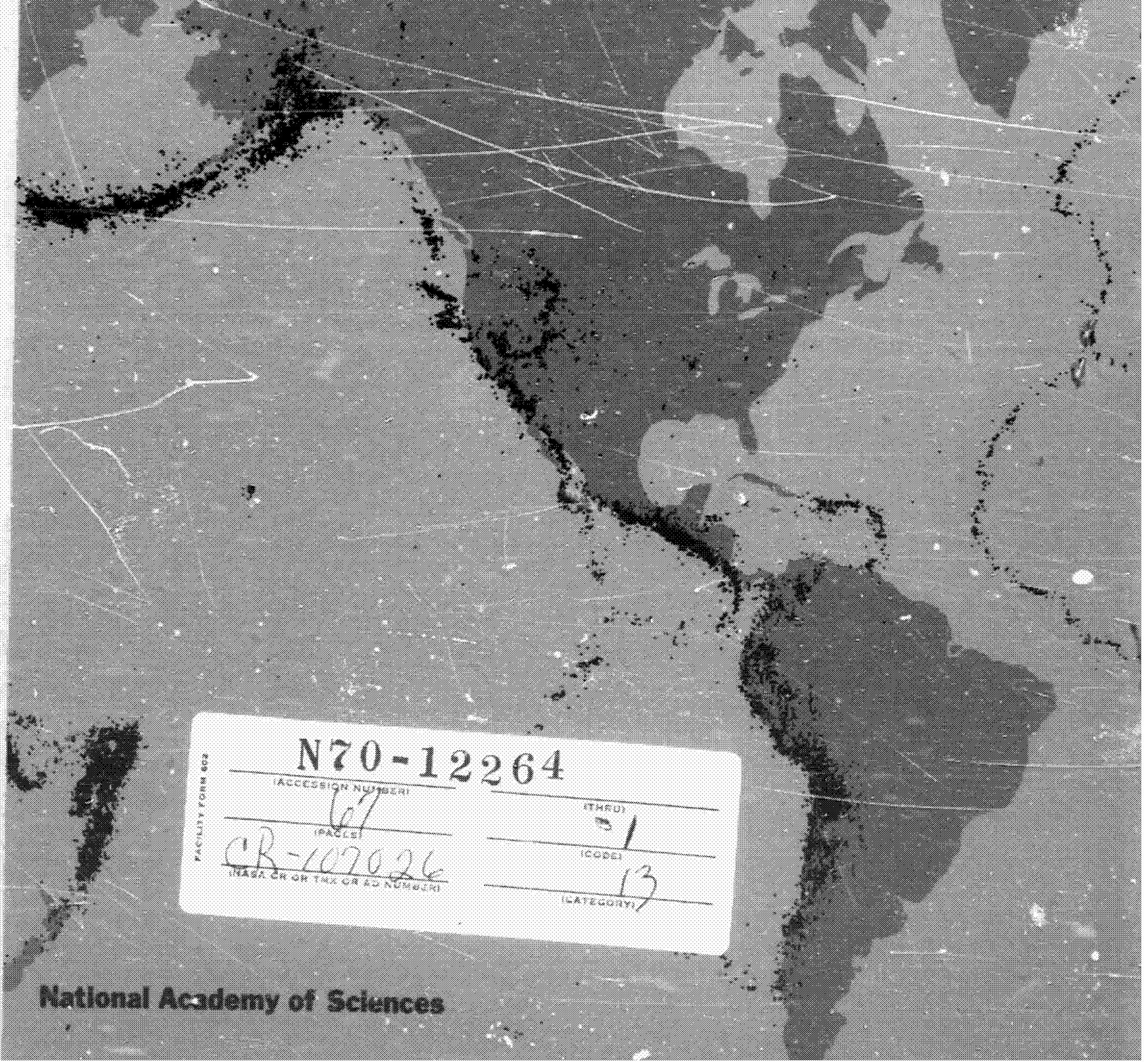
SEISMOLOG[illegible] Responsibilities and Requirements of a Growing Science

Part II

Problems and Prospects



National Academy of Sciences

SEISMOLOGY

Responsibilities and Requirements of a Growing Science

PART II: PROBLEMS AND PROSPECTS

A REPORT OF THE
Committee on Seismology
DIVISION OF EARTH SCIENCES
NATIONAL RESEARCH COUNCIL

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FOREWORD

The science of seismology has made major contributions to human welfare. It has given us our basic understanding of the interior of our earth, a scientific and technical base for exploration for the oil and mineral resources so necessary to our economy, the means for lessening the hazards of earthquakes, and the scientific and technical knowledge essential to certain international political interactions and military efforts. Recent scientific and technological developments as well as changes in the base of support have made necessary a review of the progress of the science. This report by the Committee on Seismology serves that purpose and makes recommendations that, it is hoped, will increase the effectiveness of seismology in service to the nation.

Philip Handler, *President*
National Academy of Sciences

PREFACE

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Seismology is the study of earthquakes and attendant phenomena. The past two decades have seen rapid growth in the field of seismology as the science has been increasingly called upon to help meet vital needs of the nation. Part of this growth was associated with the general expansion of scientific research and technology that followed World War II, coupled with an expanding exploration program for petroleum. Much of this growth was spurred and underwritten by the Vela-Uniform Program of the U.S. Department of Defense. And part of it was related to and grew out of the vast International Geophysical Year program of multination cooperative scientific research and the subsequent program, the Upper Mantle Project, an intensified investigation of the outermost 1,000 kilometers of the earth.

The Vela-Uniform Program, begun about eight years ago, has been a medium for major expansion of the field of seismology. Its main purpose is to improve our nation's capability to detect remote underground nuclear tests. Its primary scientific tool is seismology. It has contributed to the growth of the science by stimulating and supporting a great increase in the number and variety of seismologic research programs, in the improvement of instrumentation and techniques, in our knowledge of the characteristics and behavior of elastic waves in the earth, and in prospects for increasing and improving the application of seismology in civil and mining engineering, prospecting, and many other vital activities of man.

Vela-Uniform activities have been undergoing reorientation, with a changing program emphasis that markedly decreases support for basic research in seismology. The International Geophysical Year ended a decade ago, and the Upper Mantle Project is in its final years. These programs have brought seismology in the United States to a position of world leadership. But as they end or are redirected, they leave much of the field with decreasing support for worthwhile older objectives, while advances and potentials within the field are leading to exciting and necessary new ones. The hard core of seismologic manpower built during these years is excellent in quality, and there have been large advances in equipment and technology. These assets should not be dissipated now, for the nation requires today, more than ever in the past, knowledge of the nature of destructive earthquakes and the means to cope with them, including a comprehensive and effective observational network to monitor current seismic events, a steady output of well-trained seismologists to carry on the search for oil and mineral wealth, and an understanding of earth structure and tectonic processes to provide a solid base for man's exploitation of the earth's resources and for safe and satisfying use of the living environment it gives him. A revolution in our understanding of earth processes appears to be in progress, a revolution that will affect all the earth sciences and one in which seismology plays a key role. At such a time, a strong basic program in seismology is vital.

For these reasons, the present appears to be a critical time for seismology and for its potentials for service to the nation. A fresh assessment of the status of the science seems essential–its past, the present, and its prospects and orientation for the future.

This report has been prepared by the Committee on Seismology of the Division of Earth Sciences, National Research Council. The report is divided into two parts: *Part I, Summary and Recommendations;* and *Part II, Problems and Prospects*. Each part is intended to be complete within the context of its particular purpose.

Part I, Summary and Recommendations, summarizes essential background information and lists the Committee's major recommendations and comments. Part I is intended primarily for use of those for whom a concise version, emphasizing only the essentials, may be of special value.

Part II, Problems and Prospects, reviews the history of the science of seismology, in the United States in particular; discusses the main areas of research effort and interest and the main applications of seismologic methods over the years; and attempts to provide insights into new or insufficiently exploited areas of research and application that can benefit the nation. Part II is intended to give planners, administrators, educators, and students who may be interested in current and potential uses of seismology a reasonably comprehensive overview of the science, including its relationship to national purposes and its uses and potentials with respect to achieving these purposes.

Jack E. Oliver, *Chairman*
Committee on Seismology

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SEISMOLOGY COMES OF AGE

From its rather modest beginning, centered around those who had experienced destructive earthquakes and those few scholars who sought the cause of earthquakes and the information about the earth that earthquake studies could provide, seismology has blossomed into a full-fledged scientific discipline with contributions and ramifications of interest to much of society. The great intellectual challenges associated with the genesis of earthquakes and the nature of the earth's interior still remain, but seismology has now also become extremely important as a practical commercial tool–in the search for oil and mineral wealth; in civil engineering and the construction industry through their concern with earthquake-resistant design, vibration effects, and subsurface characteristics; politically, socially, and militarily, through the monitoring of nuclear explosions and of such effects of natural earthquakes as tsunamis; and in many other applications.

On the intellectual level, where probing of the earth's interior is of primary interest, there is currently the air of excitement that occurs in a scientific discipline only when a major–in this case revolutionary–advance is being made. This spirit now prevails throughout all of the earth sciences, for it appears that man is on the verge of understanding at last the vast tectonic processes that are responsible for most of the surface features of the earth on which he lives. This optimism is rooted in the recent widespread verification of the sea-floor-spreading hypothesis, which proposes that the active world rift system, lying largely beneath the sea, is a source of new surface material that spreads away from the rifts and ultimately sinks again beneath the earth's crust. Migration of "drifting" continents, creation of mountain ranges and deep-sea trenches, volcanoes, earthquakes, and a variety of other observed effects appear to be manifestations of this process, which probably involves massive, slow convection in the subcrustal materials driven by heat from the earth's deep interior (see Figure 12 in Part I of this report).

Observations from the science of seismology, our prime source of information about the earth's interior, are vital to the testing and development of these new theories of global tectonics. Some crucial contributions have already been made, but much remains to be done. The new understanding of the earth's tectonics, on the other hand, provides fresh stimulus for further seismological research. Appreciation of the great mobility of the earth's surface features and appreciation of the relation between these features and the earthquake phenomenon will surely provide new inspi[illegible] for solution of the classical problems of seismology.

As another result of "the new tectonics," with [illegible]t breadth and its capacity for unification, much greater coupling between seismology and other disciplines of the earth sciences must be anticipated. Information from one field will be relevant to the concepts of another to a much greater degree than in the past. This increased interplay between the subject matter and the scientists of various disciplines will have a healthy, stimulating effect on all of the earth sciences, and particularly on seismology, which is so intimately involved in this research area.

While the new tectonics commands much attention among seismologists, there are clear-cut indications of latent discoveries of major importance in other areas. The structure of the earth's core, for example, is not yet determined with the precision that is within the capabilities of seismology. The close relation between this structure and the properties of matter under high pressure and temperature calls for direct interaction between seismology and solid-state physics and suggests an approach toward a better understanding of the basic properties of matter as well as of the characteristics of the earth.

For those whose prime interests lie outside the realm of basic science, there are other stimulating topics involving seismology. Politically, the prospects for a comprehensive nuclear-test-ban treaty improved markedly with the acceptance in mid-1968 of the nonproliferation agreement. Seismological techniques will play a key role in the negotiations for such a treaty and in the monitoring that will be vital for the protection of the signers of the treaty. Commercially, the future of seismology as an exploratory method seems bright. In spite of the advances made or anticipated as a result of the introduction of nuclear fuels, there is no indication of a slackening of petroleum consumption, and recent major discoveries of oil reserves, and assessments of future power needs indicate that it is far too soon to discount the value of fossil fuels as a power source.

The following chapters discuss the various aspects of the field of seismology in greater detail. They demonstrate the broad scope and range of applications of the science, emphasizing its potential promise for the future.

EARTHQUAKE SEISMOLOGY IN RETROSPECT

Historically, the science of seismology has been largely the science of natural earthquakes, although in the last few decades artificial means of causing vibrations in the earth have been used increasingly and with increasing effect. Although natural earthquakes, together with volcanic eruptions, have always deeply impressed mankind, the scientific study of earthquakes is a young subject. The quantitative side of seismology goes back only about seven decades, but seismology has already provided most of the knowledge available about the physical properties of the earth's interior. Seismological theory and observations have given us the ability to predict the regions in which strong earthquake activity is highly likely; and, in mineral prospecting, seismological techniques have been developed that can locate buried rock strata precisely.

In earthquakes, strain energy is released in the outer part of the solid earth and seismic waves thus generated penetrate the earth. As earthquake science has developed, its content has come to have five main parts: the genesis of the strain; the mechanism of energy release; the nature of the ground dynamics, particularly near the source; the nature of the seismic waves; and the physical properties of the transmitting medium.

The theory of waves in a deformable material has become a highly developed part of mathematical physics. It attracted the attention of such distinguished mathematicians as Poisson, Kelvin, Rayleigh, Lamb, Love, and Jeffreys, each of whom worked on specifically seismological problems.

It was recognized during the nineteenth century that if an elastic solid is excited in any way, such as by hitting it with a hammer, waves are generated that leave the point of excitation and travel through the body of the solid. If there is a free surface to the solid—such as between the solid earth and the atmosphere—other waves are also generated that travel around the surface of the solid rather than through its body. The body waves are of two types—P waves, or compressional waves, and S, or shear, waves. The shear waves are produced essentially by the shearing or tearing motions of earthquakes. The wave forms of the body waves and the velocities of travel yield information about the nature of the medium through which they travel. At any interface, body waves are reflected or refracted with or without change of type. This possibility of change of wave type at an interface makes for complexity of the seismic record, but it also provides additional information. Thus, it soon became clear that information on the earth's internal structure could be deduced from the measurements of the arrival times, periods, and amplitudes of the seismic waves recorded on the earth's surface. Moreover, the longer-period surface waves, which are affected by the properties of the earth to a depth of 3,000 km, permit us to look at the earth in a different way than do the P and S body waves.

By 1907, papers by R. D. Oldham, M. P. Rudski, A. Schmidt, and E. Wiechert were calling attention to the fact that the speed of body waves increases generally with depth in the earth and inferring the presence of discrete "shells" in the earth—crust, mantle, and core—having different compositions and characteristics. Somewhat later, it became apparent that seismic waves could be used to obtain information on the dynamics of earthquakes themselves, including the energy released and the geometrical form and extent of the source.

GREAT EARTHQUAKES

Nothing advances the study of earthquakes more than a large shock in a populous region—provided the studies are made by competent seismologists. In retrospect, certain earthquakes stand out sharply as illustrations of this facet of seismology's development.

The great earthquake under the Iberian peninsula on November 1, 1755, was felt over much of Europe; more than 50,000 people were killed, and Lisbon was devastated from the shaking, fires, and a series of tsunamis (seismic sea waves). This catastrophe inspired considerable scientific speculation about earthquakes; it stimulated seismological work by the Reverend John Michell, Professor of Geology at Cambridge University, who invented the torsion balance later used by Cavendish to determine the constant of universal gravitation and, from this, the mean density of the earth. Michell, rather than relying on the writings of Aristotle, Seneca, and Pliny, as most earlier seismologists had done, approached his inquiries in terms of Newtonian mechanics.

Italian earthquakes have for centuries stimulated pioneering research by Italian and other European workers. The Calabrian earthquakes of 1783, which killed over 35,000 people, led to one of the first "earthquake commissions," sponsored in this case by the Academy of Science of Naples. Later, the Neopolitan earthquake of December 16, 1857, was studied by the Irish engineer Robert Mallet; his writings define not only many of the seismological terms in use today (e.g., seismic focus, isoseismal line, meizoseismal area) but also many of the cardinal problems of seismology. He thought of seismic vibrations as caused by "a wave of elastic compression in any direction from vertically to horizontally, through the surface and crust of the Earth. . . ."

