installation of the NDSN. Comparative site studies should be carried out within existing OBS research programs to determine optimum sites for the proposed deployments. Instrumentation that is currently under development (i.e., "pop-up"

OBS's with short- and long-period instrumentation) should be used in these studies.

Following the comparative site studies program, selection of sites for the OBO's should be made. A detailed study of these locations using long-term-recording, pop-up OBS's should be carried out over a one-year period to determine fluctuations in noise levels on the bottom under a broad range of ambient conditions to evaluate potential "detection" capability of the site.

While the site studies are proceeding, the academic community and funders of OBS programs should be encouraged to develop ocean-bottom seismic systems especially suited to the *observatory* function. At the same time, studies of the choice of hard-wire telemetry to the nearest land versus satellite data telemetry should be carried out to determine the most reliable and cost-effective method of recording these data.

The remainder of the OBO program involving installation of the two prototype OBO systems, and the handling of the resulting recorded signals, should be carried out in the same time frame as the NDSN program.

6.4 STRONG-MOTION SEISMOGRAPH DEPLOYMENT: INDIVIDUAL SITES AND RESEARCH ARRAYS

A sound physical basis for understanding the dynamics of faulting and transmission of seismic waves through rocks and soils near to a large earthquake depends on availability of suitable "strong-motion seismographs." This knowledge is essential for the development of improved methods for estimation of future strong shaking in an earthquake of given source characteristics. This task is one of the essential foundation blocks in zoning against seismic risk and for use in design of seismic-resistant man-made structures.

Since the 1930's when the first strong-motion accelerographs were designed and deployed, the number of strong-motion accelerographs has grown to well over 1000 in the western United States and over 100 in the rest of the country (Mattiesen, 1978) (see Figure 4.5). During the past 40 years, the number of organizations involved in instrument deployment, maintenance, and data collection and dissemination has also increased sharply. Both circumstances have contributed to the present variety in the quality and completeness in data reporting, record digitization, and distribution.

The frequency of occurrence of strong earthquake ground motion is irregular. Few large earthquakes occur every 10 to 20 years that trigger more than 10 or more instruments. This poses organizational problems in maintaining long-range programs for instrument maintenance, data analysis, data use, archiving, and distribution. The only solution is long-range government funding in order to allow constant re-evaluation of siting of strong-motion instruments and instrumental upgrading. Continuous, stable commitment of supporting agencies and organizations is necessary to maintain and develop better methods of deployment of instruments and the related data processing and dissemination. The National Science Foundation (NSF) has provided significant support for this effort, so far, but there has been some uncertainty that requires resolution between the USGS and the NSF on the long-term funding and management responsibility for a national program.

The conception of the United States Seismograph System provides a singular opportunity to improve the overall approach to strong-motion instrument location by considering (a) North American tectonics, (b) the variety of active fault types, and (c) the variability of geological conditions. Such continental-wide considerations will help to ensure that the observations of strong ground shaking are optimized and representative of all conditions. The recent instrumental recordings in California of the moderate but damaging 1979 Coyote Lake and 1979 Imperial Valley earthquakes are creditable to the Seismic Engineering Branch of the USGS and the State of California strong-motion instrument program operated by the State Division of Mines and Geology. Yet, there remain many parts of the United States, including California, where a great earthquake might occur but leave no residual strong ground-motion measurements.

Much discussion is now focused on the need for digital instruments (see Section 7.4). Most recording instruments, however, remain analog, and this format represents a limitation for achieving an extended dynamic range, although their reliability is, at present, superior to existing digital instruments. As the new digital systems are introduced, care should be taken and the following questions asked: What is the expected life of each system, and how will limitations on its operational life affect the objectives for long-range recording of strong ground motion in the region?

Finally, the Panel took note of the strong effort, internationally at present (Iwan, 1978), to install and operate networks (or arrays) of strong-motion accelerometers. Indeed, such arrays are already in place in Yugoslavia and Taiwan (see Figure 6.3), and others are being considered

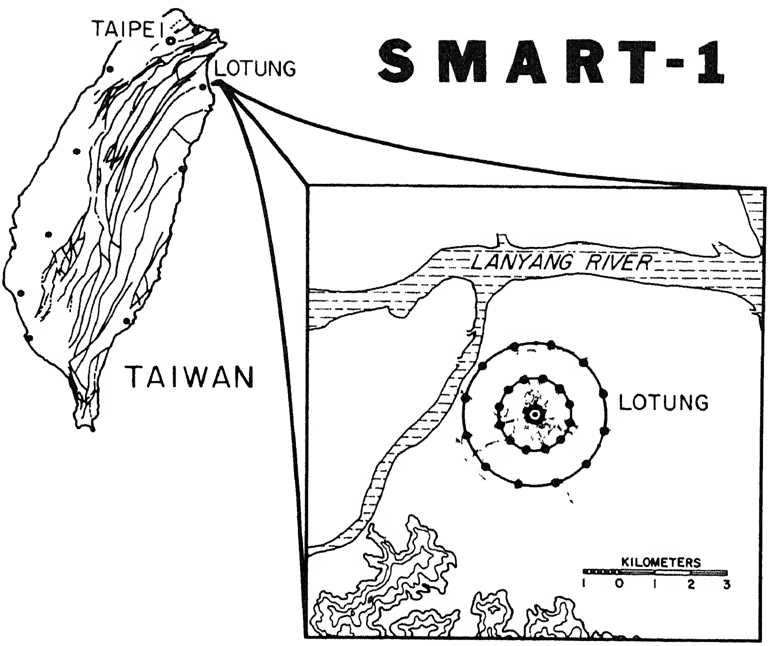

FIGURE 6.3 Strong-motion array of 37 digital accelerometers in Taiwan.

in India and the People's Republic of China. General objectives and guidelines for the deployment of strong-ground-motion arrays have been suggested, but much more study than the Panel could undertake is required to predict specific array sites in the United States with a high level of confidence. In the interim, the following additional guidelines may prove valuable*:

1. Arrays should be deployed with specific objectives to measure certain well-defined and well-formulated aspects of strong ground motion.

2. Studies should be undertaken to optimize the placement of instruments given the three-dimensional geologic environment, the distribution of earthquake sources, and the desired output from an array.

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*These recommendations do not address the engineering questions concerning the earthquake response of buildings, dams, and other structures.

7 INSTRUMENTATION FOR THE PROPOSED UNITED STATES SEISMOGRAPH SYSTEM

7.1 NATIONAL DIGITAL SEISMOGRAPH STATIONS (NDSN)

The required quality and quantity of instrumental records of earthquakes at the local, regional, and national levels in the United States in the 1980's involves a wide range of instrumentation, with many common features. To avoid duplication of effort and to encourage integration, all network instrumentation should be considered as complementary components of the United States Seismograph System (USSS). Information, preparedness, and research requirements at various levels (local, regional, national) should draw on those components of the USSS required for their specific needs. For example, NDSN stations might be considered as a subset of stations in regional networks (where regional "networks" in some areas may consist of only one station); instrumentation for a regional station can be considered as a subset of that at a national first-order station.

The stations of the NDSN must satisfy the manyfold requirements for seismic data by the nation for the next 10 years. Response characteristics of these standardized digitally recording stations must cover the entire range of interest, and data handling may require increased transmission rates or even new transmission techniques.

The response curves (see Figure 7.1) of seismographs at WWSSN stations earmarked for upgrading to digital recording (DWWSSN), in general, provide the coverage now required in frequency and amplitude of seismic waves. Any modifications in the detail of the instrumental system response for the NDSN should be considered by the Working Group on the USSS (Recommendation 6). Among these modifications the following might be considered:

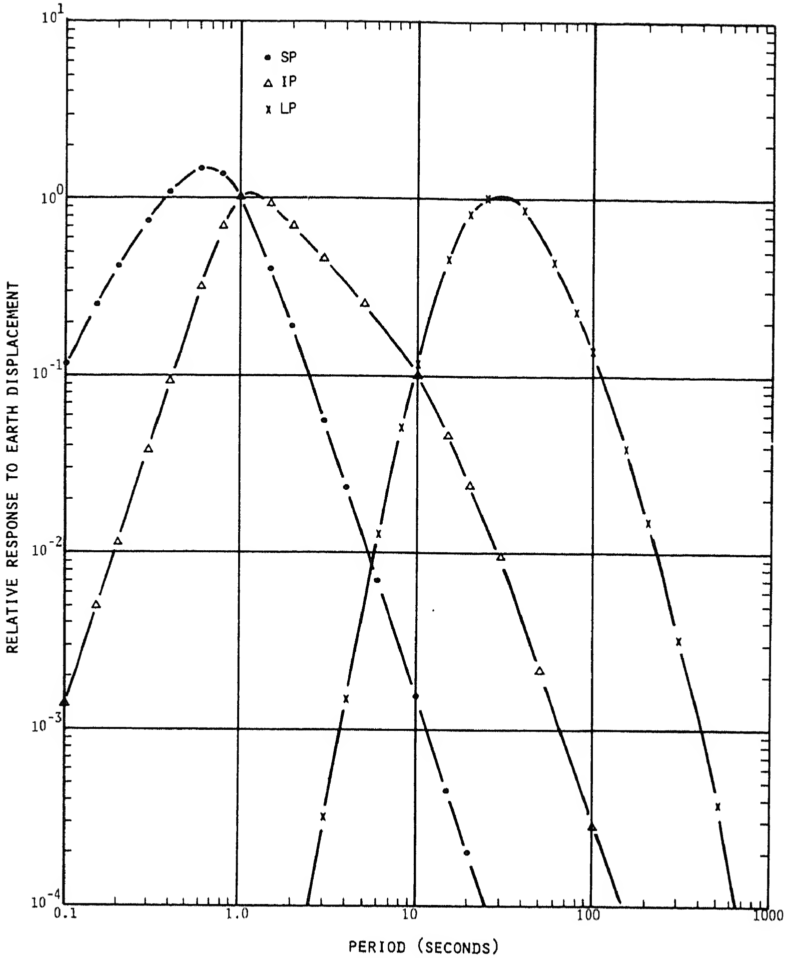

FIGURE 7.1 Amplitude response curves for the short-, intermediate-, and long-period channels recorded on the digital WWSSN (DWWSSN). The intermediate-period channels will be set to a very low sensitivity in order to record large body-wave signals without overdriving the recorder.