Japanese earthquakes have also played a historically important role in seismology. It is said that the Yokohama earthquake of February 22, 1880, stimulated John Milne, who had just been appointed Professor of Geology and Mining at the Imperial College of Engineering, Tokyo, to devote his life's work to seismology and to play a leading role in the founding of the Seismological Society of Japan, the first professional seismological group in any country. In 1891, further interest was aroused by a damaging earthquake in the provinces of Mino and Owari, associated with substantial faulting. Professor B. Koto of Tokyo University made one of the first *geological* studies of faulting as it appears just after an earthquake. He ventured the opinion that "the sudden formation of the 'great fault of Neo' was the actual cause of the earthquake. . . ." Although the theory that fault rupture *causes* earthquakes has not appealed to many leading Japanese seismologists, it became the most widely held theory for earthquake genesis following the work of H. F. Reid on the 1906 California earthquake.

The great California earthquake of 1906 definitely marked the beginning of a new era in the history of seismology in the United States. It was realized that the science was unorganized in America, that seismographic stations were too sparse and too widely located and generally not equipped with the best modern instruments, and that an important field of research exists concerned with the physical, geological, and engineering aspects of earthquakes (see Figure 11, Part I). The first effect of this realization was the organization of the Seismological Society of America in San Francisco in late 1906. This society has done much to further seismology and continues to publish the only journal devoted solely to earthquake science in the English language, the *Bulletin of the Seismological Society of America.*

Agitation grew for new seismographic stations and improvement of those already in existence. Professor Andrew C. Lawson, Chairman of the California State Earthquake Investigation Commission that studied the 1906 earthquake, printed a statement in 1907 pointing out the deficiencies in knowledge of earthquakes, their causes, factors controlling the distribution of intensity, the constant destructive effects, the practical question of minimizing the loss of life and property; and he also stressed the lack of sufficient numbers of trained seismologists.

The Carnegie Institution of Washington became interested in seismology during this period. In addition to supporting the State Earthquake Investigation Commission, it arranged with the California Institute of Technology to build a seismological laboratory to serve as the center for the research work in seismology for the Carnegie Institution, and also as the central unit of a group of seismographic stations (later to form a network maintained by the California Institute of Technology).

Although not in the "great" category, two California earthquakes that occurred more recently deserve mention. A shock of magnitude 6.3 on the Richter scale occurred on March 10, 1933, centered about 10 miles from Long Beach; 120 people were killed and many schools damaged. Fortunately, the schools had already closed for the day, but the public realization that an awful calamity had been narrowly escaped led the California State Legislature to pass the Field Act, which regulates the construction of public schools (see Figure 3, Part I). Earthquake provisions have recently been incorporated into the building regulations of the State Health and Safety Code (Assembly Bill Number 1136 [1965]).

A continuing engineering use of seismology is the measurement of the kinematics of the ground near the centers of large earthquakes under various soil and geologic conditions. Despite the slow but steady spread of strong-motion recorders in the western United States, Japan, New Zealand,

and elsewhere, the ground acceleration near the source of a great earthquake has not yet been recorded. The most widely used records of strong motion were obtained by a U.S. Coast and Geodetic Survey instrument at El Centro, California, during the Imperial Valley earthquake of May 18, 1940. The shock had a Richter magnitude of slightly over 7, and the crucially important records were obtained some seven miles from the epicenter.

In the last decade, two truly great earthquake sequences, both containing shocks with magnitudes exceeding 8¼, have contributed heavily to seismological knowledge. The first of these sequences occurred along the coast of Chile in May 1960. Damage was widespread, the Chilean economy was seriously affected, and over 1,500 persons were killed as a result of the shaking and the tsunami. (The tsunami from this earthquake caused loss of life in Japan, almost halfway around the globe.) Many novel theoretical and practical studies have been made of this great sequence of shocks. A series of eight papers (mainly on engineering aspects) was published as a special volume of the *Bulletin of the Seismological Society of America.*

The most recent "great" earthquake, which occurred on March 28 (GMT), 1964, near the head of Prince William Sound, Alaska, has been the most studied earthquake in the history of seismology (a comprehensive, multi-volume report is in preparation by the Committee on the Alaska Earthquake of the Division of Earth Sciences, National Research Council). Painstakingly detailed investigations have been carried out concerning all aspects of the earthquake, from the effect on marine life to the effect on the upper atmosphere, from the psychological reactions of the inhabitants to the changes in glacier flow. Special volumes are being published by the U.S. Geological Survey and by the Environmental Science Services Administration as well as by the National Academy of Sciences, and many special studies of social, geological, engineering, and seismological interest have been carried out. The earthquake was the most energetic in the United States since the 1906 California shock, and it occurred in a region of known recent seismological activity. In retrospect, it is hard to understand why, given the known history, more steps had not been taken both to mitigate the earthquake hazard and to exploit scientifically the occurrence of a large earthquake in Alaska. Building codes were not restrictive enough to prevent construction in unsuitable areas such as the Turnagain slide area and waterside areas at Seward and Valdez. No strong-motion accelerometers had been installed in Alaska at the time of the earthquake, and there was a general lack of specially equipped seismological observatories.

These two great earthquakes provided for the first time unequivocal records of the free oscillation of the whole earth. Since 1960, theoretical and observational work on the free oscillations have expanded into a special branch of seismology, called "terrestrial spectroscopy" by C. L. Pekeris, H. Jarosch, and Z. Alterman, who have made notable contributions in this field. The frequency spectra of the oscillations, recorded by special long-period instruments, showed multiplets due to the earth's rotation. Analogous multiplets had already been studied in quantum physics and in astronomy in connection with the rotation of massive stars.

FUNDAMENTAL SEISMOLOGICAL PROBLEMS

Throughout the history of the science, seismologists have continued to give special attention to two central questions: The first is the quest for a full understanding of the causes of earthquakes and of their mechanism (or mechanisms); and the second is a complete explanation of the elastic waves recorded at seismographic observatories, in terms of wave theory and the inferred structure of the earth.

There is as yet no fully worked-out description of earthquake genesis that will allow, for example, the prediction of the occurrence of an earthquake in both time and space. Indeed, the possibility cannot yet be ruled out that earthquakes at different depths have different mechanisms. One essential difficulty is that the global forces that deform the earth are not well understood; two of the main competing hypotheses are (a) radial contraction (or expansion) of the earth as a whole and (b) slow convective motion of the material in the earth's upper regions. These regimes may, of course, occur together or at different times. Recent findings concerning sea-floor spreading and continental drift have stimulated new thinking about these problems. Despite the difficulties, statistical analyses have been made of the frequency of occurrence of earthquakes; early seismologists such as Knott, Montessus de Ballore, Omori, and Davison devoted much time to the subject of earthquake prediction, but no reliable periodicities have yet been detected.

The immediate cause of earthquakes has been held by some seismologists to be fast dilatation or compression of a volume of rock and by others to be a sudden rupture of the rock. The first theory goes back at least to the Greeks who favored explosive sources, probably because of the proximity of the Aegean volcanoes; in its present form, rapid phase changes in a restricted region are postulated. The second theory is the most commonly held in the United States; it envisages the release of elastic strain energy by fracture of previously strained rock. (Earthquakes occurring in the neighborhood of volcanoes involve some special problems, and volcanic earthquakes are usually treated separately from tectonic shocks.) In the nineteenth century, Robert Mallet wrote that earthquakes are generated by the sudden change in constraints of the elastic materials of the earth's crust "or by their giving way and becoming fractured." It was Professor H. F. Reid who in 1906 formulated the theory in terms of elastic rebound along a tectonic fault. Although only a relatively small percentage of all earthquakes (but many destructive earthquakes) have been accompanied by observable faulting at the earth's surface, this concept has proved a very fruitful one and is the basis of much theoretical and observational work. One argument that has been advanced against the theory is that even at moderate depths in the crust the overburden pressure becomes so great that ordinary brittle fracture becomes mechanically impossible. Work in rock mechanics is now directed toward a better understanding of the fracture of rocks at high temperatures and pressures and of the nature and role of lubrication.

SEISMOMETRY

Before about 1880, attempts at recording were aimed at showing only that an earthquake had occurred. The recording devices were called seismoscopes; they often also indicated the direction of the disturbance, and a few attempts were made to determine amplitudes. Professor L. Palmieri, in his observatory on Vesuvius, introduced timekeeping in 1856. He arranged short pendulums so that the motion generated by an earthquake would cause them to make an electrical contact and so start or stop a clock.

At the end of the nineteenth century, a group of seismologists in Japan helped to open up modern observational seismology. Notable among them were John Milne, J. A. Ewing, and F. Omori. Tangible results were achieved in designing horizontal pendulum seismographs that recorded seismic waves continuously on a moving strip of paper; the system was wholly mechanical, but time marks were placed on the records. Many instruments based on the pendulums of Milne and Omori were to find their way to stations around the world, and they contributed much to seismology.

About the turn of the century, instruments with more-suitable magnification, timekeeping, and recording characteristics were constructed. Particularly important were the Wiechert seismographs, developed in Germany, which recorded both horizontal and vertical ground motion. The San Francisco earthquake of 1906 was recorded by some 90 seismograph stations outside the United States, of which eight were equipped with Omori or Bosch-Omori seismographs and over 15 with Milne instruments. (The Wiechert instruments gave by far the clearest resolution of the seismic waves.)

Most seismograms written by instruments of these types, however, did not resolve the wave trains sufficiently to allow the time of wave arrivals to be read reliably; instrumental frequency responses were quite restricted, and, because of low magnifications, only the larger or nearby earthquakes were recorded. Fundamental advances in seismometry came with the work of B. B. Galitzin in Russia and H. Benioff in the United States. Galitzin connected a galvanometer to a transducer coil on the pendulum and recorded directly on photographic paper, thus eliminating frictional drag between stylus and paper. (Milne also used photographic recording in Japan.) Galitzin also devised a method to calibrate his seismograph and worked out a theory for it. Modified Galitzin instruments were installed at a number of observatories after the First World War. These seismographs recorded with fidelity trains of earthquake-generated surface waves with periods greater than 10 seconds, and opened the way for research into the nature of these waves. The recording of shorter-period waves with high magnification of the ground motion was achieved by Benioff about 1930. The basic modification was to replace the "moving coil" with a "moving magnet" so that pendulum displacements varied the reluctance of a magnetic circuit. These instruments, installed in seismological observatories, led to an immediate improvement in the precision of the measurement of travel times of seismic body waves through the earth's interior.

Later research in seismometry has been directed toward the design of recording systems with greater dynamic range, bandwidth, and sensitivity and toward the development of special devices to measure directly such elastic parameters as dilatation and strain. A recent major advance has been the development of large seismic arrays used in conjunction with high-speed data-processing equipment.

NETWORKS OF OBSERVATORIES FOR A GLOBAL SCIENCE

Just as optical astronomy has depended primarily upon astronomical observatories for the study of the universe, so seismology has depended upon seismographic stations for the study of the earth's interior. The principal raw materials of the science have been the seismograms from stations distributed around the world. The need for a global network was recognized by the early seismologists. John Milne wrote in 1883, "It is not unlikely that every large earthquake might, with proper instrumental appliances, be recorded at any point on the land surface of our globe." A few years later Milne was responsible for a small worldwide network of stations (many at astronomical observatories) equipped with Milne seismographs. Nowadays, earthquakes as small as magnitude 4 are recorded at all distances at well-equipped observatories.

Hans Benndorf, in two papers published in 1905 and 1906, demonstrated how travel times of seismic waves give information on the terrestrial structure; he computed velocities at certain depths from observed distance curves and noted that shadow zones may arise from low-velocity shells. His contemporary, R. D. Oldham, showed unequivocally the power of this method by using extensive empirical travel-time curves for P and S waves as a function of distance. The curves were plotted using travel times of waves from earthquakes to the first worldwide seismographic stations. Based on these observations, Oldham inferred that the crust could not be thicker than ten or twenty miles and that the increase of wave speeds with depth is mainly due to changes in temperature and pressure. He inferred a central core with 0.4 times the earth's radius, with its outer boundary where the speed of S waves seems to drop significantly.

Through such early findings, the global network took on a clear geophysical significance; improvements in the network made it possible not only to compile much more complete catalogues of the occurrence of earthquakes (previously, earthquake atlases depended only on "felt" reports) but also to work out the detailed structure of the earth. (A similar seismological development can now be contemplated for the other terrestrial planets and the moon.) At the time of the 1906 California earthquake, seismographic stations with timekeeping capabilities to within a few seconds operated on all inhabited continents of the world and on some Pacific islands. Along with the rapid improvements in the science of seismometry after 1906, such as better resolution of the waves and better timekeeping, came an increase in number of stations; in addition, by about 1930, radiotelegraphic signals and radio time signals were being placed on the records at some stations.

A useful contribution was made by a global network of stations established by the Society of Jesus after about 1910. Very carefully maintained Jesuit observatories at such places as Manila (Philippines), Riverview (Australia), Zi-ka-wei (China), and La Paz (Bolivia) proved crucial to much early research. In the United States, a network of stations was operated under the control of the Jesuit Seismological Association at a time when little government or university support for seismology existed.

An International Association of Seismology was founded in 1905 and, after the dislocation caused by the First World War, it sponsored the publication under the direction of Professor H. H. Turner at Oxford of the *International Seismological Summary,* which contains lists of earthquake data computed from observations read from seismograms from the global observatories. The *I.S.S.* commences with earthquakes of 1918, and the lists continue to the present. The International Association was renamed, in 1951, the International Association of Seismology and the Physics of the Earth's Interior.

The work of the IAS, the Bureau Central Séismologique, at Strasbourg, and national organizations such as the U.S. Coast and Geodetic Survey in the United States has led to thorough catalogues of instrumentally recorded earthquakes. The most complete global catalogue remains that of Professors Gutenberg and Richter entitled *Seismicity of the Earth*—a masterpiece of care and systematization; editions were published in 1949 and 1954.

The processing of seismological observations now follows a general pattern all over the world. Most stations make immediate readings of the more legible waves and note them in bulletins. If the stations are part of a regional (or national) network, the regional center makes estimates of earthquake locations and often of earthquake magnitude. Certain stations (including many of those of the World-Wide Standardized Seismological Network), providing more-or-less worldwide coverage, send their readings quickly to the U.S. Coast and Geodetic Survey, where rapid determinations of earthquake locations anywhere on the globe are made. There is a long-standing tradition in seismology of free interchange of station bulletins, seismograms, and other data. As Professor K. E. Bullen has written, "This is the raw material from which much of the knowledge of the Earth's interior ultimately emerges."

SOME HIGHLIGHTS IN THE HISTORY OF SEISMOLOGY

The years between 1900 and the Second World War were particularly fruitful and exciting in the history of seismology. Great progress was made in Germany, particularly at the Geophysical Institute in Göttingen, under Professor E. Wiechert. In the papers "Über Erdbebenwellen," Wiechert and his colleagues and students described methods for inferring velocity distribution from travel-time curves and presented their results. (An analytical method for seismic-travel-time inversion, based on the Abel integral transform, was published by Herglotz in 1907.)

Wiechert thought that few earthquake foci were deeper than 100 km and that most shocks were caused by faults. By the 1930's, studies of the instrumental recordings of seismic waves by H. H. Turner, K. Wadati, S. K. Banerji, R. Stoneley, F. J. Scrase, and others showed that foci occur at depths down to about 700 km, depending on the geographic region. The geophysical implications of this depth distribution are only now beginning to be understood in the light of the hypothesis of sea-floor spreading. There is still no decisive evidence that faults are not the common cause for tectonic earthquakes independent of depth.

Beno Gutenberg, a student of Wiechert and later Director of the Seismological Laboratory, California Institute of Technology, presented new curves from which he inferred for the first time that the depth in the earth to the boundary between a rigid mantle and nonrigid core is 2,900 km. All later work has tended to closely confirm this value. Gutenberg later (in California, in collaboration with C. Richter) pioneered the identification of the complicated seismic phases that arise from reflection and refraction at boundaries within the earth.