1. The sampling of the short-period data should be carried out at 50 samples per second.

2. The long-period response curve should be broadened, and the maximum response should occur between 30 and 40 sec.

3. A strong-motion response, flat to acceleration (similar to the SMA-1 response), should be available from the system.

These responses can be achieved using conventional seismometer systems, or they can be derived from borehole sensors (even one sensor in each direction) with sufficient dynamic range (>96 dB). The choice of the exact sensor configuration will be partially site-dependent and should, in any case, be left to the Working Group.

A well-known drawback with the present U.S. seismograph network is its inability in general to record great earthquakes. The seismographs of the WWSSN, for example, are driven off scale by the large-amplitude ground motion that occurs in such cases. The great 1964 Good Friday Alaska earthquake, which had a magnitude M_S = 8.6 provides an illustration. This earthquake was so large that WWSSN seismographs in the United States remained off scale through the greater part of the seismic motion so that research on the earthquake based on national observatories depended on very-low-magnification instruments of early types. The aim, then, is to design the NDSN so that some channels are capable of recording not only small earthquakes nearby and moderate earthquakes regionally but also great events like the 1906 San Francisco earthquake with minimum loss of information.

Digital technology makes it practical to achieve the desired range of recording. Digital recorders, using 16-bit data words with gain ranging, have in excess of 120 dB of recording range. This is well over 1000 times the recording range of the chart recorders used in the WWSSN. Nevertheless, it is expected that the NDSN will require two or more sets of sensors in order to provide the desired coverage in both frequency and amplitude.

The NDSN systems should be designed with a modular approach so that they may be adapted to a number of different operating configurations. Some of the NDSN stations will be located at WWSSN sites and will therefore be manned. Analog recording, as well as digital recording, may be desirable at these stations. Some may be unattended for periods of weeks or months, and the data recorded on site will have to be stored on magnetic tapes or disks. Others may be located at sites that are inaccessible for long intervals each year, and all the data will have to be transmitted to regional or national centers for recording. Ideally, selected data from all the NDSN stations will be telemetered to a national center so that the data are available rapidly for processing and analysis. Although it may not be possible to employ this mode of operation initially at all stations, the NDSN systems should be adaptable with minimum reconfiguration for data telemetry via dedicated or dial-up circuits. Of particular interest to the Panel is the increasing use of communication satellites for the telemetry of geophysical data.

The formulation of detailed NDSN specifications is best left to the Working Group on the United States Seismograph System. Important decisions will have to be made concerning the type of recording (whether continuous or event mode), and the Working Group will no doubt address problems of instrument linearity and calibration, both of which have increased importance in digital data anlaysis.

7.2 DETECTION OF REGIONAL AND LOCAL EARTHQUAKES

Even with the establishment of the "first-order" NDSN stations, there will remain the need for large numbers of low-cost single-component stations to provide rapid and accurate locations. Short-period networks of telemetered type have now been operating for more than 10 years, and the overall design philosophy has proven adequate. There is a need, however, to review the system components, update design, and attempt to standardize equipment and calibration procedures.

One of the first responsibilities of the proposed Working Group on Seismic Instrumentation (Recommendation 12) should be to evaluate present practices in instrumentation for telemetered regional networks and recommend minimum standards for components and calibration. Introduction of a new generation of instruments should begin with those stations used in the national monitoring network by NEIS.

Digital data transmission of short-period data using the present telemetry capabilities is expensive. The main need for continuous on-line data at the Regional Research Centers and NEIS is for earthquake location and magnitude determination, which does not require high-dynamic-range digital data and can be done using analog data transmissions. The Panel suggests that in the first stage of implementation of the USSS a continent-wide network to monitor significant U.S. earthquakes be selected and analog transmission of short-period data (and digital transmission of long-period data) be used. Selection of stations by the NEIS from the NDSN and regional networks should be evaluated and upgraded as required. Acquisition of data from NDSN and other digitally recording stations might develop along the lines used for the satellite system (see Appendix F). A select set of analog seismograms should also be recorded continuously at NDSN and other first-order stations.

7.3 OCEAN-BOTTOM SEISMOGRAPHS

Because of the relative difficulties in establishing permanent ocean-bottom instrumentation, discussed in Section 6.3, the packages (see Figure 7.2) for the ocean-bottom observatories designated as part of the NDSN should record a broad range of seismic and associate phenomena. The packages should include the following instruments:

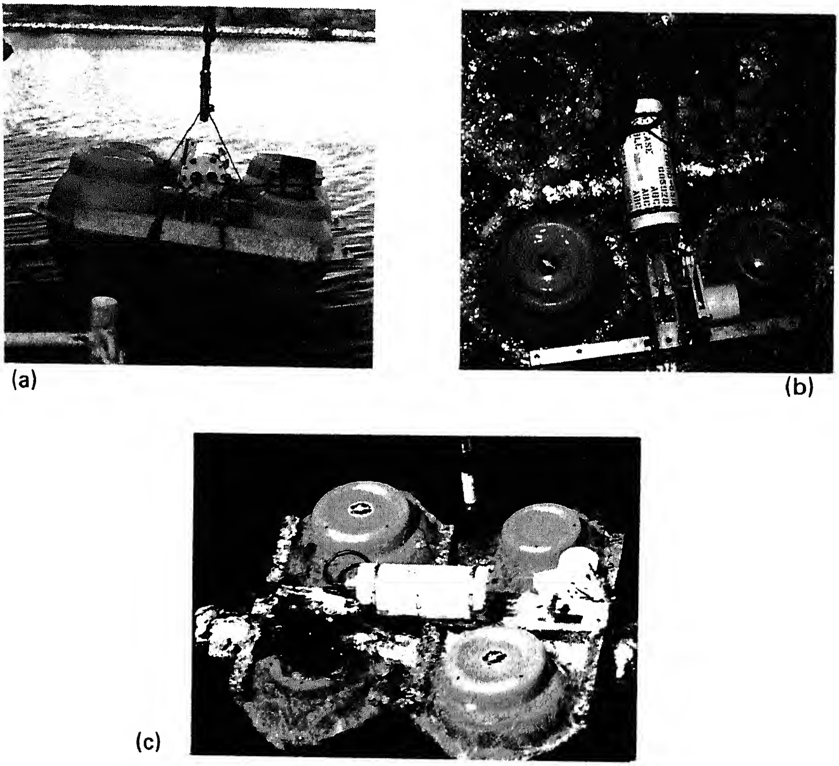

FIGURE 7.2 (a) Ocean-bottom seismograph system prior to deployment. Seismograph system is in the larger lower center cylinder. The four drums are for flotation. Top cylinder is the acoustic release system. System is hanging from crane.
(b) System being lowered into water.
(c) System at recovery. (Photographs by Robert Bookbinder, Lamont-Doherty Geological Observatory, Columbia University.)

Three-component short-period transducers with response
similar to the NDSN short-period band
Three-component long-period-displacement transducers with
response similar to the NDSN long-period band
One-component hydrophone-standard long-period output
1 pressure transducer
1 temperature transducer
1 current direction and magnitude indicator.

Signals should be recorded within the ocean-bottom package transmitted to the ocean surface for retransmission or to be transmitted via cable to a shore-based station (as in the present Japanese OBS system off eastern Honshu).

Instrumentation like the above was contained in the successful system installed off Port Arena, California, in 1966 mentioned in Section 4.4. Similar instrumentation with upgraded electronics, microprocessor control, and options of digital recording is currently being developed within the university community. These development efforts supported by the Office of Naval Research and the National Science Foundation should be encouraged. Additional funding for instrument packages may be forthcoming from the Defense Advanced Research Projects Agency (DARPA) in view of the renewed national interest in discrimination between underground explosions and earthquakes using seismograph stations located at regional distances (5 to 20°).

7.4 STRONG-MOTION EARTHQUAKE INSTRUMENTATION FOR ENGINEERING AND SCIENTIFIC REQUIREMENTS: CONVENTIONAL AND DIGITAL RECORDERS

At present, strong-motion accelerometers with both conventional analog photographic recordings or digital tape recordings are commercially available. The advantages of the older devices are their proven reliability and availability of data-processing procedures, including analog-to-digital conversion. The main advantages of the newer digital recording are the direct access of the raw data to computers without the need for any intermediate digitization and the greater dynamic range. It should be pointed out that a number of digital recording seismographs of portable type have been tested successfully in the field during the last few years for the recording of seismic waves in small earthquakes. The conversion of these recording devices to digitally record strong-motions presents a few problems in theory. [It has been recommended (see

Recommendation 14) that a set of portable digital recording instruments be manufactured to constitute a national movable digital array. These could be designed to record both small- and large-amplitude ground motion.]