In 1910, A. Mohorovicic published some historic discoveries. On the basis of data from local Balkan earthquakes, he concluded that the top of the mantle is at a depth of 50 km and that a major discontinuity exists between the mantle and the crust. The nature of this discontinuity, since named the Mohorovicic discontinuity, is still a geochemical puzzle. A considerable number of seismological field investigations have been carried out since then to determine the structure of the earth's crust. Reflection and refraction profiling methods using artificial explosions and surface-wave-dispersion techniques have become highly developed for this purpose. (Robert Mallet used a gunpowder blast to measure a velocity of propagation as early as 1851.)

Surface-wave studies first provided evidence that on the average the crust is appreciably thinner under oceanic regions than under the continents. The development of oceanography has led to refraction shooting from ships in a great many locations, particularly in the Pacific, Atlantic, and Indian oceans; intercomparisons of the computed velocities and thicknesses are leading to revolutionary speculations about the geological history of the ocean basins.

During the period 1920–1940, the velocity distributions of P and S waves and structural features below the crust were worked out to a close first approximation. The principal investigators were H. Jeffreys, Gutenberg, and Richter. By 1939, following exhaustive programs of research, tables and curves of average travel times in the earth for all the main seismic phases had been published both by Jeffreys (in collaboration with K. E. Bullen) and by Gutenberg and Richter. In the main, there was agreement between the two solutions and between the velocity distributions calculated from them. Broadly speaking, these researchers showed that the earth consists of a solid mantle some 2,900 km thick, between the crust and the liquid core. They found no S waves that appeared to have penetrated the core, although at the very center of the earth there appeared to be an "inner core" (first proposed by I. Lehmann), about 2,500 km in diameter, that might be solid.

Conclusions of different seismologists in the 1920's and 1930's concerning the structural implications of the available observational material differed in detail. Gutenberg, for example, construed his travel-time and amplitude measurements to imply a reduction in the speed of seismic waves at a depth of about 80 km. Jeffreys, on the other hand, interpreted the evidence as being in favor of increasing velocities at all depths in the mantle. In 1939, he computed the depth of a first-order increase of velocity as 413 km; this solution rested upon the adoption of a discontinuity in the travel-time curves at an epicentral distance of 20°, first inferred by P. Byerly in his 1925 study of a Montana earthquake. Many seismologists in more-recent years have returned to these controversial problems, and many independent techniques, involving body waves, surface waves, and vibrations of the whole earth, have been brought to bear on them. In particular, special research ventures were launched during the International Geophysical Year, beginning in July 1957, and later during the course of the International Upper Mantle Project. The use of travel times from nuclear explosions near the earth's surface has been useful; knowing the location and time of origin reduces the various uncertainties considerably. (The present evidence seems to favor a Gutenberg "low-velocity layer," at least in certain regions, and more definitely for S waves; there is also additional support for a marked velocity increase near the 400-km depth.)

Other currently controversial problems concern the nature of the fine structure within the earth's core and the nature and extent of lateral variations in the physical properties of the mantle. The competing views are in part related to the inductive nature of seismology. Because direct observation of structure is usually out of the question, special attention must be given to methods of inference. The use of mathematical models, crucial tests, and measures of significance have played an especially important role. Much of the seismological interaction with probability theory and scientific inference stems from the classical work of H. Jeffreys, and the interaction is growing. As well as travel-time studies, statistical methods have been developed and refined in seismological studies of focal mechanism, time-series analysis of earthquake occurrence, array design and processing, and Fourier analysis of waves and vibrations.

Once global seismic velocity distribution functions are established, it is possible to derive related distributions for density, rigidity, and incompressibility in the earth. Despite early attempts by Laplace, Wiechert, and others, based on measurement of the earth's mass and figure, it was not until after seismology provided speeds of P and S waves as a function of depth that any detailed knowledge emerged about the density and constitution of the earth. The work of L. H. Adams, E. D. Williamson (both of the Carnegie Institution of Washington), K. E. Bullen, and F. Birch on these problems is particularly significant.

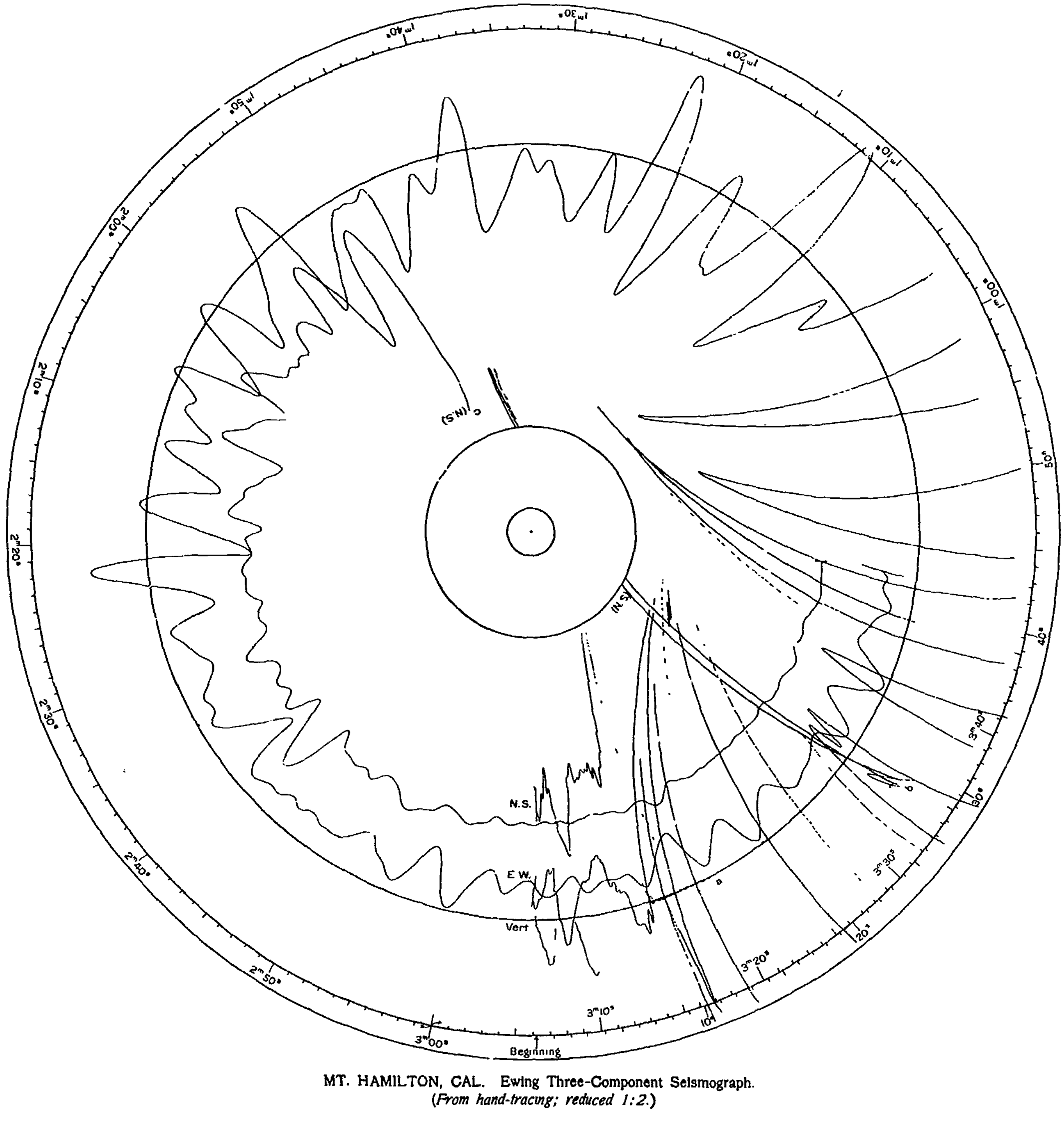
U.S. Contributions

The first seismographic stations in the United States were established in 1887 at Mt. Hamilton and Berkeley, California, through the interest of E. S. Holden, President of the University of California and Director of the Lick Observatory at that time. Holden considered it necessary to "keep a register of all earthquake shocks in order to be able to control the positions of the astronomical instruments." He came to the conclusion that "the most satisfactory instruments which I have seen are those invented by Professor Ewing, F.R.S." One of the Ewing instruments gave the first measurement of strong ground motion in America during the 1906 earthquake (Figure 1).

Under the influence of the experiences of the 1906 earthquake, the two University of California stations were supplied with modern equipment, and periodical publication of their observations has been made in the *Bulletin of Seismographic Stations* (January 2, 1912, to the present). Regional stations were set up after 1925 in southern California, with headquarters at Pasadena and under the supervision of H. D. Wood and J. A. Anderson; these stations are equipped with specially developed Wood-Anderson torsion seismographs.

For many years, the U.S. Coast and Geodetic Survey, now part of the Environmental Science Services Administration, has performed an important service in seismology in the United States. Work with strong-motion seismographic instru-

EARTHQUAKE INVESTIGATION COMMISSION



MT. HAMILTON, CAL. Ewing Three-Component Seismograph.
(*From hand-tracing; reduced 1:2.*)

FIGURE 1 Record from early Ewing three-component seismograph at Mt. Hamilton, California, showing east-west component of strong-motion acceleration during the 1906 San Francisco earthquake. (Courtesy of the University of California, Berkeley.)

ments was started in 1932 and was considerably stimulated by the destructive Long Beach earthquake of 1933. In 1936, the work was officially organized as the Seismological Field Survey. The Survey maintains a questionnaire program, collects field data on important earthquakes, and is in charge of the installation and operation of strong-motion seismographs at various locations. The Environmental Science Services Administration was responsible for the upkeep (in 1967) of 186 strong-motion accelerometers: 144 in California, 15 in Alaska, and 27 elsewhere. The knowledge acquired about local earthquakes is published in the yearly report entitled "United States Earthquakes" and in other publications of the U.S. Coast and Geodetic Survey.

In any scientific activity it is always difficult (and often invidious) to try to determine what is unique in the contributions of a particular country or particular scientists. Seismologists of the United States have both learned from the work of colleagues in other countries and contributed significantly to the whole spectrum of seismological research. By way of illustration, we might select seismometry and studies of earthquake mechanism and long surface waves as three parts of the subject that owe much of their vitality to the work of U.S. seismologists.

As we have noted, it was about 1930 that Professor Hugo Benioff began work on earthquake instrumentation. His first great success was the high-sensitivity short-period seismometer with the variable-reluctance unit. He followed this success by publishing in 1935 a description of an electromagnetic linear extensometer that could measure directly the strain between two points in the rock. Benioff then invented a variable-capacity transducer to measure the minute displacements. Benioff strain seismometers that can measure strain of 10^{-10} are now in operation in the United States.

A particularly useful instrumental advance, the small torsion seismometer with a period of 0.8 sec and station magnification of 2,800, was designed by Wood and Anderson in 1922. The instrument was relatively inexpensive and recorded local earthquakes clearly. A consequence of the existence of the network of these seismometers in California was the introduction by C. Richter in 1935 of an instrumental "magnitude scale" for earthquakes. The success of the idea has been extraordinary and has led to a great deal of research in many countries into the concept of magnitudes. Richter's original definitions have been extended with varying degrees of success to magnitude scales that apply to earthquakes outside California and are not necessarily recorded on Wood-Anderson instruments. Part of the strong demand for magnitude information comes from earthquake engineers who wish to compare the "strength" of earthquakes in the historical record within and between seismic regions. Somewhat faltering steps have been taken to correlate magnitude with both earthquake intensity and the energy released by an earthquake. Much remains to be done on these problems.

Attention has been given in the United States to the design of strong-motion accelerometers. The most successful current instruments contain torsion pendulums of the type used by Wood and Anderson. (Useful strong-motion seismographs have also been developed in Japan, New Zealand, and the Soviet Union.)

In the last decade, two developments in observational seismology have occurred in which the United States has played a leading part. The first has been the design of systems with broad-band frequency-response characteristics for recording, either analogue or digital, on magnetic tape. The second has been the use of arrays of seismographs, linked by telemetry, to enhance the signal-to-noise ratio and also to study the behavior of wave fronts propagating across a region. Although analogous systems had been introduced into seismic prospecting much earlier, the necessary funds for earthquake seismology became available only through the Vela-Uniform Program of the Advanced Research Projects Agency, in which large federal support was given to general seismological research.

The most ambitious seismic array to date is the Large Aperture Seismic Array (LASA) built near Billings, Montana, under sponsorship of the Vela-Uniform Program (see Figure 16, page 56). The LASA experiment attempts to exploit in seismology techniques already used in radar, sonar, and radioastronomy, such as signal processing and array theory. This array consists of over 500 linked seismometers distributed in 21 clusters over a 200-km aperture. The availability of digital data on magnetic tape now makes possible processing and analysis by high-speed computers, signal enhancement by combinatorial and velocity filtering techniques, and beam directivity.

There is little doubt that most quantitative work on earthquake mechanisms has been crucially affected by the conjectures of H. F. Reid, based upon the U.S. Coast and Geodetic Survey triangulation measurements before and after the 1906 earthquake and tested using models made of jelly. Most mathematical treatments of the earthquake source, many of which have been developed by U.S. theoretical seismologists, attempt to model the strain-release-by-rupture mechanism of Reid, with additions such as the propagation of dislocations, effects of the fault boundaries, and viscoelasticity.

The study of seismic waves themselves sheds light on the source mechanism. Because the mathematical description of elastic waves from even such an elementary source as a point impulse on the surface of a homogeneous elastic half-space, dealt with in 1904 by H. Lamb, is quite complicated, the problem must be approached piecemeal. Laboratory experiments employing seismic models have proved suggestive, as have numerical approximations to the equations of motion. Perhaps the most thoroughly developed technique involves the determination of the directions of onsets of the first P waves at the earth's surface. Early in the century, patterns of first motions in individual earthquakes were plotted in Japan by Omori, Shida, Kawasumi, and others. In 1923, H. Nakano derived the mathematical representation of various force systems at an earthquake focus. P. Byerly examined the global distribution of P-wave polarity in an unsuccessful attempt to determine the orientation of the plane of faulting in the Montana earthquake of June 28, 1925; in 1938, he presented the stereographic-projection method of treating first P motions. The technique and underlying theory of first-motion fault-plane analysis have been greatly elaborated in the ensuing years, and the focal mechanics of a great many earthquakes have been studied in this way. Recently, in order to help remove an indeterminacy in the solutions using P waves alone, Byerly and his students extended the method to include the polarization of S waves. Additional work has shown that the phase relations in the harmonic components of surface waves can also be used, in certain circumstances, to determine the orientation and extent of the fault and even to obtain an estimate of the velocity of rupture. It is likely that, with future refinements, focal-mechanism solutions of small local earthquakes, as well as teleseisms, will become an integral part of geological studies of contemporary regional tectonics and even of global deformation.

For about the last two decades, U.S. seismologists have had success in investigation of the long-wavelength part of the seismic-wave spectrum. In this work, the design and successful operation of seismographs and gravimeters with stable long-period response characteristics have been decisive. Workers at the Seismological Laboratory of the California Institute of Technology and at the Lamont Geological Observatory, Columbia University, have been in the forefront of these developments. The modification of the Galitzin instrument by F. Press and M. Ewing in 1955 enabled the assembly of empirical data concerning the dispersion of surface waves from earthquakes with periods as long as 500 seconds. Such waves involve significant particle motions through much of the earth's mantle, and by comparison with appropriate mantle models, inferences on structure can be made. The ability to construct realistic theoretical models from the complicated equations that describe elastic waves has hinged on the availability since about 1960 of high-speed computers and on the development of a matrix computational algorithm for layered elastic media. The relevance to seismology of transfer matrices, already used in structural engineering analysis, was first seen by W. T. Thomson and N. A. Haskell and subsequently has been greatly extended, to both surface and body waves, by a number of seismologists.