The recommendations made by the Panel to upgrade the national capability to record large-amplitude seismic waves falls into two classes (Recommendation 13). First, all first-order seismograph stations, especially the Regional Research Centers, in seismic areas should install special seismograph equipment that can record three components of strong ground motion from nearby earthquakes. Such instrumentation would normally be capable of recording three channels of acceleration or velocity. The systems may or may not be triggered by the onset of strong ground motion, but the instruments must have the capability of recording numerous events with incoming signals as high as 1 g or greater. There is room here for considerable innovation and local initiative. Some of these strong-motion devices could be of torsion type with magnifications of 100 or 10, rather than the standard Wood-Anderson magnification of 2800. It should be pointed out that it is now possible to produce a standard Wood-Anderson record (used for magnitude determination) numerically from regular strong-motion accelerometer records with known response (see Figure 8.2).

Other options include both analog and digital transducers located in small arrays on the surface or downhole with as many as 13 channels of data amplified and recorded photographically or on magnetic tape. Prototype systems are already available that are capable of recording a wide range of acceleration levels using amplifier switching regulated by the magnitude of input signals. These strong-motion seismographs use microprocessor control, but as yet there is little field experience with them.

The second recommendation of the Panel related to large-amplitude seismic waves is that NDSN stations record "low-gain" channels. These amplifier settings reduce the signal by orders of 100 or more, so that energetic signals are not clipped by the electronics. Such low-gain channels are likely to make a great contribution to seismological research in the next decade.

7.5 INSTRUMENTATION DEVELOPMENT

More than 20 government and university groups are operating seismic networks, and at least 6 have advanced in-house projects on instrumentation development and assembly. In addition, some local networks are operated by private geotechnical companies. Virtually no formal, sustained communication exists between these groups at the engineering/technical level. Manufacturers of seismological equipment often have inadequate information on the desired characteristics of instruments or insufficient feedback from the scientific community on the best avenues for future instrument development. The diversity of instruments now being developed and used reflects this lack of communication. At the same time, there is growing interest from the scientific and industrial groups, both in the United States and worldwide, to obtain equipment for seismic monitoring. The American scientific community should make an effort to ensure that equipment is commercially available that meets specific standards. Such an effort would not only improve the quality of instrumentation, but the establishment of a large and unified market could result in lower costs.

It would appear advantageous at present to form a working group on seismic instrumentation consisting of representatives from government, private, and university groups operating seismograph networks (see Recommendation 12). The responsibility of the group would be to recommend and monitor minimum standards for seismic instrumentation, to provide forums for improved communication between those involved in using and manufacturing equipment, and to recommend future lines of instrumentation development.

In past generations of instrumentation, many of the components of a seismograph (seismometer, long-period amplifiers and galvanometers, drum, recorders, timing systems) had to be designed and manufactured specifically for seismological applications. With the advent of digital recording, much of the seismograph system draws on components from telecommunications and computer technology. The special-purpose requirements of seismology will be met by software development and by integration of available hardware into a complete digital system. There will need to be continued feasibility studies from groups within and outside the seismological community on the transmission, storage, and access of digital data as applied to the needs of the USSS.

Two examples of future USSS developments are of special interest. First, the concept of a seismogram as a 24-hour record of one component of ground motion at a single station may develop into one of an "event-gram" of a single earthquake as recorded on various components and bandwidths at a number of stations. With all data available in digital form at a central location, the Regional Research Centers, NEIS, and EDIS will be called on to "tailor-make" seismograms for each user application. For example, the user may specify filter characteristic, rotation of axes, type of response (displacement, velocity, acceleration), or request spectra to be produded. If digital data are requested, it may be more convenient to provide data on a floppy disk (phonograph record size) for each event, with an accompanying analog record, summarizing the data on each disk.

Second, the Panel foresees that a major practical question will be the relative costs of transmission of data by conventional land lines and satellite. The main operating cost in the collection of digital data and the limiting factor in the amount of data gathered will be the cost of conventional telephone-line transmission. The question arises whether we should be considering the launching of a dedicated satellite for relaying seismic and compatible geophysical data.

Regardless of the exact form that the national network finally takes, digital data acquisition will play the central role. To ensure a reasonable degree of data uniformity, the Panel makes the following suggestions:

(a) The working group on the USSS (Recommendation 6) should be generally concerned with digital data formatting, distribution, and perhaps processing algorithms, for the National Seismograph System as well as administrative and technical problems of data standardization and distribution. It should also ensure that there be coordination with international committees on observatory practice and instrumentation [such as those sponsored by the International Association of Seismology and Physics of the Earth's Interior (IASPEI)] and with working groups involving Canada and Mexico.

(b) Specification of data should be framed in terms of minimum required information to be included with each unit (e.g., magnetic tape, Holofile) of digital data. Within these requirements, data should be formatted as freely as possible to allow for differences in instrumentation, computing systems, and technical capability at different institutions.

8 UPGRADED EARTHQUAKE DATA STORAGE AND RETRIEVAL

8.1 SEISMOGRAMS AND MAGNETIC TAPES

The success of seismology in the last decades is due primarily to the easy accessibility of recorded data on earthquakes by scientists throughout the world. This in turn has led to profound results about the nature of the interior of the Earth, the physics of earthquakes, and the spatial and temporal distribution of earthquakes. Further advances in seismology of a basic kind require that even more care must be devoted to data management than in the past.

The Panel concluded that the operation of Worldwide Standardized Seismograph Network (WWSSN) stations with their easily accessible photographic recordings must be continued at least until the new digital network is thoroughly proven. If it is necessary to cut back marginal WWSSN stations in the United States to support National Digital Seismograph Stations (NDSN), efforts must be made to generate equivalent analog data sets. A program is now under way by the U.S. Geological Survey (USGS) and the Environmental Data and Information Service (EDIS) to photograph important paper seismograms from the beginning of the U.S. permanent seismograph stations, and these copies will be archived with the film chips of the WWSSN. This program of preservation is to be applauded. A considerable amount of analog microfilm from regional networks has now also accumulated. Information contained with each roll of film should be standardized, and facilities for long-term archiving should also be considered for these irreplaceable records.

At some observatories a library of analog earthquake signals has already been preserved on magnetic tape for over a decade. Specific events from such libraries could be played back for incorporation in a designated data set for the USSS to be preserved in some practical manner for future study. The preservation problem is that long-term storage of *analog* data on magnetic tape has not had the attention it deserves.

A centralized vehicle for the distribution and preservation of digital seismic data should be encouraged. In the context of a USSS the EDIS is the logical candidate to work out and manage these essential tasks. Consideration has to be given to the long-term commitments required of the National Oceanic and Atmospheric Administration (NOAA), with respect to personnel, computer facilities, and storage facilities.

The NOAA digital data base should include data from the International Deployment of Accelerographs (IDA), the Seismic Research Observatory (SRO), DWWSSN, and NDSN. Computer program development should be encouraged so that the digital data from the networks mentioned, as well as from future sources, can be provided to the user in a standard format. This would enable routine servicing of user requests, which in turn would encourage optimal use of digital data.

8.2 NATIONAL AND REGIONAL EARTHQUAKE PARAMETERIZATION AND CATALOGING

At present, the USGS and NOAA maintain catalogs of felt earthquakes in the United States; in general, these all have magnitudes greater than 3.5. These agencies should continue to perform this function (see Figure 8.1). The collection of readings and locations of smaller earthquakes is best left in the hands of the operators of the regional networks, i.e., the Regional Research Centers.

A clearinghouse for regional earthquake data should be established to provide them in suitable form, such as microfiche. This procedure would fit in with the program to copy all past seismograph station catalogs for archiving purposes. Uniform goals for the optimal content of regional catalogs should, however, be established. Microearthquake locations from regional networks should be incorporated into the annual report entitled *U.S. Earthquakes* published by NOAA by inclusion of a seismicity map for each region.