With certain restrictions, it is possible to investigate the motion of the earth from earthquakes either in terms of traveling waves or in terms of normal modes of oscillation. The modal theory has proved increasingly valuable in seismology. It has achieved particular success in the analysis of the earth's free oscillations. The problem was first treated theoretically by Lamb in 1882. It was not until 1954, however, when H. Benioff described as a free oscillation an oscillatory movement with a period of 57 minutes from a great earthquake in Kamchatka, that the likelihood of experimental confirmation was taken seriously. The renewal of interest was reflected in the publication of many theoretical papers in the following years. The search for these free oscillations of the earth had a final spectacular success with the analysis of records from the great 1960 Chilean earthquake. In July and August 1960, three groups from the United States presented preliminary communications of observations of these graver modes at the Helsinki meeting of the International Association of Seismology and the Physics of the Interior of the Earth.

This branch of earthquake science continues to grow. Since 1960, analyses made in the United States and elsewhere of records from other earthquakes have isolated the complete normal-oscillation frequency spectra (in the fundamental mode) for the two types of particle motion, from the gravest period (54 minutes) down to periods usually associated with body waves. Hand-in-hand with this work have gone measurements of the attenuation of the vibrations and waves. Such measurements lead seismology from the study of a purely elastic earth to the behavior of a viscoelastic one; preliminary estimates of the frictional dissipation as a function of depth in the earth have already been made.

Current seismological research is influenced by facilities and techniques growing out of the Vela-Uniform program—the World-Wide Network of Standardized Seismograph Stations (WWSSN), for example; by the new concept of sea-floor spreading; by the possibility of earthquake prediction; and by powerful computer-aided analytic techniques designed to study wave propagation.

Instrumental studies are being made in the higher and lower frequency ranges—higher to study micro-earthquakes and lower to overlap surface-wave with free-oscillation studies. Measurement of earth strain is made over long time periods for prediction purposes and also for short time intervals to detect rapid strain changes associated with the earthquake source.

Many focal-mechanism studies are being made both to achieve a better understanding of the mechanism and to obtain the sense of motion at the source for comparison with the theory of sea-floor spreading.

A major revision of the seismic-travel-time tables has just been completed. This work was partly the result of the great increase in the amount of data from WWSSN stations and from chemical and nuclear shots associated with the Vela-Uniform program, and partly because of the need for better tables to obtain more-accurate hypocenter locations.

Great strides are being made in determining lateral inhomogeneities in the crust and upper mantle and in relating these variations to differences in heat flow, gravity field, and the concept of sea-floor spreading.

Powerful analytic techniques, usually computer-aided, are making possible preparation of synthetic seismograms for comparison with observed recordings. These will be of increasing importance in unraveling focal mechanisms, lateral inhomogeneities, and the structure of the deep interior.

EARTHQUAKE GEOGRAPHY

Earthquakes do not occur randomly either in time or in space on the surface of the earth. Fundamental contributions of the science of seismology during the first half of the twentieth century were the documentation of the existence of distinct earthquake belts in various parts of the world and recognition of the fact that the occurrence of earthquakes is closely related to mountain-building processes. Field geological studies during the same period demonstrated that earthquakes tend to occur in regions having distinctive geological "earmarks," and it is now possible to identify most regions of high seismicity on geological grounds alone, even in the absence of seismographic records. The recognition that the cause of many earthquakes is fracturing, or faulting, of rocks at depth in the earth's crust is based partly on geologic observations of faulting that reached the earth's surface during large earthquakes, and many earthquake-producing faults have now been identified and geologically studied in detail.

THE CIRCUM-PACIFIC BELT

The great majority of the world's earthquakes occur around the rim of the Pacific Ocean (see Figure 2)–a belt that is also characterized by abundant evidences of recent mountain-building, such as active volcanoes, deep offshore oceanic trenches, and rugged mountain chains underlain by highly deformed young rocks. The westernmost continental United States is clearly part of the seismic zone, as indicated by its characteristic geologic features as well as the historic record of large earthquakes in such states as California, Nevada, and Alaska. Within this highly seismic circum-Pacific belt, many of the largest earthquakes have occurred because of displacements along clearly defined through-going major fault zones, such as the famous San Andreas fault of California. Most earthquakes in this belt, however, have occurred beneath the sea or in areas where the geology is inadequately known, so that it is not yet clear to what extent faults such as the San Andreas are typical of the entire circum-Pacific rim. Geologists have recognized similar features in Mexico, Chile, New Zealand, the Philippines, Sumatra, and Taiwan, but it is possible that some highly seismic regions, such as Japan, are not characterized by major through-going fault systems of this type. One of the major challenges of seismic geology is to try to understand the reasons for the differences and how they affect the evaluation of local seismicity.

THE MID-OCEAN RIDGES

Another very significant belt of seismicity, in terms of our understanding of the mountain-building process, is that associated with the mid-ocean ridges, such as the East-Pacific rise and the mid-Atlantic ridge. One of the great triumphs of modern earth science has been the combined attack by geologists, geophysicists, and oceanographers on the problems concerning the nature and origin of the mid-ocean ridges; the most recent major finding of these studies is that they apparently represent the axes of material rising from deep within the earth–slowly flowing rock that rises beneath the ridges and then spreads out symmetrically on both sides of them to form the ocean floors. Detailed studies of the earthquakes of the mid-ocean ridges, and especially the analysis of seismic waves in order to infer source mechanisms, have proved to be the clinching arguments in establishing the theory that "sea-floor spreading" results from what is probably the dominant dynamic process within the earth; it probably represents the beginning of the long-sought-for answer to the problem of mountain-building (see Figure 12, Part I).

The closely related concept of "continental drift" has in the past been held alternately in favor and in contempt by most geologists; not only does this concept seem at last to have been demonstrated, but its mechanism appears to have been virtually explained at the same time. Many aspects of the problem, nevertheless, remain perplexing—and opinions on the subject are by no means unanimous. For example, the Gulf of California represents one of the very few places in the world where a mid-ocean ridge (in this case the East-Pacific rise) goes "astray" and intersects a continental margin; thus, California and Nevada apparently share some of the characteristics of both the circum-Pacific seismic belt and a mid-ocean seismic belt. How the San Andreas fault and other geologic structures of the Pacific Coast region are related to these two global features remains a major enigma that is currently being attacked on many fronts.

SEISMICITY IN THE UNITED STATES

Despite the concentration of the world's seismic activity in well-defined belts, almost all parts of the world have occasionally experienced earthquakes. Damaging earthquakes in the United States (see Figures 3 and 4) have occurred most frequently in California, Nevada, and Alaska, but two of the largest and most disastrous historic earthquakes have been in Missouri and South Carolina (New Madrid, 1812; Charleston, 1886; (see Figures 5, 6, and 7)—regions characterized by relatively infrequent shocks. Not only is this a perplexing problem for geologists, who are as yet unable to relate these events to obvious geologic causes, but it also puts engineers in the very difficult position of having to decide whether these areas are really any more hazardous than other parts of the eastern United States that do not happen to have experienced similar earthquakes within the relatively short period of historic time. Could a great earthquake like the Charleston earthquake of 1886 strike Washington, D. C., or New York, or Baltimore, tomorrow? (A small earthquake was widely felt in Philadelphia in late 1968.) This problem will probably not be solved until we gain a much more thorough understanding of exactly how and why earthquakes occur.

Some of the most detailed studies of seismicity within an active seismic belt have been carried out in California and Nevada. These studies reveal some important conclusions both for the earth scientist and for the engineer, as well as pointing up some conspicuous gaps in our understanding. Although small earthquakes occur in almost all parts of these areas, virtually all large earthquakes have occurred in close association with major faulting. Likewise, the majority of future large earthquakes will probably be limited to areas of active faulting, and most active faults in this region can be recognized by physiographic features such as scarps, elongate closed depressions, linear rift valleys, groundwater effects, and displaced stream channels (see Figure 8). Indeed, the geologist is often in a better position to delineate these areas of possible large earthquakes than is the seismologist, who must necessarily work with a relatively short history of instrumental records.

PREDICTION

Despite the completeness of the history of seismicity in California since 1800—for the last 35 years based on the records of many local seismograph stations—there are many reasons for believing that this history does not constitute a statistically adequate sample for extrapolating into the future. To achieve reliable extrapolation of historical seismicity information into the future, many hundreds of years of data must be available. Similarly, a recent study of micro-earthquakes at many sites along the San Andreas fault system indicates that micro-earthquakes share the same statistically unreliable distribution as the larger shocks and are not better indicators of future activity. Parts of the San Andreas fault that have experienced further slippage during great earthquakes as recently as 1857 and are prime candidates for future great earthquakes, nevertheless show a virtual absence of micro-earthquakes today. Segments of active faults characterized by occasional very large earthquakes may, in the intervening periods, have extremely low seismicity, possibly owing to some "locking" mechanism. At the same time, segments of fault characterized by the absence of very large earthquakes may experience more or less continuous seismic activity on a smaller scale. In any given area, it will take the close cooperation of geologists and seismologists to arrive at the best evaluation of potential seismicity, but engineers and planners must recognize that *precise* evaluation is impossible at the present state of the science. The same problem, of course, plagues attempts to construct "seismic zoning maps." Although we are in a position to say that some large regions are clearly more hazardous than others, it is not possible to say that there is no hazard in any particular region, and detailed zoning maps must be interpreted with this in mind.

RESEARCH NEEDED TO IMPROVE PREDICTION

It is clear that because the historic record alone cannot give us the answers to the problems of delineating seismicity and constructing seismic-hazard maps, the need for a better understanding of the mechanism of earthquakes is even more pressing. It now seems apparent that our best possibility for predicting earthquakes—or at least for estimating seismicity in a given area—depends more on a true physical understanding of how and why earthquakes occur than it does on the statistical extrapolation of past seismic events. Four particu-

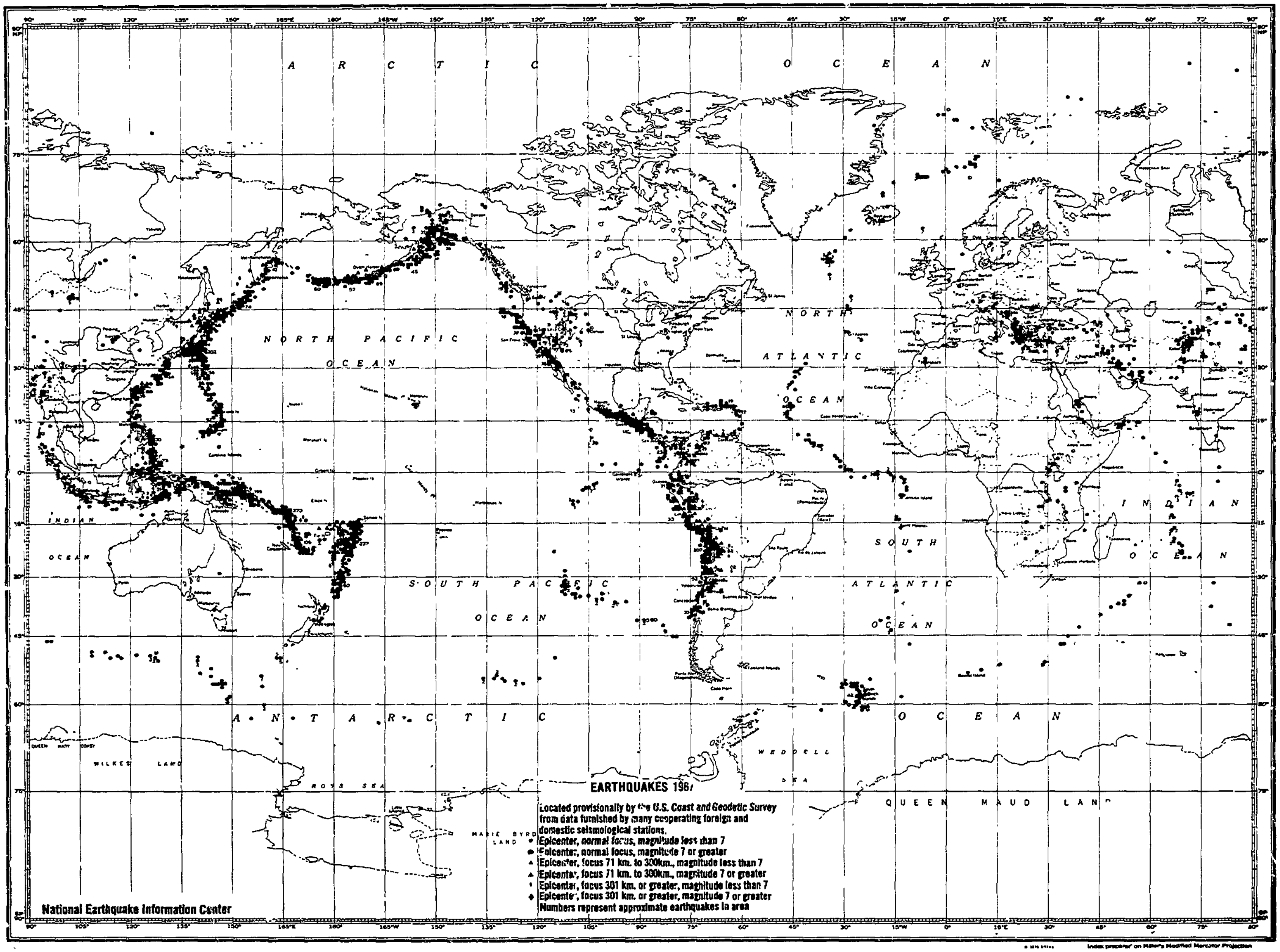


FIGURE 2 World Seismicity, 1967.