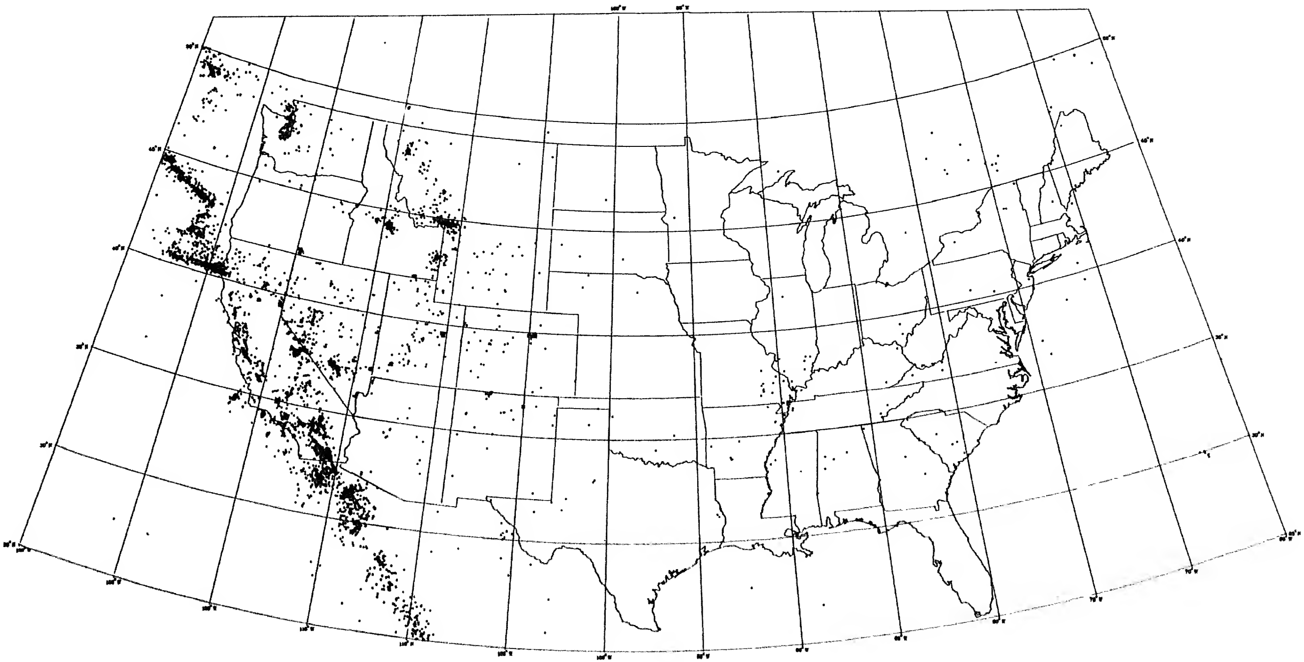

FIGURE 8.1 U.S. earthquakes of magnitude 3.5 and greater for 1963-1979.

8.3 STRONG-MOTION RECORD STORAGE

Approximately 5000 strong-motion instruments of various types are distributed worldwide. The number of strong-motion records available for analysis in 1980 is on the order of 2000. These strong-motion records are available in a variety of formats, ranging from full-size copies of records to punched card or digitized records on magnetic tape.

Up to the present, the great majority of accelerograms were first recorded in analog form on paper or film and afterwards visually digitized. In the future, direct digital recording on cassettes or 9-channel tape in ASCII (American Standard Code II) will become more common. Standardization of all the important strong-motion data now stored is needed to encourage the use of this asset. For the past few years, excluding a number of large earthquakes in the western states, agencies that directly operate the strong-motion networks and the large earthquake engineering research centers can store the original records or their digitized forms. Long-term storage should, however, be undertaken by EDIS as part of its contribution to the United States Seismograph System.

8.4 USER SERVICES

The aim must always be to encourage the use of the observations of earthquakes. Like many other aspects of its study, the Panel found that seismograph data services have evolved into a great variety of forms in the United States. They range from services rendered to the public, industry, and the seismological community by earthquake research centers at universities to wide services offered more formally by the USGS through NEIS, and particularly by EDIS of NOAA.

Until the recent advent of digital recording on magnetic tape, the main scientific user service on observatory records was provision of film chips and full-size copies of WWSSN seismograms. User service by EDIS with respect to WWSSN seismograms is well done and has contributed to the widespread use of the data. As has been pointed out in earlier sections, however, data-storage methods are now becoming more complex so that a greater contribution to users must now be made by all seismograph libraries. Such contributions, led by EDIS, will be best carried out in the overall context of a mutually beneficial USSS. There is an obligation to ensure that the more sophisticated

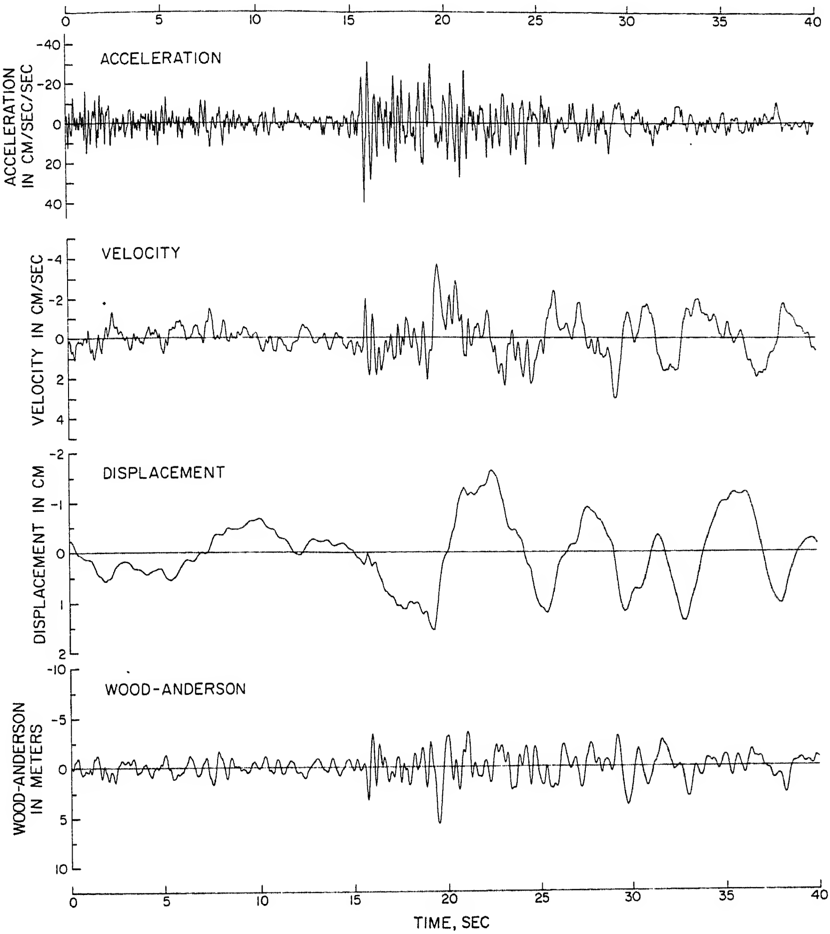

FIGURE 8.2 Accelerogram and derived records from the Borrego Mountain earthquake, 1968. San Onofre 33° E. (From H. Kanamori and P. C. Jennings, Determination of local magnitude, M_L, from strong-motion accelerograms, *Bull. Seismol. Soc. Am. 68*, 471-485, 1978.)

data formats do not block any seismologist, no matter how limited the local data-processing facilities are, from requesting earthquake records from NDSN and associated networks in usable form.

Use of digital data from the NDSN would be encouraged by a number of steps. There is a need for computer programs that would read digital records on different computers, e.g., a separate retrieval or access program for each common computer system. Minimum requirements would be that the user have the ability to search the tape for a particular time frame, that the user be able to fill an array with the specified seismic trace, and that the user be told how to interface the trace array with his own analysis program.

Second, analog services are needed to provide a user a plot of digital data within a given time frame for his research (see Figure 8.2). The requirements of high resolution and a fast plotter are in some ways contradictory, and such problems would have to be worked out. We might ask how much of the low-cost personal computer technology we can incorporate in our applications. For example, it might soon be practical to generate WWSSN-type film chips from digital data using laser technology, either off-line at a central data center or on-line at the seismometer site. As the television set becomes an important part of the home computer market, hard-copy seismograms might be produced from information displayed on a television screen.

The Panel concludes that it is essential to provide facilities for direct use of the data at EDIS as part of a visiting scientist program (Recommendation 8). A limited number of analysis routines would have to be written to encourage profitable use of resources by visiting scientists.

In its considerations of the problems that arise in the storage and retrieval of digitally recorded seismic data, the Panel had the advantage of a report on application of large-capacity devices for the storage of such data (Committee on Seismology, 1978). This study investigated the usefulness of large digital storage devices to seismology and discussed them in the context of the management of large volumes of such data. They found that, at present, mass storage devices are available that would be suitable for the archival of digital data, but because of their expense and the newness of the technology, their application should probably be delayed. They found further that mass storage devices may in the long run contribute significantly to seismological data management, but that the more pressing problem at the moment is the need for coordinated management of the data resources on earthquakes.

9 IMPLEMENTATION AND SUPPORT

9.1 SCHEDULE OF IMPLEMENTATION

The recommendations of this report when put into effect will raise U.S. observational seismology to a new level. The Panel has set down broad guidelines for the systematic improvement of earthquake recording in the United States in the next decades. Specific upgrading of both the observatories and data handling is seen within a framework of a new United States Seismograph System (USSS). In this respect, we can only repeat the highly successful recommendation of the 1959 Berkner Panel that the proposed program be viewed "as a package in order to derive the fullest benefits." Throughout the report, reference has been made to a number of federal and state agencies that either have obligations concerning seismological research support or depend on earthquake information in order to meet their public duties. We have also referred to the major industries that benefit substantially from the availability of quantitative earthquake information and to the universities where much of the seismological and earthquake engineering research is carried out. The success of the USSS will clearly depend on the combined support of all of these groups, as well as the seismological community.

The implementation of the USSS (as shown in the flow diagram given in Figure 9.1) will clearly be a continuing interest for the Committee on Seismology of the National Research Council. The Panel expects that the Committee will continue to take an active role in developments, offer advice as required, and lend assistance to the various working groups recommended in the report. The Panel recommends that the Committee review the whole question of the USSS in 5 years in order to assess the progress that has been made.