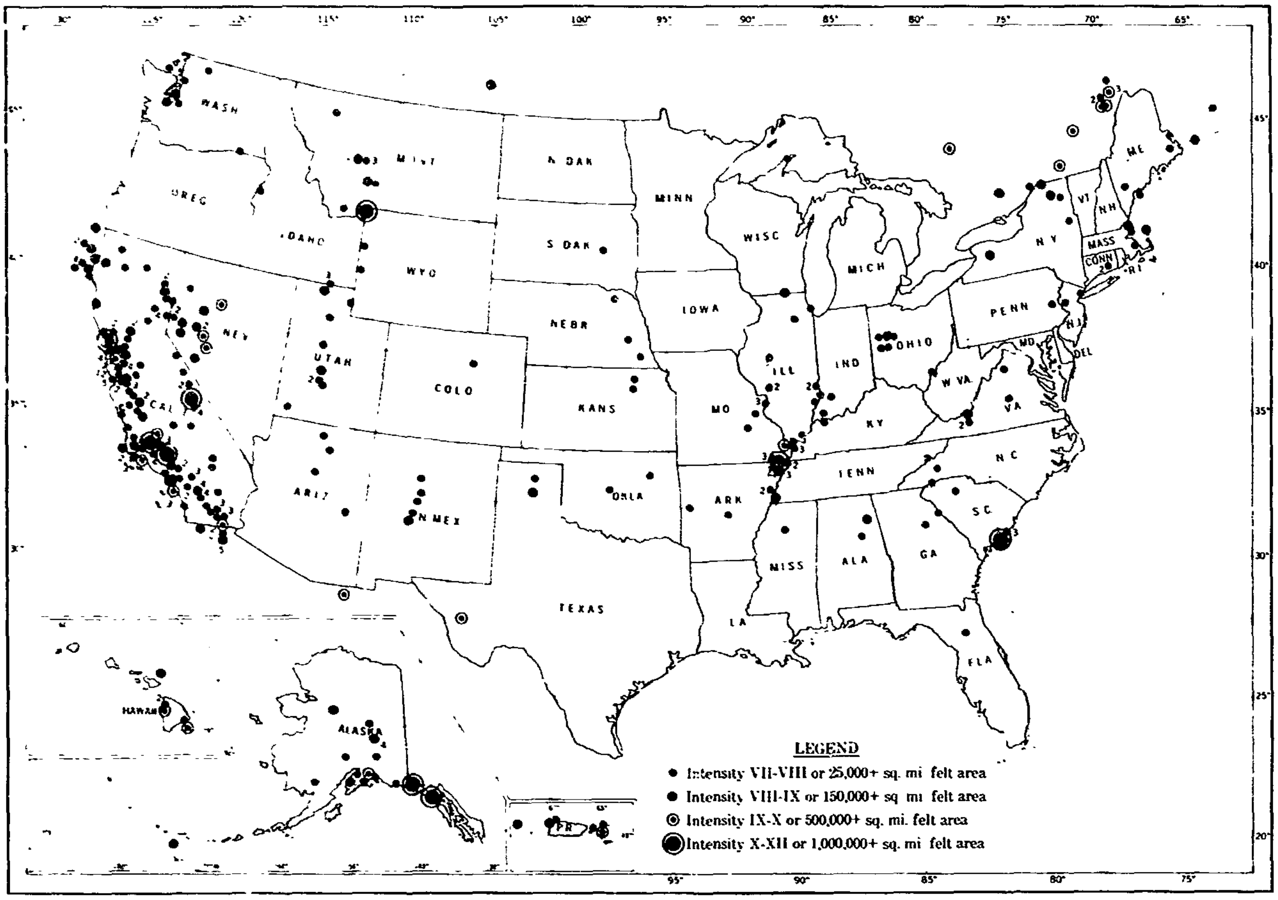


FIGURE 3 Damaging earthquakes in the United States through 1967. The Modified Mercalli Scale of earthquake intensity is used. The following is a slightly reduced and adapted version of the MM scale:

I. Not felt.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt. Standing automobiles rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. Wooden walls and frames may creak.

V. Felt outdoors; direction estimated. Sleepers awakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors, shutters, pictures move.

VI. Felt by all. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., fall off shelves; pictures off walls. Furniture moved or overturned. Weak plaster and average-quality masonry cracks. Small bells ring (church, school). Trees, bushes shake.

VII. Difficult to stand. Noticed by drivers of automobiles. Hanging objects quiver. Furniture broken. Damage to weak masonry. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, etc. Waves on ponds; water turbid with mud. Small slides and caving-in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of automobiles affected. Damage to average masonry; partial collapse. Some damage to good, partly reinforced masonry; none to good, fully reinforced masonry. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Weak masonry destroyed; average masonry heavily damaged, sometimes with complete collapse; good, partly reinforced masonry seriously damaged. Frame structures, if not bolted, shifted off foundations. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown onto banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

larly important avenues of research related to gaining this understanding are discussed below.

- The study of earthquake and fault models, both in the laboratory and from the theoretical point of view, has recently produced many exciting results and holds great promise for the future. Formulation of theoretical elastic and dislocation fault models has already given much insight into what might reasonably be expected within the earth and has pointed up such important parameters as fault offset, peak acceleration, and rock strength that should be measured in the field and in the laboratory. It is hoped that, similarly, laboratory studies of rock failure at high pressures will be able to duplicate some of those aspects of earthquake production that cannot be observed directly in the field. Already, some physical changes precursory to rock failure have been suggested in laboratory experiments; these, in turn, suggest field experiments that might lead to a better understanding of expected seismicity in a given area.
- Much has already been learned through field geologic and geodetic studies of earthquake environments. Such studies must be continued and expanded. Much can be learned in the future concerning earthquake mechanisms by studying ancient fault zones and by studying surface faulting during contemporary earthquakes. Field studies of the 1906 San Francisco earthquake (see Figure 9), for example, stimulated much new thinking about earthquake mechanisms. Studies of stress and strain associated with active faults are particularly important. Although these studies have been dependent primarily on classical geodetic surveying techniques in the past, most of the new and imaginative instruments and techniques are being developed by seismologists and geologists. Laser distance-measuring devices and supersensitive tiltmeters are two examples. The *in situ* measurement of stress, particularly at depth in bore holes, is also currently being vigorously pursued by seismologists and geologists and represents a particularly critical experiment.
- Seismological studies of earthquake source mechanisms based on the interpretation of seismic waves have played an important part in confirming the fault-rupture theory of earthquake genesis and in promoting understanding of the regional stress systems of individual earthquake environments. Several imaginative new techniques based on analyses of various parts of the seismic spectrum have been developed in recent years, and it is clear that this is an area in which new instrumentation and new analytical and computational techniques will bring dividends in the future.
- Seismographic observations must be continued on an expanded scale in active areas such as California, Nevada, and Alaska, both to increase the statistical base from which we may someday be better able to extrapolate into the future, and, by using more and better instruments, to gain a more thorough understanding of the relationship between seismicity and local geologic environments.

FIGURE 4 Damage to buildings on Howard Street, San Francisco, resulting from 1906 earthquake. (Photograph from University of California, Berkeley.)

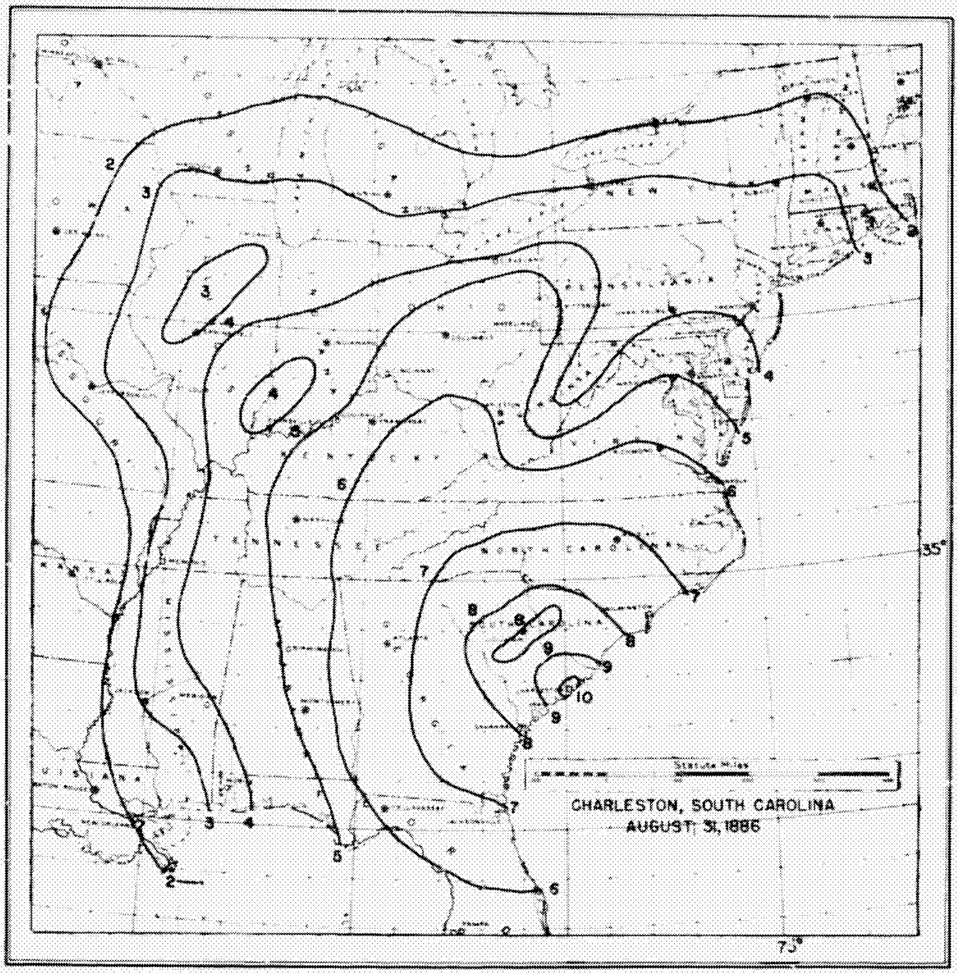


FIGURE 5 Isoseismal map of earthquake at Charleston, South Carolina, August 31, 1886. The Rossi-Forel Scale, 1878, is used. The following is a slightly reduced and adapted version of the R F scale:

1. Microseismic shock. Recorded by a single seismograph or by seismographs of the same model; shock felt by an experienced observer.
2. Extremely feeble shock. Recorded by several seismographs of different kinds; felt by a few persons at rest.
3. Very feeble shock. Felt by several persons at rest; duration appreciable, and direction may be estimated.
4. Feeble shock. Felt by persons in motion; disturbance of movable objects, doors, windows; cracking of ceilings.
5. Shock of moderate intensity. Felt generally by everyone; furniture, beds, etc., disturbed; some bells ring.
6. Fairly strong shock. General awakening of those asleep; general ringing of bells; chandeliers oscillate; clocks stop; trees and shrubs shake visibly.
7. Strong shock. Movable objects overthrown; plaster falls; church bells ring; general panic, without damage to buildings.
8. Very strong shock. Chimneys fall; cracks in building walls.
9. Extremely strong shock. Partial or total destruction of some buildings.
10. Shock of extreme intensity. Great disaster; ruins; disturbance of the strata, fissures in the ground, rockfalls from mountains.

FIGURE 6 Old Guard House at Charleston, South Carolina, following the earthquake of August 1886. (U.S. Coast and Geodetic Survey.)

FIGURE 7 Tradd Street, Charleston, South Carolina, after the August 1886 earthquake. (U.S. Coast and Geodetic Survey.)

FIGURE 8 Trace of San Andreas fault near Simmler, California, looking north. (Courtesy of John S. Shelton.)

FIGURE 9 Offset of 21 feet in a road at the south end of Tamales Bay, California, resulting from the 1906 earthquake. Road segment at lower left was formerly joined to partly obscured segment in exact center. (Photograph from University of California, Berkeley.)

SEISMOLOGY AND OTHER BRANCHES OF EARTH SCIENCE

No branch of science stands alone. Seismology draws heavily on physics and applied mathematics. It requires engineering skills in wide variety. It commonly grades so smoothly into other branches of earth science that any attempt to fix sharp limits to the field of seismology must be arbitrary. This chapter discusses some of these bordering fields of science and some of the relevant topics within them.

Many of these disciplines are brought together in the study of the earthquake mechanism, a fundamental problem of seismology. Information drawn from analysis of seismic waves, such as location of the focus movement along the fault surface, stress drop, and size of the focal zone, must be understood not only in terms of simplified mathematical models but ultimately in terms of the real rocks of the earth. Thus, laboratory data concerning rock deformation under stress drawn from *rock mechanics* information are essential to seismology. This field must be developed to explain rock-deformation characteristics throughout the range of pressures, temperatures, and rock types likely to be found throughout the seismic zones.

The observations of *field geology* are essential not only following a large earthquake, when spectacular effects are immediately visible, but also to determine the past deformational history of the area through the techniques of *structural geology* or *geomorphology* and to uncover information about current deformation through the study of fault creep or slippage. Studies during the past ten years have demonstrated, particularly in California, the great importance of fault creep in the tectonic process; such studies may well provide the key to earthquake prediction and perhaps even prevention, and they must be accelerated.

Measurements of earth deformation using the techniques of *geodesy* are also of great importance to seismology. Leveling and triangulation by conventional methods, as well as by more-modern devices such as tiltmeters and gradiometers, on the continental scale, on the scale of a single state, and even on the scale of a single building, play a vital role in understanding the earthquake mechanism.

Geophysical information from *gravity, geomagnetism,* and *heat flow* studies is also likely to provide important clues to the earthquake process.

The seismologist concerned with earthquake mechanisms and effects must work closely with the *earthquake engineer*, for their fields of interest overlap markedly. The source mechanism, the propagation of seismic waves near the source, the effects of various earth structures on seismic waves, and temporal and spatial properties of seismic activity are interests common to both and subjects to which each can contribute essential information.

Finally, on the grand scale of global *tectonics*, in which man seeks the answer to the long-standing but most fundamental questions of geology, seismology relates closely to almost all of the various disciplines of geology. Recent developments in this field have been spectacular, and many earth scientists are convinced that a single unifying concept is being developed, a concept that will explain why the earth's surface is divided into continents and oceans, why mountains grow in some regions and deep sea trenches are formed in others, why we have earthquakes, why there are volcanoes, and why the earth has gone through the complex deformations that are evident from the geological record.

If this concept of earth tectonics proves correct, it will unify the earth sciences. The data of seismology will be directly related, for the first time, to such widely different areas of study as the *petrology* of volcanic rocks in an island arc, isotope *geochemistry*, the *geomorphology* and *structural geology* of tectonic arcs, the *marine geology* of the ocean floor, *stratigraphy*, even certain aspects of *paleontology*, and certainly *economic geology*. If such a major advance in our understanding of the earth is indeed in progress, then an inescapable consequence is that our ability to find mineral deposits of economic value will be strongly enhanced.

Thus, many aspects of seismology are closely linked with other disciplines of the earth sciences. The student of seismology is frequently the student of other disciplines as well. This coupling effect, which we can easily lose sight of in our efforts to classify and organize our efforts, is an intrinsic property of our science, and its importance to earth science and its potential benefits both scientifically and in terms of man's practical needs are of inestimable, but clearly very great, importance.

THE INTERIORS OF THE EARTH AND PLANETS

THE EARTH

Seismic waves penetrate to all parts of the body of the earth and are our principal tool for exploring and mapping the earth's interior. Just as thorough analysis of starlight and other electromagnetic radiations is giving us a comprehensive understanding of the universe beyond our own planet, thorough analysis of seismic waves is revealing the nature of the earth's interior.

As a result of seismic studies, the general structure of the earth is well known. There is a crust, generally 30 to 40 km thick in continental areas and only about 6 km thick beneath the deeper parts of the ocean. Below the crust lies the solid mantle, extending to a depth of 2,895 km; then the liquid outer core, extending to about 5,150 km; and finally the solid inner core to the center of the earth, at a depth of 6,371 km. (See Figure 13, Part I.)

The Near-Surface Region

In many areas, the shallow layers of the earth's crust have been studied extensively in the course of seismic exploration for oil. A U.S. innovation was the use of the seismic-reflection method for oil prospecting. In this method, seismic pulses generated by shallow explosions or by other types of energy sources are reflected from subsurface rock layers, recorded, and interpreted in terms of oil-producing geologic structure (see Figure 14, Part I). The oil industry provided the stimulus needed to develop the present sophistication of this method–which now includes multiple arrays of instruments, complex digital processing of data, powerful analytical methods and informative displays of results. Reflections at narrow angles of incidence at or near total crustal depths have been observed on occasion, but no systematic continuous profiling of the kind that has served the oil industry so well has been used in crustal-structure studies except at sea; and even at sea, depths of penetration of more than two or three kilometers are not common. The continuing application of these techniques to studies of the total crust of the earth is necessary if we are to extend our knowledge beyond its present rather broad-brush stage.

Studies of crustal structure have thus far been based almost exclusively on refraction methods, and through their use during the past few decades, substantial progress has been made in understanding the entire crust of the earth. The programs of various universities and cooperative studies of the Carnegie Institution of Washington and the Crustal Studies Branch of the U.S. Geological Survey, such as the Lake Superior Seismic Experiment and the East Coast Onshore-Offshore Seismic Experiment, have led to more-detailed knowledge of the crust of North America. Perhaps the most surprising result of these and other studies has been the finding that the crust in the basin-and-range province of the western United States, with mean elevations of two or more kilometers, is thinner (20-25 km) than that in the central plains (40-50 km). It had been thought that the major isostatic compensation takes place at the boundary between the crust and the mantle. Thus, it was expected that the crust would be found to be much thicker in the mountainous regions than in the plains. The contrary finding implies that much of the compensation of some of the elevated regions in the western United States is provided by lower densities within the mantle rather than at its boundary.

A good understanding of the shape and character of the crust-mantle interface would illuminate the processes by which the earth has been formed. It would be extremely worthwhile to find out whether major faults penetrate the Mohorovicic discontinuity, and it would be interesting to know in general how much relief there is at that interface. Our knowledge of certain special regions, such as the continental margins, is vague. The recent increase of interest in continental drift raises the question of whether there are systematic differences between the leading and trailing edges of the continents. There are regions of the world whose geologic structure is little known. Knowledge of the structure of some of these regions is crucial to the broad comparative studies that must form the basis of any complete understanding of earth history. Examples are the African Rift valleys and the greatest of the mountain ranges on earth, the Himalayas.

The Deep Interior

Thus far we have discussed only those seismic measurements, involving surface distance ranges of 300–400 km, that are basic to an understanding of crustal structure. Great progress has been made in establishing travel times for the distance range of 400 to 2,500 km. Since 1955, large-scale chemical and nuclear explosions have made possible detailed studies far superior to earlier studies. It has been established beyond doubt that there are significant regional differences in the travel times in this distance range, and thus there are significant regional differences in the structure of the upper mantle. It now appears probable that there is a low-velocity layer for S waves, and perhaps for P waves, at depths of about 100-300 km beneath parts of the western United States; and there appears to be no doubt also that any low-velocity layer beneath the central United States is insignificant in size in comparison with that beneath the western United States. But there are no efforts of comparable scope and precision elsewhere in the world, and such efforts are essential for comparative studies of structure, which must form the basis of our goal of understanding the internal processes of the earth. It is especially important that we should be able to observe travel times beneath the oceans. This goal is within our technical capability, but more research is needed.

Recent studies have established that there are at least two zones of very rapid change of velocity in the upper mantle, one at a depth of about 350 to 400 km, the other at about 650 km. These changes of velocity are so rapid that it seems likely that there are first-order discontinuities at these depths, probably related to changes of phase, i.e., changes in the crystal structure of the minerals to higher-density and higher-velocity arrangements of the atoms. Careful study, particularly using arrays, should sharpen our knowledge of the behavior of travel times near these zones of rapid velocity change to the point where we will be able to place very close limits on the depth range over which the changes occur and, it is hoped, detect differences in depth from one region to another.

During the past decade, seismologists have come to the firm conclusion that there are considerable regional variations in upper-mantle structure, and methods by which these variations can be determined have been developed. It is generally believed that regional variations are intimately related to the processes that are shaping the earth today and that shaped it in the past. Thus, we see the need to extend detailed seismological studies, previously carried out only in limited areas, to the whole of the surface of the earth and especially to those areas covered by the oceans.

Careful study has shown the travel times measured before 1955 to have been quite accurate. Since then, significant further advances in the study of travel times at teleseismic distances have been made, and it has been shown that these times too have a regional component.

Surface Waves Great advances have been made in the study of surface waves. These advances rest on two developments: seismographs with greatly improved long-period response and electronic computers. As a result of the second development, it has been possible to calculate phase and group velocities of waves as functions of wave period for realistic earth models. Thus, careful comparison of theoretical models and observations has been made possible.

Surface-wave studies established very early that there is a low-velocity layer for shear waves in the upper mantle, as inferred by Gutenberg, and that its nature beneath the continents differs from its nature beneath the oceans. Surface-wave studies demonstrated the existence of zones in which shear velocity changes rapidly. It is not only in terms of velocity, however, that surface-wave studies have thrown light on the properties of the earth. Another important property of any solid material, such as the rocks of the crust and mantle, is its resistance to long-term creep. A measure of this resistance is the proportion of the energy of a wave passing through the material that is absorbed and converted into heat. Resistance to creep is extremely difficult to determine from body-wave studies because of severe problems in determining and allowing for amplitude changes associated with such factors as reflection and refraction at interfaces. Studies of the attenuation of surface waves have led to the speculation that the low-velocity zone is a major region of weakness in the earth, that it is possibly in this zone that the earth accommodates itself to changes of shape and perhaps also that the relative changes in the positions of the large land masses take place.

Spectacularly successful as surface-wave studies have been, there is much more still to be done. The methods of determining the velocities from the records can be greatly improved by digital processing techniques.

Earthquakes and Processes in the Earth's Interior It is not only the velocity structure of the earth that has attracted the attention of seismologists. An earthquake is a complex phenomenon in which large quantities of stored elastic energy are released (for a large earthquake about as much energy as could be generated by a 1,000-megawatt power station in 20 years). Comparatively recently, it has been found possible to make estimates of two important parameters—the physical length of the faulting involved in large earthquakes and the speed of rupture. For large earthquakes, the faults involved have been found to be many hundreds of kilometers in length. Still more recently, it has been found that the earth undergoes a significant and "permanent" change of shape when a large earthquake occurs. Study of the ground motion close to a large earthquake over the full range of wave frequencies, extending to the zero-frequency component, will, it is hoped, lead to better understanding of the failure process and to a firm basis for estimating hazards in active earthquake zones; it is also hoped that these studies will provide some inkling of the processes deep in the interior that store the vast energies released in the earthquake. One interesting question still to be resolved is that of the nature of the failure in earthquakes centering at depths between 300 and 700 km. It is difficult to conceive of failure of the kind that occurs near the surface taking place under the enormous pressures existing at these depths. Studies of the shape of the impulse over a very wide range of frequencies may resolve this question.

Free Oscillations

The development of new forms of earth-measuring equipment, such as the strain seismometer and the tidal gravimeter, has led to the recognition that the earth is set into free oscillation by very large earthquakes. The periods of the free oscillations were well determined for the first time in studies of records of the Chilean earthquake of 1960. There is, in general, good agreement between the observed free-oscillation periods and those calculated for models of the earth. There are, however, some discrepancies for the graver modes, which have led to suggestions that either changes are required in our models of the density distribution in the lower mantle or our estimate of the core radius should be increased. Observation of the free-oscillation periods of the earth is important because it provides some degree of control for the determination of the density distribution at depth.

Theoretical Studies

Theoretical studies have gone hand in hand with observational developments. Theoretical studies of body waves have thus far been based mainly on ray theory, whereas surface-wave and free-oscillation theoretical studies rest on mode theory. The two approaches are necessarily closely related, and studies of these relationships are being carried out. In one development, theoretical seismograms are being calculated. In others, the effects of crustal and upper-mantle structure on seismic-wave velocity and motion are being studied—i.e., the transfer function of the crust and mantle is calculated for model structures.

Sea-Floor Spreading and Continental Drift

During the past decade, a perhaps revolutionary new understanding of earth dynamics has been achieved, and in its further elucidation seismology will play a very significant role. This is the recognition of a continuing process of "sea-floor spreading" associated with drifting of the continents.

The earth sciences have only recently reached a state at which we are beginning to see the overall patterns of how the evolution of the earth is controlled. Classical geologic studies were able to examine only surface processes. These exhibited great diversity, and failed, until recently, to fit any recognizable worldwide systematic pattern. Two of the most readily observed geologic processes, which have been understood in some detail for many decades, are the steady destruction of the continents by erosion and the formation of new rocks by some sort of cyclic system of igneous intrusion. Why the erosional mechanism did not long ago completely level all continents and what controls the pattern of igneous activity were not and still are not completely clear. In the past few years, however, it has been discovered that there is a worldwide pattern of deformation going on, slowly but at a measurable rate, that is probably capable of renewing the continents and explaining igneous activity. The clearest surface expression of this process is the spreading of the ocean floors, now recognized as characteristic of the Atlantic, Pacific, and Indian Oceans, and probably present in all oceans. This observation strongly supports the concept of thermally driven mass currents as the dominant process in the evolution of the earth. Many lines of evidence, such as island-arc arrangements, seismic focal patterns, some spatial variations in the magnetic field, and the structures of the continents and of mountain ranges, can be consistently explained by this hypothesis.

It is clear that the earth sciences may be on the verge of achieving a consistent overall picture of the earth—as a heat engine in which a large proportion of the details of geology can be explained as local consequences of the larger pattern. The possibility of such a major advance in geology has excited earth scientists throughout the world. If this systematic treatment can be achieved, then a whole series of breakthroughs can be expected in problems such as that of determining the control mechanisms of ore deposition. The capability of long-term prediction of seismic and volcanic events may be another breakthrough. Ultimate understanding of the basic causes of these events is conceivable—in the distant future perhaps, followed by control.

Some traditional forms of seismological research have already contributed findings related to the theory of sea-floor spreading. Studies of the direction of first motion of earthquakes have contributed significantly to our understanding of large-scale tectonic problems. These, in turn, have led to the recognition of systematic patterns in the circum-Pacific earthquakes and have made it possible to assert that the faulting associated with the spreading of the Atlantic Ocean floor is one of the type called "transform" by J. T. Wilson (1965), a finding of importance to our understanding of the process by which the spreading occurs.

THE MOON AND PLANETS

The character of the earth's surface is the result of a complex chain of processes. Some of these are obvious—changes wrought by wind and water are so rapid that we can observe them going on today—but these simple, direct processes are the consequences of other processes that have acted throughout the history of the earth in its deep interior. It is already clear from the results of the space explorations of the past decade that the atmospheres and surfaces of the other planets differ remarkably from those of our own planet. These differences may have arisen in many ways, but we may be certain that processes in the deep interiors of these planets have played a most significant role in their development. The air we breathe and the water of the sea, for example, came from the interior as part of the same process in which the rocks of the earth's surface were formed.

The growth and advance of space technology over the past two decades have made the exploration of our moon and the planets of our solar system a realizable goal. Scientific experiments included in the Apollo manned lunar landing program, for example, involve measuring the moon's seismicity and determining its geologic structure with seismographs. These and other lunar and planetary investigations should yield information of considerable importance to our understanding of the evolution of our solar system and its components. An understanding of the data obtained from such experiments, however, depends on the scientific methods, techniques, and knowledge developed through investigations of the earth.

As soon as it was realized that geophysical measurements on the moon are feasible, plans were made for a seismometer to be part of the earliest set of equipment. It was taken almost for granted that a determination of the seismic state of the moon must be one of the earliest geophysical experiments. The structure of the near-surface layers of the moon may be of such a nature that small-scale seismic work of the geophysical prospecting type will be essential to its study.

The power of seismology to probe the interior of a planet is such that even though the moon may not prove to be strongly seismic, early attempts are being made to determine velocities in the interior using shocks from meteorites or rocket impacts, and, until accomplished, the establishment of a network of seismographs on the moon will have high priority with geophysicists.

All that has been said regarding seismology and the moon applies with equal if not greater force to the planets. The greater difficulties in sending man to them, and their similarities and differences with the earth, make the emplacement of seismographs on them one of the great scientific challenges of the century.

SEISMIC SOURCE MECHANISMS

Despite the large advances in seismological knowledge during the past few decades, the fundamental problem of what physical process is taking place at the earthquake source remains only partially solved. There are many seismological and geological reasons for believing that most earthquakes—particularly shallow ones, at depths of less than about 60 kilometers—involve the sudden fracturing of rocks. The exact mechanism by which this takes place, however, is a matter of considerable debate. And even more problematical than the question of *how* the failure takes place is the question of *why* it takes place.

It is safe to say that the concept of faulting as the immediate cause of most shallow earthquakes rests on a much firmer scientific basis than does our understanding of why faulting should occur at all. Furthermore, it is now thought that a few earthquakes—particularly those originating at great depth—are not caused by fracturing in the normal sense, but instead by some physical process involving abrupt changes in volume and density, such as might be related to sudden phase changes of earth materials at very high pressures.

This subject of the focal mechanism of earthquakes is so fundamental to the entire science of seismology that it clearly deserves very high priority in the overall seismological research effort, and much of the potentially valuable spin-off to applied fields such as engineering seismology awaits a more definitive solution of the focal-mechanism problem.

Earthquakes that cause damage to structures and loss of life usually have shallow foci, and many, such as the 1906 California earthquake, the 1891 Mino-Owari earthquake, the 1964 Alaska earthquake, and a number of earthquakes along the Anatolian fault in Turkey, are accompanied by fresh surface faulting. The theory of fault origin of earthquakes postulates that sudden displacement starts at a point of rupture somewhere along a fault. The rupture then propagates along the fault plane; the greater the extent of fault rupture, in general, the greater the wave motion from the earthquake. The actual source of the wave trains is a matter of controversy. One view is that they are the direct consequence of the "fling" or rebound along the fault; the alternative is that the elastic waves are generated at numerous places along the fault by friction just as "vibrations of a violin string are caused by the friction of the bow" (Reid, 1910). The hazard to man in the vicinity of the fault is probably different for the two cases, and there is an urgent need to settle the issue for engineering design purposes alone.

Many attacks are under way at present and deserve increased support. They include theoretical studies based on dislocation theory and solid-state physics, laboratory studies of rock failure at high pressures, geologic field studies of fault zones and of earthquake sites where faulting has reached the ground surface, thorough instrumentation of fault zones in order to improve definition of the stress-and-strain fields associated with the earthquake-producing forces, seismographic observations close to earthquake foci, and sophisticated analytical efforts to determine source functions from seismic waves recorded at some distances from earthquake epicenters.

Much new work, some of considerable mathematical sophistication, concerned with the problem of seismic source mechanisms has recently begun. The indications are that great steps forward will be made in this field within the next decade. It must be emphasized that the focal-mechanism problem is at the very core of seismology and represents one of the most challenging and most promising of current research efforts. It is clear that these physical processes must be better understood if the science of seismology is to continue to move forward and if its contributions to more-applied fields such as earthquake engineering are to continue to be pertinent and significant. In this field particularly, geologists and seismologists must continue to work closely together.

One of the surprising recent discoveries in the field of earthquake mechanisms has been the field observation of continual slippage or "creep" along several active faults in California. Although we do not yet fully understand this phenomenon, it is clear that it has many ramifications important to the long-term effort to predict and perhaps prevent earthquakes. Furthermore, fault creep, together with the recently documented triggering of movement on one fault by displacement on another nearby fault, emphasizes the growing problem of the engineering of structures that must cross or straddle active faults. It is essential that instrumental measurement of creep and associated effects be greatly improved and expanded, and this is well within present technological capability.

The process by which an explosion in the earth generates seismic waves is understood quantitatively to a much greater extent than is the earthquake process. In the explosion problem, the total amount of energy deposited in the earth at the moment of detonation can be measured, and instruments that measure the response of the materials around the energy source provide the data from which the distribution of the energy can be calculated. The observations provide the factual information against which theoretical treatment can be tested. A complete, closed-form solution to the problem has not been achieved, but numerical methods using finite-difference techniques have been successful in predicting ground effects that are in reasonable agreement with those observed. Research into this problem has been conducted in several laboratories, chiefly the Sandia Corporation and the Lawrence Radiation Laboratory. The results of this research has direct application to nuclear-test monitoring and to studies of nuclear-weapons effects as well as to the development of improved techniques in the use of explosives as energy sources in seismic exploration, in mining and quarrying, and in the construction industry.

Experience with explosive seismic sources gives some idea of how much information about a seismic source can be recovered from distant seismic signals. Although not all details of the wave-generating mechanism of a buried explosion are understood quantitatively, the fact that observations of ground motion have been made in the close-in region provides an empirical check on attempts to recover source parameters from seismic waves. Because the processes in the source region are nonlinear and irreversible, only an equivalent source can be reconstructed by the analysis of linear phenomena in the region of small motions. The results of this work give some measure of the confidence to be placed in attempts to reconstruct the physical processes in an earthquake source from the radiated seismic energy.