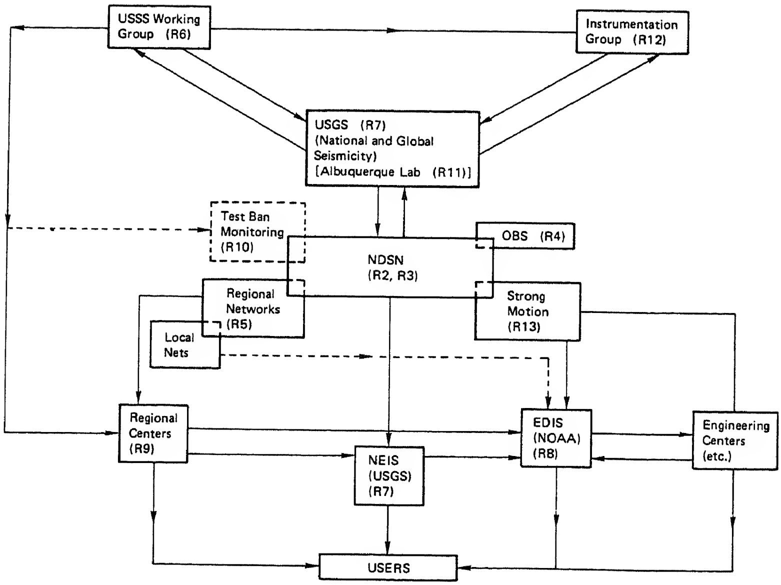

FIGURE 9.1 Flow diagram for the United States Seismograph System (R1). R1 refers to Recommendation 1 text, R2 to Recommendation 2, etc.

The main responsibility and expertise on aspects of observatory seismology now reside with the U.S. Geological Survey (USGS). The Panel is convenced that, given sufficient support, the USGS can not only take a lead in making the present recommendations reality but can undertake many of the necessary cooperative agreements to ensure the operation, maintenance, and consolidation of the new NDSN and upgraded regional networks and regional research centers.

Similarly, the major responsibility for the management of the archived seismological data acquired through the upgraded USSS resides with the Environmental Data Information Service. The service must be funded so that it can undertake this responsibility in cooperation with the USGS and regional research centers in a satisfactory way.

The Panel considers that a 4-year period is sufficient to complete the installation of the minimum number of National Digital Seismograph Network (NDSN) stations recommended in this report. This conclusion is based on experience with the installation of the Worldwide Standardized Seismograph Network (WWSSN) in the United States in the early 1960's and with the subsequent installation of more modern equipment of the High-Gain, Long-Period (HGLP), the Seismic Research Observatory (SRO), the Abbreviated Seismic Research Observatory (ASRO), and the International Deployment of Accelerometers (IDA) stations within the global network.

Within the USSS, the Panel has recommended that a carefully designed network of seismograph stations with the latest technical equipment be installed (the NDSN). It is reasonable to expect that the initial costs of this upgrading of the national earthquake observatories will be supported by all government agencies with interest in earthquakes (e.g., the U.S. Geological Survey, the National Science Foundation, the U.S. Nuclear Regulatory Commission, the Defense Advanced Research Projects Agency, the Office of Naval Research, the National Aeronautics and Space Administration, the Bureau of Reclamation, the U.S. Army Corps of Engineers, the National Oceanic and Atmospheric Administration, and the Department of Energy). This support undoubtedly entails additional funding to participating agencies. Specifically, however, the Panel believes it is necessary to concentrate installation responsibilities with the USGS. The work of establishing the NDSN can reasonably be anticipated to be some mix of in-house work by federal agenices and work of outside contractors, including university groups.

As elements of the NDSN fall into place, funds must be provided for support of the station operation, data dissemination, and an adequate level of analysis activity. It is anticipated that some operators of the seismograph stations, including the Regional Research Centers, will cover some of the maintenance costs by including them in research proposals and funding proposals in the normal way. There will, undoubtedly, be savings from the closing down of older redundant seismographs at observatories and the change to less labor intensive recording and data reduction. Nevertheless, it is inevitable that maintenance and operational costs will be an extra burden on the USGS, and the Panel strongly urges that budgetary support for this agency be increased as required to ensure the stable operation of the new observational facilities (Recommendation 7).

9.2 NEEDS AND TASKS FOR A NATIONAL ADVISORY GROUP

The effective establishment of an upgraded USSS with its intimately linked observational data-processing and data-retrieval aspects is not a simple matter. Its dynamics will bring to light many questions that could not be treated by this Panel. Therefore, it is essential that there be a mechanism for continued advice and evaluation of progress as the various steps toward a high-caliber USSS are carried out.

The Panel, therefore, concluded that a working group on the USSS be established (Recommendation 6), perhaps under the aegis of the Committee on Seismology, to represent the various interested parties on earthquake observations in the United States. The title "Working Group" is deliberately chosen, because what is needed is not a series of recommendations and a formal report but a series of workshops in which members of the Panel, chosen for their special experience and knowledge, have an opportunity to discuss, debate, and advise on developments of the whole system. Earlier in this report, the Panel has suggested a number of matters that need consideration by this working group.

The working group should include members of the USGS associated with the Office of Earthquake Studies and, particularly, digital facilities and analysis; seismologists involved with regional networks and university research groups; and scientists from the federal agencies concerned with earthquake monitoring, such as the Department of Energy and the Department of Defense, and with data management and distribution. It would seem advisable for this working group to make a presentation on its progress at least annually to the Committee on Seismology.

9.3 INCREASED FUNDING OF A U.S. GEOLOGICAL SURVEY DIGITAL ANALYSIS FACILITY

The largest group of seismologists in the United States are now employed by the U.S. Geological Survey (USGS). This group includes seismologists with extensive experience in seismological observatory work. In particular, the Branch of Global Seismology has successfully undertaken the operation in the last few years of the global seismograph networks (see Figure 2.1) and the exchange and analysis of global earthquake data, including that from new digital recording stations. The Albuquerque Seismological Laboratory, part of the Branch of Global Seismology, is responsible for the design, deployment, and maintenance of digital seismological stations and arrays both within the United States and as part of the global earthquake monitoring system. Since its inception in the 1960's, this group has operated the Worldwide Standardized Seismograph Network (WWSSN) and has more recently installed and operated digital instruments, such as at the ASRO and SRO stations.

The far-reaching proposals for a USSS in this report involve the USGS in a substantial increase of work on seismological observations. In particular, the Global Seismology Branch will feel the brunt of responsibility in enlarging activities from a limited global network of digital stations to the addition of the NDSN. This group will be intimately involved in the instrumentation and data transmission to the regional research centers and to the central recording facility at Albuquerque, also in the recording and analysis of the digital data and the preparation of event and time-interval tapes.

The consequence of the central responsibility of the USGS is that funds must be dedicated for the long-term operation and maintenance of the NDSN and its associated systems, including the global networks. The precarious state and chronic funding problems for the WWSSN stations has long been a fact. Attention was drawn to this debilitating problem in *Trends and Opportunities in Seismology* (1977) and a specific recommendation made therein that "Stable and adequate funding be provided to the USGS for the necessary very long-term operation and maintenance of seismic arrays and networks." Modern earthquake observatories are the lifeblood of seismology, and the federal agency that has been given the prime responsibility for studies of earthquakes in the United States must have adequate funding to allow the uninterrupted operation and technical support for the USSS.

9.4 FUNDING

Funding for the overall upgrading of components of the USSS must come from all sources involved in earthquake studies. The funds will have to be spread over all federal agencies that make use of seismological data and also must include funds from states and private industry. As has been discussed already, it is possible that a portion of the necessary funds can be reprogrammed in various ways from ongoing observatory work that has become outdated, redundant, or achieved its objectives.

The Panel has endeavored to estimate a budget for the cost of installation and operation of the national digital seismograph network. This budget covers the cost of the seismographic instruments for 36 stations in the contiguous United States, Alaska, Hawaii, and Puerto Rico (see Recommendation 2). Estimates of installation, operation, and management costs have also been made, with no allowance for inflation. The costs include a rough estimate of the additional funds that are essential, mainly by EDIS, for the additional data archiving and distribution associated with the NDSN.

Estimated Budget for the NDSN

			4-Year Total
Cost of instruments	150K/land station	36 stations	$ 5,400K
Installation costs	60K/station	36 stations	2,200K
Operation costs	30K/station/year	36 stations	4,320K
(Includes: telemetry, manpower, computers, station operation)			
Management costs	500K/year		2,000K
		Total	$13,920K

The total amount for such a major national scientific and economic resource is relatively moderate compared with other major scientific research facilities such as linear accelerators and radio telescopes. It is estimated that seismological and geological, including strong-motion, assessments required for licensing a single nuclear power station in the more seismic areas of the country costs from $3 million to $5 million. The amount may also be compared with the total funds appropriated under the Earthquake Hazards Reduction Act of 1977 of $50 million. As set out in Appendix E, a grant total of about $12 million was spent for instrumentation operating costs for the networks during fiscal year 1979. This figure does not include most of the research expenses in seismology and does not include about $1 million provided by the Defense Advanced Research Projects Agency for seismograph research arrays in Norway and Iran.

It should be reiterated that some funds should become available to federal and state funding agencies through some reprogramming of funds now associated with costs of older stations that would be replaced by an NDSN station.