With regard to the remaining problems of the explosion source, the greatest need is for better equation-of-state data, valid over a wide range of pressures, for the earth materials within which the detonations took place—and perhaps revision of the failure criteria to be applied in each zone near the source. In addition, the interaction of the shock wave with a nearby free surface, the direct generation of seismic waves by fracturing, and the effects of pre-existing strain on the radiated seismic energy are all topics that call for more research.

Other sources of seismic energy include those of a repetitious nature (weight drops on land, and "spark" or gas in water) and are usually used in the oil-exploration industry. These sources introduce seismic signals into the earth at closely spaced points, and echoes (reflections) are obtained from the interfaces of subsurface rock layers. By mapping the attitudes of these interfaces, possible "traps" for oil and gas are located. The repetitive nature of the signals makes it possible to correlate the reflections received at one position on the surface of the earth with those received at another position. A continuous record of the reflections is sometimes produced that simulates a cross section of the geology. This type of seismic-energy source also offers a very good opportunity for experimentation with the transmission of messages through the solid earth. Some research on this problem is being carried on by the Army, and more should be encouraged.

SPECIAL EFFECTS

All earthquakes involve to some degree the propagating disturbances within the solid earth called seismic waves. Some earthquakes, for one reason or another, cause certain additional special effects that either present a special hazard to man or provide a different means for probing the earth. Among these special effects are tsunamis, the frequently destructive seismically caused sea waves that can inundate coastal regions halfway around the world from their sources; submarine landslides and turbidity currents; and subaerial landslides, mud flows, fault scarps, fault creep, and other permanent deformations of the earth. In addition, seismic tremors themselves may be generated by volcanic activity.

TSUNAMIS

Tsunamis are of considerable importance because of the great damage and loss of life they often cause (see Figure 10). These gravity waves in water are generated in the vicinity of the earthquake epicenter and propagate with small amplitudes across the deep sea, building up to destructive heights upon reaching a seacoast of appropriate configuration. The slow speed of these waves (~400 mph), compared to that of seismic waves in the earth, makes advance warning possible if the danger area is far enough from the source and if adequate seismic data are available and can be collected at an analysis center. This is the basis for the Tsunami Warning System of the Pacific, operated by ESSA. This system, established in 1948, has been very effective and valuable, but in the course of efforts to improve and expand the system, several difficulties have become evident. One is the high incidence of false alarms, a result of the inability to determine from seismic evidence alone whether a given earthquake has generated a tsunami. Another is the poor capability to predict the scale and effects of a tsunami for localities that have not experienced earlier tsunamis coming from a particular source area. A third is the difficulty of predicting tsunami and tsunami effects near an earthquake epicenter. Solutions to these problems seem to be within present capability if appropriate effort is expended.

The applications of modern high-speed data processing to information from a suitable network of stations should increase warning time for nearby events. A combination of empirical, experimental, and theoretical studies should improve our ability to predict tsunami effects under a given set of local conditions and tsunami characteristics. Studies of seismic-wave character and improved methods of collecting sea-wave data at stations near the epicenters of earthquakes may also increase the reliability of prediction. To predict tsunamis for coastal regions lacking appropriately located stations, instruments on the floor of the deep sea may be required. In some areas, an additional measure of protection against tsunamis could be provided by the construction of barriers or similar structures.

One cause of concern is the possibility that locations that have not experienced a destructive tsunami in historical times may do so in the future. Most tsunamis strike coastlines along the borders of the Pacific Ocean or the Pacific islands, partly because most large earthquakes occur in the Pacific and partly because the coastal sub-bottom configurations there are generally conducive to tsunami intensification.

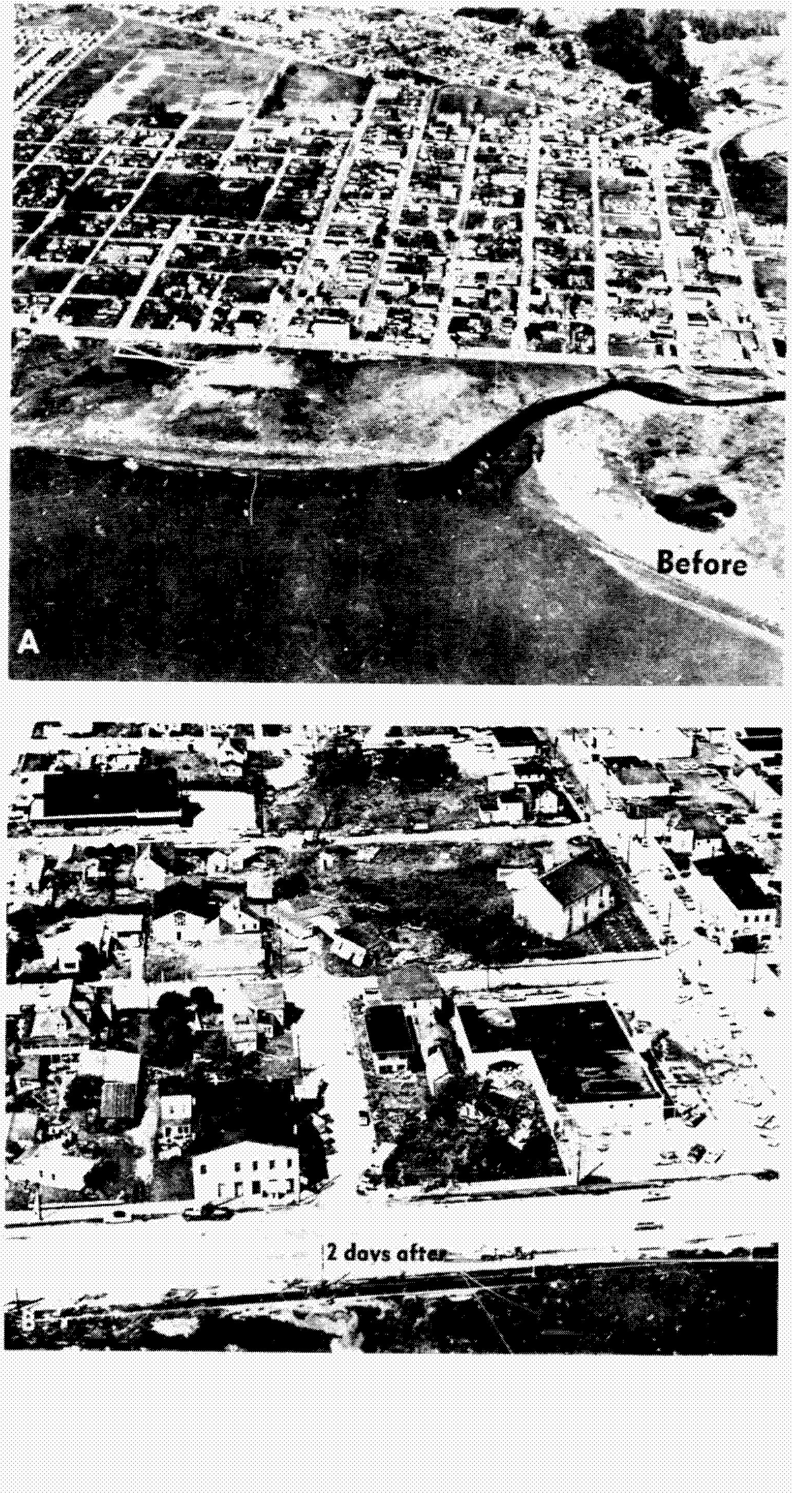


FIGURE 10 Tsunami damage at Crescent City, California, following the Great Alaska Earthquake of March 27, 1964. (A) Before; (B) after. (Courtesy U.S. Coast and Geodetic Survey.)

FIGURE 11 The Turnagain Heights residential development, Anchorage, Alaska, following the March 27, 1964, earthquake. (A) Aerial view of massive slide area; (B) close-up, ground-level view of homes in the slide zone. (A, U.S. Geological Survey; B, U.S. Army photograph.)

What might happen following a very large earthquake beneath some other ocean, such as the Atlantic or the Arctic, is a question that merits investigation, particularly in view of the high population density along most of the Atlantic shoreline. Whether the broad continental shelf along much of the Atlantic coastline of the United States would reduce the long tsunami waves sufficiently to diminish their effect is a key question.

OTHER SPECIAL EFFECTS

Earthquake-triggered landslides have often been the cause of greater loss of life and property damage than the direct structural effects of earthquake shaking (see Figure 11). A somewhat similar phenomenon—spectacularly demonstrated during the 1964 Alaska earthquake—is the earthquake-triggered submarine landslide; such slides, moreover, usually generate locally damaging waves. In combating seismic hazards, it is imperative that we gain a better understanding of such secondary effects of earthquakes and that seismic zoning practices take these phenomena into account to a greater degree than in the past.

EARTHQUAKES AND VOLCANISM

In contrast to the special effects caused by earthquakes, seismic tremors can themselves be a special effect of volcanism. Short-term prediction of impending volcanic eruptions based on the analysis of consanguineous seismicity is being done by the U.S. Geological Survey's Hawaiian Volcano Observatory. This is an example of geologists and seismologists working together in an effort to preserve lives and property as well as to gain valuable scientific information about the interior of the earth. This is extremely important work, but more research is needed if we are to gain the improved understanding of the tectonic framework of volcanic areas that we require in order to improve our ability to predict volcanic activity. It should be emphasized that it is important to conduct research and monitoring programs of this kind in many volcanic regions of the world.

EARTHQUAKE ENGINEERING

One of the major motivations for the development of the science of seismology has been the desire to relieve mankind from the hazard of destructive earthquakes. One of the main products of seismological investigations is knowledge of near-source earthquake phenomena. The translation of this knowledge into practical design and construction techniques for earthquake-resistant structures is the responsibility of structural engineers and especially of those who have specialized in earthquake engineering.

The reduction of the hazards suffered by the community as a result of major earthquakes has been discussed in four recent reports. These are:

Earthquake Prediction. Report of the *Ad Hoc* Panel on Earthquake Prediction, Office of Science and Technology, 1965. (Panel Chairman, Frank Press.)
Proposal for a Ten-Year National Earthquake Hazards Program. Report of the *Ad Hoc* Interagency Working Group for Earthquake Research, Federal Council for Science and Technology, 1968. (Working Group Chairman, William T. Pecora.)
Toward Reduction of Losses from Earthquakes. National Academy of Sciences, 1969. An advance summary report of the conclusions and recommendations of the Committee on the Alaska Earthquake, Division of Earth Sciences, National Research Council, NAS-NAE.
Report of the Committee on Earthquake Engineering Research. National Academy of Sciences–National Academy of Engineering, in preparation.

Research in the field of earthquake engineering has produced some substantiated advances: in particular, special mathematical techniques have been developed that enable strong motions of the ground to be modeled by high-speed computers in order to simulate realistic soil and geological conditions. There are already strong indications that such methods, particularly that of finite element analysis, will provide the key to the prediction of wave motions in a thoroughly heterogeneous viscoelastic earth. One of the oldest seismological problems, that of the marked variation among earthquakes in the intensity of ground shaking, also appears ready to succumb to these methods. Further crucial testing of the theoretical predictions through analysis of actual ground motions awaits more-adequate field records from strong-motion seismographs following earthquakes.

AIMS OF EARTHQUAKE ENGINEERING

The ultimate objectives of earthquake engineering are to ensure that in the event of an earthquake anywhere in the world there will be no injury or loss of life, and that, on the average, the cost of repairs of earthquake damage will not exceed the initial costs of the kind of design and construction that would prevent damage. In addition to public safety, there are thus strong economic considerations that will play a dominant role in the development of this field.

These socioeconomic aspects of destructive earthquakes are, from the engineering point of view, examples of broader problems related to the response of society to disasters of all kinds (see Figures 1-7, 10, and 11, Part I). Society reacts in characteristically different ways to different kinds of disasters. It appears willing, for example, to tolerate a large annual loss of life from automobile accidents, while an earthquake death toll that is considerably smaller than this would be viewed as a major disaster. Evidently, the public reaction is smaller if the deaths occur a few at a time and are related to activities that have become common in everyday life. In addition, people everywhere have an almost instinctive fear of large, natural, catastrophic phenomena, which gives a destructive earthquake an almost unique psychological impact. These factors, along with the very real social and economic losses involved, have induced the United Nations Economic and Social Council to consider earthquakes to be the single most important natural disaster with which their organization is concerned.

Much of the basic information needed by the earthquake engineer is derived directly from seismology. In particular, it is from the worldwide network of seismological stations that the engineer learns about the numbers of earthquakes of various sizes that occur in various parts of the earth. From this information, the basic distribution of seismic risk can be estimated, with the ultimate objective of ascertaining for any region of any size the likelihood of occurrence of earthquakes of different magnitudes during a specific time interval. It is thus of the utmost importance to the engineer that the worldwide instrumentation capabilities of seismology be not only maintained but constantly improved and extended. It is also important that seismological studies aimed at achieving the most meaningful descriptions of the magnitudes and effects of earthquakes be expanded, since an accurate measure of seismic events in terms that can be correlated with structural damage is an essential starting point for any rational development of earthquake-resistant design.

Another seismological subject of direct importance to earthquake engineers is the study of the basic mechanisms of earthquakes and of the generation and propagation of seismic waves. The damaging surface motions of earthquakes must be intimately related to these basic mechanisms, and an understanding of fundamental principles is needed in order to generalize the knowledge obtained from past earthquakes. Recent advances in the understanding of fault motions, for example, will most likely result in improved methods of using geological information to assist in the assessment of seismic risk. As another example, recent recognition that the Alaska earthquake of 1964 was a multiple event, with repeated shocks, throws new light on the engineering interpretation of damage. Such examples indicate clearly that even the most fundamental investigations of seismologists can have a very direct influence in matters of practical engineering application.

Strong-Motion Seismology

Some problems in seismology have been of minor interest to many seismologists and yet are of major importance to earthquake engineering. Research into these problems must often be initiated and carried out by earthquake engineers themselves. Chief among them are the measurement and detailed investigation of the large ground motions responsible for damage. The instruments used in the worldwide network of seismographic stations are not suitable for the measurement of destructive ground motions. These instruments are too sensitive, too independent of local geologic conditions, and too widely spaced to give the basic data needed by earthquake engineers. Earthquake engineers have, therefore, developed and deployed special strong-motion accelerographs to record destructive ground motions. These studies are in early stages of development and need to be greatly expanded. For the following recent important destructive earthquakes, for example, not even one measurement of strong ground motion is available: Mexico (1957); Chile (1960); Agadir, Morocco (1960); Iran (1962); Skopje, Yugoslavia (1963); Alaska (1964); and Turkey (1966). The absence of such basic information has made it difficult if not impossible to explain many important features of these earthquakes. Only for the Pacific Coast states of the United States and for Japan does anything approaching an effective strong-motion instrumentation network exist.

Seismologists have a growing interest in strong-motion seismology. It is evident that measurements of true ground motion near faults will be essential for a full understanding of earthquake mechanisms. Effective cooperation can and should be established between seismologists and earthquake engineers for the measurement of strong ground motion generated by earthquakes.

Micro-earthquakes

Small earthquakes occur much more frequently than large earthquakes, and there are thus many more opportunities to study small earthquakes than large ones. For this reason, many investigative techniques have been developed based on the very small ground motions associated with micro-earthquakes and small earthquakes. In interpreting the results of such studies, the earthquake engineer must always consider very carefully the extent to which certain conclusions might be extrapolated from such small motions to the motions several orders of magnitude larger involved in destructive earthquakes. It is known that strongly nonlinear effects may often be involved. This is clearly another study area for which closer cooperation between seismologists and earthquake engineers is not only desirable but essential.