In its advice on funding, the Panel draws attention also to the general recommendations made in *Global Earthquake Monitoring* (1977). This earlier report, after dealing with the budget requirements for an improved worldwide standardized seismograph network, turned its attention to the need to update the instrumentation and data analysis of the basic U.S. observatory system. It concluded "that mechanisms be established in the federal government to ensure sufficient and appropriate funding, within the USGS, for the operation and timely upgrading of those most basic facilities and services, and within NOAA-EDIS for the seismogram and digital data organization distribution and services." The present Panel also agrees with the 1977 report in the recognition that a number of government agencies have basic responsibilities in this upgrading program. Specifically, based on the past interest and support (Appendix E), perhaps some of the capital cost of NDSN might be expected from the National Science Foundation (both for geophysical research and applied needs). Significant support might also be expected from the Department of Energy, the Department of Defense, the Nuclear Regulatory Commission, and the U.S. Bureau of Reclamation.

Finally, it would be noticed that the funding for the ocean-bottom seismograph stations, as elements of NDSN, are not included in the above estimates. The most recent evidence is that the cost to build and install each of the ocean-bottom observatories (Recommendation 3) would be approximately $120,000. The operating cost would depend on the mode of data transmission or the method of recording that is utilized. Similarly, the maintenance would depend primarily on the cost of service vessels.

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APPENDIX A: Charge to the Panel on National, Regional, and Local Seismograph Networks

The Panel is to prepare a report for publication by the National Academy of Sciences on the subject of National, Regional and Local Seismic Networks. The report will address current practice, but will emphasize and present recommendations for future developments of such networks. The general topic is to be treated under the following headings:

1. The need for, design and implementation of a U.S. National Network.

   1.1 Objectives of a national network, e.g., the long-term surveillance of seismicity within the U.S. for purposes of scientific work and earthquake hazards reduction. Specific goals may be set by the Panel, such as the development of a network that will assure that every earthquake with magnitude greater than X occurring within the U.S. will be recorded at a minimum of Y stations.

   1.2 Design of a national network, including density of stations, choice of instrumentation for standardized stations, identification of instrumentation needs not met by current equipment, methods of data transmission and recording.

   1.3 Management of the data produced by the network, including assembly, storage, reproduction, and distribution to users for short- and long-term applications.

   1.4 Administration and funding of the network, with emphasis on the need for long-term stable management and support.

2. Regional and local networks.

   2.1 Objectives. Because such networks are usually designed around a particular research or operational goal, and are often intended to have a relatively short lifetime, the Panel should consider the extent to which standardization might be desirable and how such networks can supplement a permanent national network.

2.2 Guidelines for network design.

2.3 Need for new instruments and data systems.

2.4 Use of data, especially by others than the original investigators. Should such data be archived for later distribution? Should the data be available for routine PDE work by NEIS?

3. Seismic arrays.

3.1 Objectives. Are seismic arrays developed for specific research tasks of sufficient importance to the general scientific community to justify their operation after the original objectives are satisfied?

3.2 Funding and management. What is the best institutional arrangement for operating arrays as major national research facilities? How should funding be handled?

3.3 Data Management.

4. Strong-motion recordings.

The instrumentation to be used for the networks to be developed will presumably provide for high dynamic range, probably through digital recording. In addition, special low-gain channels can be incorporated as desired as long as the sensors and front-end electronics do not saturate under strong ground motion. The Panel should consider the approaches to using the instruments in the networks to supplement and extend the capability now provided by conventional strong motion instruments to record strong ground motion. A deficiency in the present distribution of strong-motion equipment is the absence of recording sites at depth below the surface. The Panel may consider the desirability and feasibility of the development of three-dimensional arrays of conventional strong-motion instruments and other instruments in regional and local networks.

5. Ocean-bottom seismographs.

The Panel should consider, at least, how a distribution of ocean-bottom seismographs can effectively supplement the land-based networks which are its primary concern. The Panel should judge, on the basis of its findings, whether a further comprehensive study of an ocean-bottom network, by a different panel, is desirable.

July 22, 1977

APPENDIX B: Present U.S. Seismograph Networks and Stations

INTRODUCTION

It is estimated that more than 1000 seismograph stations are included in the seismograph networks operating within the United States; these are organized in a wide diversity of configurations. The instrumentation has considerable variance in dynamic ranges, passbands, and in recording media. Station density among the networks is variable, from clusters of 4-7 stations in a 30-km or less aperature to broad coverages of less than one station per square degree. Instrumentation includes short-period vertical seismometers with some horizontal instrument coverage (often only one component) and a few long-period instruments. Dynamic ranges are usually constrained by the bandwidth of telephone line that transmits up to nine signals on a single line. A number of stations are not telemetered but are recorded locally. The data are mostly analog, although some stations have digital capabilities, but sampling rates are not uniform.

Types of recording include all available methods: photographic paper, heat-sensitive paper, pen and ink, film, and magnetic tape. Because the networks in the United States are operated by more than 400 organizations, the data are stored at the respective institutions. Data dissemination and transfers are usually done on individual bases. Quarterly bulletins, which list seismic events, are published by some operators. Some stations are operated only temporarily by academic, federal, state, or commercial organizations to answer specific questions; others have semipermanent (5 to 10 years) or permanent status, the latter usually within the academic sector.

The existence and growth of this network diversification has been dictated by the emergence of a wide range of critical problems that needed to be solved more or less on a regional scale. Some important objectives for operating networks are the evaluation of seismic risk, determination of active tectonic areas, study of the structure of the earth, research on the discrimination between earthquakes and explosions, and determination of earthquake parameters.

NORTHEASTERN U.S. SEISMIC NETWORK

There are approximately 100 stations in the northeastern U.S. network. Except for the worldwide stations at Weston, Massachusetts; Palisades, New York; Ogdensburg, New Jersey; and State College, Pennsylvania; all instrumentation is composed of short-period vertical and some short-period horizontal component seismometers. The principal mode of data transmission is FM analog via voice-grade telephone circuits to eight subnetwork-recording centers. The modes of recording include 16-mm Develocorder film (most common), analog magnetic tape, photographic heat-sensitive and ink paper, and occasionally digital tape.

Funding for network operations is provided by the Nuclear Regulatory Commission, U.S. Geological Survey, National Science Foundation, N.Y. State Energy and Resources Development Authority, and U.S. State Sciences Service.

Earthquake information is published in quarterly bulletins and in progress reports to various agencies.

SOUTHEASTERN U.S. SEISMIC NETWORK

There are 81 network stations in the southeastern United States. Three (Atlanta, Georgia; Georgetown, Washington, D.C.; and Blacksburg, Virginia) are Worldwide Standardized Seismograph Network stations (WWSSN). The other stations have short-period verticals, and about one fifth have short-period horizontal component seismometers.

A substantial number of the stations are recorded locally by pen and ink or heat-sensitive paper and occasionally by analog event tape recorders. Some stations (in Georgia, South Carolina, and Virginia) have data transmitted via telephone lines or radio-frequency transmission to subnetwork centers for recording on film and analog magnetic tape.

Funding for network operations is provided by the National Science Foundation, Nuclear Regulatory Commission,

U.S. Geological Survey, Department of Energy, and power companies.

Information is published in a semiannual bulletin and in progress reports to various agencies.

CENTRAL MISSISSIPPI VALLEY NETWORK

There are 31 network stations in the Central Mississippi Valley. Except for the WWSSN station at St. Louis, all sites have short-period vertical component instruments telemetered to a central recording facility. Recording is by 16-mm film, pen and ink, and analog magnetic tape.

Funding is provided by the U.S. Geological Survey and the Nuclear Regulatory Commission.

Data are published in a quarterly bulletin.

OTHER EASTERN NETWORKS

Several other small networks or arrays are in operation, mainly supported by the Nuclear Regulatory Commission. These include the Anna, Ohio, network of 10 stations (SP-Z) recorded on analog tape; the Michigan Peninsula network of 6 stations (SP-Z); the 6-station Minnesota array (SP-Z); and the widely spaced Nemeha network will total 25 stations--9 in Oklahoma, 9 in Kansas, with 4 being planned, and 3 in Nebraska being planned.

WESTERN U.S. SEISMOGRAPH NETWORKS

For this report, western United States refers to areas west of the Rocky Mountains, including Alaska and Hawaii. The term "network" means a collection of seismograph stations operated coherently, normally by one organization, with a common basis for data collection and analysis. In recent years, to a large extent, the term network has come to mean that data from a number of stations are telemetered to a central recording and analysis facility. Virtually all networks in the western United States have this characteristic. In general, the operating and reporting methods are the same as for the eastern networks.

There are in excess of 900 short-period (SP) stations currently operating in the western United States. Most of these stations are in "telemetered networks," which range in size from 5 to 6 to over 250 stations. A much smaller number of broad- and long-period (LP) stations are in operation, and these, for the most part but with the exception of four LP stations of the University of California at Berkeley network, have on-site recording. An even smaller number of strain seismographs and other types of sensors are in use. In addition to the networks listed in this report, an undetermined number of small networks (3-6 seismic stations) are operated around dam sites, reservoirs, reactor sites, and other engineered structures. So many organizations are engaged in these operations that it is difficult to obtain complete information.

Special note needs to be taken of several networks of unusual nature. The USGS National Earthquake Information Service (NEIS) utilizes phone-line telemetry to transmit signals from about 35 SP stations of existing networks in the West to Golden, Colorado. This system constitutes a very-large-scale network, which assists rapid detection and location of larger regional earthquakes. The 12 or so WWSSN stations in the western conterminous United States also comprise a very-large-scale network of LP and SP instruments with on-site recording. The Alaskan Long Period Array (ALPA) may be considered a special-purpose network. Organizations that operate LP or broadband instruments for special investigations include Palmer Observatory and Honolulu Observatory (Tsunami Warning Network, NOAA); University of California at Berkeley; University of Nevada (temporary LP array); Albuquerque Laboratory (USGS); California Institute of Technology; University of Hawaii; and University of Alaska. The Tsunami Warning Network operated by NOAA utilizes commercial satellite telemetry to return signals from a widely spaced network extending from the central Aleutians to the interior of Alaska.

The Caltech network uses digital recording for its large network of SP stations. Under USGS support, several additional networks throughout the United States will soon have digital data acquisition. Such systems will vastly improve our ability to exchange and analyze seismic data.

APPENDIX C: Canadian Seismograph Network

The Canadian Seismograph Network consists of standard stations, regional stations, and a number of specialized installations. The objectives for operating the network are threefold: (1) to document the seismicity and seismotectonics of Canada; (2) to provide information on a global basis; (3) to provide information that can be used for discrimination research.

The locations of the standard and regional stations are shown in Figure C.1. The 19 standard stations consist of three short-period (SP) and three long-period (LP) instruments that record in analog format. The seismograms are copied on film (35 mm) and are available to all investigators through World Data Center A (WDCA). The regional stations are used to supplement the standard network in regions of high seismicity and for special studies. Most regional stations visually record a single SP vertical component and, in a few cases, three SP components. The numbers, locations, and lifetime of the regional stations will vary.

The operational and proposed stations in eastern Canada are shown in Figure C.2. Nine telemetered digital stations are in operation at Manicouagan, Maniwaki, Gentilly, Montreal, Fitzroy Harbour, Ottawa, and La Grande (3), near James Bay. These stations have a dynamic range of 100 dB and are linked to a minicomputer system in Ottawa. Progress will be in upgrading software and increasing the

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This Appendix is a summary of a presentation to the Panel on National, Regional and Local Networks made by Kenneth Whitham, Assistant Deputy Minister, Conservation and Non-petroleum, of Energy, Mines, and Resources, Canada, Ottawa, Canada.

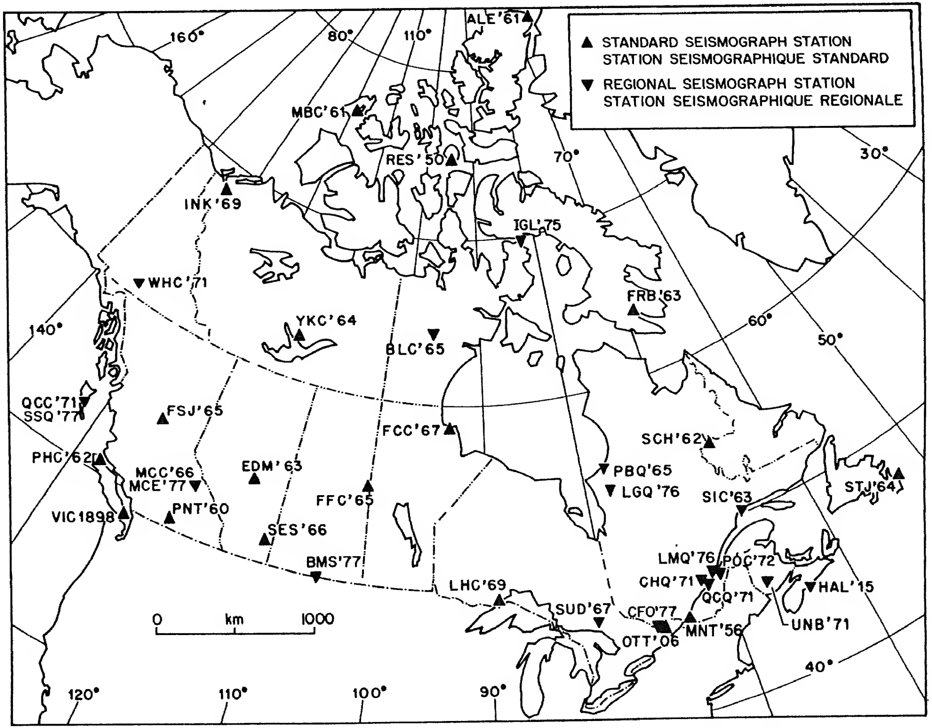

FIGURE C.1 Canadian standard and regional seismograph stations in 1977 (from *Canadian Seismograph Operations--1977*, W. E. Shannon, R. J. Halliday, F. Lombardo, and D. Schieman, Seismological Series, No. 80, Ottawa, Canada 1979).

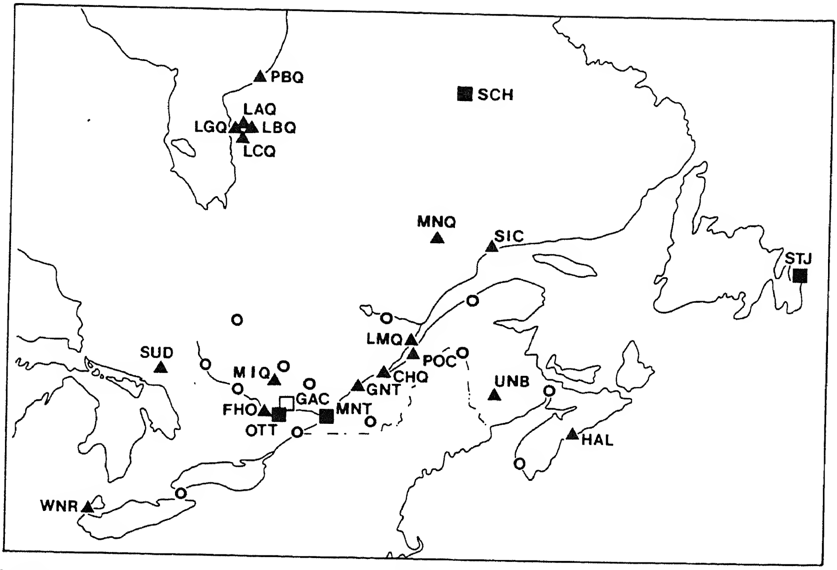

FIGURE C.2 Operational and proposed seismograph stations in eastern Canada in 1978. Standard stations are shown by squares, regional and telemetered stations by triangles, and proposed stations by open circles. (Courtesy of the Earth Physics Branch, Canadian Department of Energy, Mines and Resources.)

number of stations and overall capability. The plans for additional stations include completion of the borehole installation (seismic-research observatory equivalent) near Ottawa (GAC in Figure C.2) from which tapes will be provided to the USGS Albuquerque Laboratory.

The operational and proposed stations in western Canada are shown in Figure C.3. The telemetered digital network consists of four stations, Haney, Port Alberni, Pender Island, and Sidney, recording at the Pacific Geoscience Centre at Sidney. The system is comparable with that in eastern Canada, and it is planned to add additional stations in the next few years, using a mixture of radiotelemetry and telephone-line transmission.

Several additional stations and special networks, not shown in Figures C.1–C.3, are in operation or proposed by a number of Canadian universities.

A medium-aperture array (YKA, Figure C.3) has been operating at Yellowknife since 1962. The 19 SP vertical

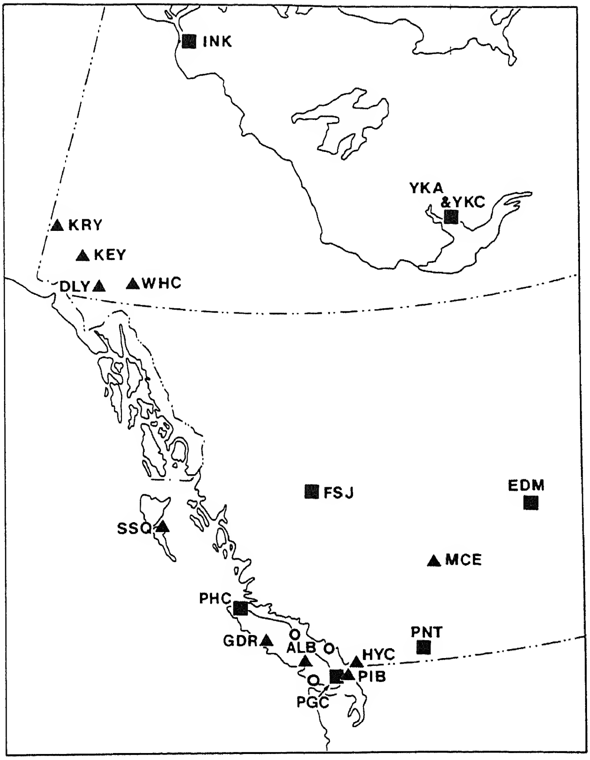

FIGURE C.3 Operational and proposed seismograph stations in western Canada in 1978. Symbols as in Figure C.2. (Courtesy of the Earth Physics Branch, Canadian Department of Energy, Mines and Resources.)

seismometers are arranged in two orthogonal lines with 2.5-km spacing. A three-element SP vertical array is also in operation with LP horizontals at one site. The data are radiotelemetered to the control center, processed on-line by computer, and recorded on digital and FM tape. The standard station YKC is located within the array.

Strong-motion instruments in Canada exist in two networks: one in western Canada, which is maintained by the Earth Physics Branch of the Canadian Department of Energy, Mines, and Resources, and one in eastern Canada, which is maintained by the National Research Council of Canada, Division of Building Research. At the end of 1978 there were 48 accelerographs and 73 seismoscopes in the two networks. Most of the seismoscopes are associated with the accelerograph networks; 63 are located in British Columbia and 10 in the St. Lawrence region. The principal objective is to obtain information on strong ground motions for building codes.

APPENDIX D: Mexican Seismograph Stations

Responsibilities for seismograph networks in Mexico reside with four groups as follows: (1) The Institute of Engineering (of the National University of Mexico, UNAM); (2) The Institute of Applied Mathematics and Systems (UNAM); (3) The Institute of Geophysics (UNAM); and (4) The Center for Scientific Research and Higher Education of Ensenada (CICESE).

SISMEX (The Seismotelemetric Information System of Mexico) is operated by the Institute of Engineering. The array is composed of 12 (x,y,z) strong-motion stations in and near the Valley of Mexico, and five with short-period vertical instruments for the purpose of aiding in the interpretation of strong ground motion. Three of these stations form a triangle, with sides of about 160 km, around Mexico City. Selected events can be digitized on demand, and archives include standard seismograms on paper as well as on analog and digital tapes. A total of 86 strong-motion instruments are operated nationwide by the Institute of Engineering (some 35 of these belong to the Federal Electricity Commission).

Another major emphasis in Mexico is RESMAC (Continental Aperture Mexican Seismic Array), which is being installed and operated by the Institute of Applied Mathematics and Systems (IIMAS). Three stations are currently operating, one at UNAM in Mexico City, one at Toluca (Cerrillo), and one at Acapulco; the output of four more is received from SISMEX. Plans are to locate about 24 stations in all parts

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This Appendix is a summary of a presentation to the Panel on National, Regional, and Local Seismograph Networks made by Jorge Prince, Subdirector of the Instituto de Ingenieria, Cd. Universitaria, México.

of Mexico. The seismic signals from vertical short-period seismometers are digitized and transmitted to an analysis center. An event detector operates on-line, and event records are stored on disks until transferred to magnetic tapes for archiving.

The Institute of Geophysics may reinstall the station that was part of the Worldwide Standardized Seismograph Network. The former station is inoperable. The Institute of Geophysics continues to operate several stations of the national array of instruments installed beginning about 1910.

An array of approximately 10 instruments is operated at Ensenada by CICESE, which was created by the Science and Technology Council of Mexico. The instruments were installed by UNAM and the University of California at San Diego (UCSD) to monitor the earthquakes in Baja California and the Gulf of California. A telemetered array of 12 stations in this area is being installed by CICESE and UCSD with joint funding through CICESE and the U.S. Geological Survey.

APPENDIX E: Financial Support of U.S. Seismograph Networks for Fiscal Year 1979

Inquiries were made to U.S. Government agencies, state agencies, and private companies and other private institutions about the money spent for instrumentation and operations (including installation of instruments and maintenance) of seismograph networks during fiscal year 1979. A summary of this information is given below and in Tables E.1-E.4.

A total of about $8.3 million was spent for high-magnification instrumental networks. It is estimated that about 20 percent ($1.6 million) of these funds was spent for the purchase of instruments, and the balance ($6.4 million) was spent for operating the networks.

Total expenditures for low-magnification instrumental networks (strong-motion) used primarily for engineering purposes were about $3.9 million, of which about 33 percent ($1.3 million) was spent for instruments and 67 percent ($2.6 million) was spent for operating the networks.

A grand total of about $12.2 million was spent for instrumentation and operating the networks during fiscal year 1979. It is believed that research expenditures have been largely deleted from these figures. The above amounts do not include about $1.1 million provided by the Defense Advanced Research Projects Agency to support seismograph research arrays in Norway and Iran.

TABLE E.1 Support of U.S. Seismograph Networks for Fiscal Year 1979 ($1000's)

	Instruments	Operations (Includes Installation and Maintenance)	Total
High-Magnification Instrumental Networks (Sensitive)			
U.S. Government	$508 (est. 1,000+)	$2,447 (est. 5,000)	$6,459[a]
States	281	986	1,267
Private companies and other private institutions	7	523	530
TOTALS	$796	$3,956	$8,256
Low-Magnification Instrumental Networks (Strong-Motion)			
U.S. Government	$ 670	$1,811	$2,481
States (California)	260	603	863
Private companies and other private institutions	400	170	570
TOTALS	$1,330	$2,584	$3,914

Grand Total spent for seismograph networks: $12,170

[a] A breakdown of costs was not estimated by one agency.

TABLE E.2 Support of U.S. Seismograph Networks for Fiscal Year 1979 ($1000's) for U.S. Governmental Agencies

	Instruments	Operations (Includes Installation and Maintenance)	Total
Sensitive Instruments			
NSF-EAR	$184	$ 80	$ 264
U.S.NRC	20	1,160	1,180
U.S.BuRec	10	190	200
NOAA (BLM)	60	440	500
NOAA (Tsunami)		105	105
ONR	30	46	76
NASA	4	26	30
DARPA	200	200	400
COE		200	200
TOTALS	$508	$2,447	
USGS (Internal			2,680
USGS (External - total of $1,648 includes research)			824
		Cumulative Total	$6,459
Strong-Motion Instruments			
NSF-PFR	$600	$1,450	$2,050
U.S.BuRec	70	75	145
VA		36	36
COE		250	250
	$670	$1,811	$2,481

TABLE E.3 Support of U.S. Seismograph Networks for Fiscal Year 1979 ($1000's) for Private Companies and Other Private Institutions

	Instruments	Operations	Total
Sensitive			
New York		100	100
California-Oregon		100	100
S. Carolina		80	80
Georgia	7	35	42
Washington		40	40
N. Carolina		55	55
Virginia		43	43
Colorado		50	50
Private universities and individuals		20	20
	7	523	530
Strong-Motion			
Alaska (Alyeska Pipeline Company)	400	100	500
Nuclear power plants (est.)		70	70
	400	170	570

TABLE E.4 Support of U.S. Seismograph Networks for Fiscal Year 1979 ($1000's) for States

State	Instruments	Operations	Total
Sensitive			
California	256	318	574
Alaska	15	235	250
Utah	10	110	120
Nevada		51	51
New Mexico		36	36
Tennessee		50	50
Washington		25	25
Michigan		18	18
New York		90	90
Virginia		25	25
Indiana		16	16
Georgia		6	6
Maine		5	5
Other		1	1
	281	986	1,267
Strong Motion			
California	260	603	863

APPENDIX F: Comparisons of the LANDSAT/EROS System and a National Seismograph System

There are a number of government and private groups gathering, storing, and disseminating large volumes of digital data. One of these, which has many analogies with a national seismograph service, is the LANDSAT/EROS system. Below, comparisons are made between how EROS operates and the expected method of operation of a national seismograph service. The Panel considers that the development and operation of EROS may serve as a helpful model in the development of the national seismograph system.

Three main reasons for the apparent success of the LANDSAT system stand out and deserve serious consideration:

1. *The strong user orientation of the EROS Data Center*. This facility exists, unburdened by in-house research or data gathering, to provide public access to LANDSAT data. (Comparisons could be made with the success of the dissemination of WWSSN data by NOAA.)

2. *The range of user products available*. Using high-quality digital data from a single source (LANDSAT), a variety of products are available aimed at various user needs and levels of sophistication.

3. *Technical flexibility*. Technological advances in digital data transmission, processing, and storage can be continually incorporated in the system with minimal adverse effect on the user.

APPENDIX G: Abbreviations Used in Text

ALPA - Alaskan Long Period Array
ASCII - American Standard Code II
ASRO - Abbreviated Seismic Research Observatory
BMO - Blue Mountain Observatory
CIRES - Cooperative Institute for Research in Environmental Sciences
CPO - Cumberland Plateau Observatory
DARPA - Defense Advanced Research Projects Agency
DWWSSN - Digital Worldwide Standardized Seismograph Network
EDIS - Environmental Data and Information Service
EROS - Earth Resources Observation Systems
HGLP - High-Gain, Long-Period [station]
HVO - Hawaii Volcano Observatory
IASPEI - International Association of Seismology and Physics of the Earth's Interior
IDA - International Deployment of Accelerometers
IDE - International Data Exchange
LANDSAT - Land Satellite
LASA - Large-Aperture Seismic Array
LRSM - Long-range seismic monitoring
MODCOMP - Modular Computer Systems
NDSN - National Digital Seismograph Network
NEIS - National Earthquake Information Service
NOAA - National Oceanic and Atmospheric Administration
NSF - National Science Foundation
OBO - Ocean-bottom observatory
OBS - Ocean-bottom seismograph
OCSEAP - Outer Continental Shelf Environmental Assessment Program
SDCS - Special Data Collection System
SRO - Seismic Research Observatory
TEWS - Tsunami Early Warning System
TFO - Tonto Forest Observatory

UBO - Uinta Basin Observatory
UCB - University of California at Berkeley
USGS - United States Geological Survey
USSS - United States Seismograph System
WMO - Wichita Mountain Observatory
WWSSN - Worldwide Standardized Seismograph Network