Artificial Earthquakes

Another subject on the boundary line between seismology and earthquake engineering is that of underground explosions. With nuclear explosions, man can produce artificial ground motions that are comparable in many respects to natural earthquakes. Although it would be a formidable and expensive task to explode such devices deep in the earth's interior, it is within the bounds of current technology to reach depths comparable to those of many California earthquakes. Such artificial earthquakes are of interest to the earthquake engineer for at least two reasons.

The damage potential of underground nuclear explosions has many points of similarity to the damage potential of earthquakes, and protection against underground nuclear blasts can, therefore, involve many principles of earthquake-resistant design. Officials of the AEC Plowshare Program for the peaceful uses of nuclear energy recently have said that the risk of seismic damage to cities is at present the most uncertain factor, and hence the limiting factor, in the use of nuclear explosions for large-scale excavation. This problem exists in a particularly acute form in the studies for nuclear excavation of a possible Central American canal connecting the Atlantic and Pacific Oceans.

A second aspect of interest to earthquake engineers is the possibility that ground motions from underground nuclear explosions could be used as a realistic test for large structures. In view of the great difficulty of providing proper force inputs for dynamic tests of full-scale structures, no reasonable sources should be overlooked. Little work of this kind has been done in the past, although the AEC has indicated a willingness to cooperate in such tests to the extent of making available underground explosions that are planned primarily for other purposes.

Man-Triggered Earthquakes

Several examples are now available of earthquakes that have apparently been triggered by artificial disturbances of the earth's crust. The most recent is the Koyna (southern India) earthquake of December 11, 1967, which occurred near the site of a large dam and storage reservoir in a region generally supposed to be very little subject to earthquakes. Over a period of several years after the construction of Koyna Dam and the filling of the reservoir, a sequence of small earthquakes was recorded in the region, similar in size and in distribution in time and space to those that followed the formation of Lake Mead. After about five years, an earthquake of magnitude 6.5 occurred in exactly the same epicentral region, causing considerable loss of life and a large economic loss. Although one would perhaps not want to conclude that the reservoir "caused" the earthquake, it seems likely that some interesting relationships existed. Similar situations (without the large earthquake) have resulted from oil withdrawals, from deep mining excavations, and in a recent notable example in Denver, from pumping fluid waste products into a deep well.

SEISMIC ZONING MAPS

Another important subject that involves many interactions between geology, seismology, and earthquake engineering is the preparation of seismic risk or zoning maps (see Figure 8, Part I). The recognition that certain areas of the world are more subject to earthquake hazard than others immediately creates the desire for a seismic risk map that would indicate for any given locality the relative danger from earthquakes. Such maps must reflect local geological and soil conditions, which are known to have important influences on earthquake-resistant design, as well as considerations of the number of earthquakes of various sizes likely to occur in a given region in a prescribed time period.

At present, attempts are being made to base such seismic risk maps on measurements of small, frequent earthquakes, both to indicate relative seismicity of a region and to compare relative ground motions under different conditions of local geology. As indicated above, extrapolations of any kind from small earthquakes to large destructive earthquakes must be treated with the utmost caution, particularly from the viewpoint of earthquake-resistant design. If good modern maps are not available, the engineer's work is seriously hampered.

EARTHQUAKE ENGINEERING RESEARCH

In addition to problems of the type mentioned above, which excite the interest of both seismologists and earthquake engineers, there are many special problems of great practical importance to the engineer but of little or no relevance to seismology. The increasing recognition of such problems has convinced earthquake engineers that they must pursue much more vigorous research programs in the future than has been customary in the past. Several of these specific areas are discussed below.

Soils and Foundation Engineering

Ordinary soil, which forms the foundation material for many engineering structures and which constitutes the construction material for such important structures as dams and embankments, is a highly complicated material whose mechanical properties are not well understood. Such dynamic properties as stiffness and strength are known only very approximately for even simple loading conditions, not to mention the complicated transient loadings involved in earthquakes. Under certain conditions of ground shaking, soils can drastically change their mechanical properties; sometimes they may even "liquefy" to the extent of behaving almost like a fluid. Similarly, it is known that earthquake excitations may have a major influence on dynamic processes of landsliding, consolidation, and subsidence. Although such phenomena may be understood roughly in a qualitative sense, little information is at hand that would permit meaningful design calculations. New methods of analysis involving high-speed computers and finite-element soil models are now being tested. These methods may revolutionize our understanding of the old seismological problem of variation in the intensity of ground shaking.

Soil properties are known to be related to earthquake damage in at least two fundamentally different ways. First, the local properties of soil layers and other configurations may modify the ground motion itself as the seismic waves move through the medium. Second, modifications of the soil by the earthquake may result in foundation deformations or failures that can in turn cause major structural damage. The absence of strong-ground-motion measurements for most past earthquakes has made it difficult to distinguish between these two effects, with resultant confusion as to the exact role played by soils in the earthquake-damage process.

It must also be remembered that soils are highly nonlinear materials, which greatly complicates theoretical and analytical treatments of the subject.

The basic lack of understanding of dynamic soil behavior must be considered as one of the major obstacles in the rational development of earthquake engineering, and a greatly increased research effort in this direction is essential. Because of the critical influence such soil behavior may have on the surface manifestations of crustal movements, these problems are also of interest to geophysicists studying the mechanics of earthquakes.

Dynamics of Structural Response

Even with a known earthquake ground motion as an input function, the engineer is faced with a formidable problem in determining the response of actual structures to such complicated exciting forces. Although structural-response calculations are in principle straightforward, in practice they are rendered laborious and inexact by the complicated geometric shapes of actual structures and structural members, which means that large numbers of degrees of freedom must be considered; by the presence of significant local effects in joints and connections, which means that "average" conditions have little significance; by uncertainties as to the true dynamic properties of structural materials and structural configurations; by complicated interactions between structures and foundations; and by pronounced nonlinearities in structural behavior.

Because of the difficulties and expense of conducting dynamic tests of full-scale structures and of the many uncertainties involved in model tests, there has been little opportunity to assess the validity of analytical studies that have been made. In this respect, it must be pointed out that practically all civil engineering structures are unique systems—each building, bridge, or dam is different—and rarely can such structures be tested to damage levels. This makes civil engineering structural design very different from, for example, aircraft design, where one is justified in the testing to destruction of full-scale prototypes to prove all aspects of a design that will eventually be produced in a number of identical units.

Such structural-dynamics problems are, of course, the special province of the structural engineer and the research investigator in the field of applied mechanics. Closely related problems arise in structures subjected to wind loads and to blast loadings.

Building Codes for Earthquake-Resistant Design

The activities of earthquake engineers must ultimately find their expression in simplified building codes that can be given legal force by individual municipalities to ensure safe construction. Although such matters are primarily the responsibility of the engineer, seismologists are often brought closely into the deliberations involved because of their special knowledge of earthquake phenomena. It is thus important for the seismologist to be aware of some of the basic problems that face the earthquake engineer in this complicated aspect of the subject.

It is useful to keep in mind several general principles that govern the preparation of earthquake-resistant-design codes.

The code is not a technical treatise on earthquake-resistant design, but is a concise statement of currently accepted professional practice. It does not attempt to relieve the individual structural engineer of the need to exercise a high degree of judgment in design details. In general, the code is more an expression of desired results than a set of instructions as to how to attain them.

Earthquake-resistant-design codes are not intended to insure against damage to structures. It is assumed that large earthquakes will cause heavy damage (see Figures 1-7, 10, and 11, Part I), but it is intended that they will not cause building collapse with consequent loss of life and injury. The code thus contains an implicit economic judgment as to a reasonable balance between repair costs and initial costs. Since such judgments will depend very much on local conditions, it would be expected that different countries and different areas in the same country might well have very different codes.

All codes are in a constant state of development and improvement. As new research knowledge becomes available, as experience from destructive earthquakes accumulates, and as various social and economic changes appear, it becomes necessary to modify the code. A reasonable degree of flexibility in formulation, interpretation, implementation, and revision thus becomes important.

All experience has convincingly demonstrated that codes themselves are of little use unless they are backed by a powerful enforcement agency and a comprehensive inspection service.

To the earthquake engineer, the legal philosophies of regulation and control must ultimately be of as much importance as seismological information. Such legal problems can be permanently solved only in the presence of an informed public opinion, and this is an aspect of the problem in which seismologists can be of direct assistance.

It must always be remembered that no matter how effective codes become or how efficient earthquake-resistant design can be made, there will be for a long time a large number of existing old structures that cannot be brought up to an acceptable strength standard. In the United States alone there are about 200,000 hazardous structures in Zone 3 (most hazardous) seismic areas. In many parts of the world with high population densities and at early stages of economic development, this problem is especially troublesome.

EARTHQUAKE PREDICTION

Current speculations on the ultimate possibilities of earthquake prediction have stimulated a considerable amount of interest in the subject, among the public as well as among the experts. Because of the important implications of prediction for earthquake engineering, it would be well to summarize here the engineer's point of view on the matter.

A rough form of prediction is being made, of course, every time anyone consults a seismic zoning map or repeats the well-known remark that "a major earthquake is to be expected in California every 100 years." In the present context, one would mean by earthquake prediction a significant narrowing-down of the time and area involved. The earthquake engineer would probably not consider prediction as significantly different from present capabilities unless the time were narrowed to the order of days, or even weeks, and the area to about 1,000 square miles.

It is difficult at this time to estimate how much the economic loss due to a major earthquake would be reduced by a successful short-range prediction capability. It is of course not possible to remove buildings and dams from the danger area. However, although prediction would not contribute to the reduction of losses resulting from major structural collapse, many precautions can be taken by householders and others that would greatly reduce the damage to the contents of the buildings.

The successes of the hurricane- and tsunami-warning schemes are good examples of how useful short-term warnings can be in reducing the loss of life due to natural phenomena.

Furthermore, it is clear from the report of the NAS Committee on the Alaska Earthquake that many more people would have lost their lives, or been injured, had that earthquake occurred at a different time of the year or of the day. Certainly, a short-term prediction capability would permit the evacuation of buildings known to be hazardous, or of areas in which there are many hazardous structures, and thus would substantially reduce the loss of life in a major earthquake.

There can be no doubt, moreover, that the increased knowledge of earthquakes that would be implied by an enhanced predictive capability would be of immense benefit to earthquake engineers in dealing with all aspects of the earthquake-hazards problem. In this sense, prediction itself would be but an incidental factor in the development of knowledge of all aspects of earthquake phenomena.

EARTHQUAKE INSURANCE

The feasibility of a more complete and rational system of earthquake insurance is being closely examined, and it is clear that a really comprehensive study of this matter would be extremely desirable. Insurance for such unpredictable hazards as fire, accident, and disease have been highly developed, taking full advantage of the possibilities of a sound statistical foundation. There would appear to be no fundamental reasons why a similar approach could not be used for such natural disasters as earthquakes, although it must be realized that at present a similar statistical base is lacking. The fire insurance industry has millions of policies in force, and pays off on thousands of fires each year in many different places. Each earthquake insurance policy held in a given area, however, is insuring against the same earthquake, so that from the point of view of the insurance company the number of potential clients is more like the number of cities.

It is thus clear that private companies cannot be expected to handle earthquake insurance on the same basis as fire insurance. This probably means that the federal government would have to play some backup role if an adequate earthquake insurance program is to be established. There is a precedent for such federal government re-insurance for nuclear disasters, and the extent to which the federal government played a major role in the recovery of Alaska after the 1964 earthquake is well known.

GEOLOGIC HAZARDS

Engineers are now actively considering a whole range of geologic hazards, of which earthquakes are just the most spectacular example. Local subsidence, tectonic deformation, landslides, fault slippage, and a host of other problems are playing important roles in major construction projects involving such structures as dams, aqueducts, and nuclear power plants. All of these problems are, of course, intimately connected with each other and with earthquakes, and it is to be hoped that close working associations of geologists, geophysicists, seismologists, soils and foundation engineers, and structural engineers can be continued and expanded.

THE EARTHQUAKE HAZARD AND POPULATION GROWTH

Earthquakes are the result of geologic processes that involve very long periods of time, and it cannot be expected that there will be a significant reduction in seismic activity in the next few hundred or thousand years. On the other hand the population of the world is steadily increasing, and even more important, industrialization with its ever more elaborate structures is increasing even faster. It is thus clear that with each year that passes the world's economy becomes more vulnerable to the attack of destructive earthquakes (see Figures 1-7, 10, and 11, Part I). Many of the major earthquakes of the past occurred in uninhabited regions where there was no economy to destroy. This will hardly be possible in the future, as the world fills up with people and their works. A greatly increased program of research in all aspects of seismology and earthquake engineering is required if we are even to hold the earthquake hazard to its present high level.

It is fortunate that major earthquakes are comparatively infrequent events. However, the very rarity of the events makes it important that the greatest possible amount of information be assembled for each major earthquake that does occur. For this reason, the Committee on Seismology recommends the very closest cooperation with those groups studying prediction and reduction of hazards in other countries subject to major earthquakes, and especially with the very active group working on these problems in Japan.

SEISMOLOGY AND NUCLEAR ENERGY*

Nuclear energy was introduced to the world with awesome suddenness in the summer of 1945 when the atomic explosions in Japan quickly brought World War II to an end in the Pacific. Although the first uses of nuclear power were military—and this has remained the use that is most in the world's thoughts—the development of methods to turn this immense force to the service of man has proceeded almost from the first. Such developments have taken several directions. By far the most important is the use of nuclear reactors, involving the controlled release of nuclear energy to produce electrical power. The development of reactors has proceeded rapidly, and a number of them are already in use throughout the world, some having operated a decade or more. In the United States, experimentation has for some years also been carried out in the use of nuclear explosions for excavation—largely under the Plowshare Program of the Atomic Energy Commission.

Seismology has been closely associated with the world's efforts to control the testing and prevent the use of nuclear weaponry, since this is the only method developed thus far that can detect large underground explosions. Such explosions generate seismic waves in the earth that are very similar to those generated by earthquakes. Seismology is also a vital tool, in various ways, in advancing the peaceful uses of nuclear energy—primarily in site selection for nuclear reactors and in monitoring the effects of test explosions for rapid excavation.

NUCLEAR-TEST DETECTION

During the last ten years, because of international discussions and negotiations regarding a nuclear-test-ban treaty, seismology has become associated with nuclear-weapons policy. Few laymen, or scientists, recognize clearly the nature of this association or why, because of it, the advancement of the science of seismology has become essential to our national interest.

The Development and Proliferation of Nuclear Weapons

It became obvious very soon after World War II that other major powers would strive to develop similar weapons, their scientists and engineers being encouraged by the technical successes of the United States. In this country, two policy groups developed almost immediately—one dedicated to complete control of nuclear energy and to the banning of the use of nuclear weapons, and the other advocating a great intensification of research and development in nuclear weaponry, arguing that we must maintain superiority in the technology of nuclear warfare. These differences of viewpoint, evident in both public opinion and official actions, continue in a modified form to this day. They have often led to bitter discussions in the United Nations and the Geneva Disarma-

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*The discussions in this chapter are not intended as a complete historical account of the interplay between seismology and the use of nuclear energy, but only to give important highlights.

ment Conference as well as in the public forum. In July 1946, for example, public demonstrations were held in Times Square protesting all [illegible] weapons tests while an atomic weapon was being [illegible] underwater at Bikini Atoll.

At the end of 1946, a United Nations commission of 11 nations recommended the "Baruch Plan" for the international control and inspection of the use of atomic energy. This plan failed because the Soviet Union refused to allow inspection of its territories by international commissions.

In August 1949, much earlier than had been expected by most experts, the Soviet Union tested a nuclear device. After an extensive, classified study, often marked with bitter policy conflicts, President Truman authorized development of a fusion weapon, the "hydrogen bomb." In July 1952, "Ivy Mike," a thermonuclear fusion device with a yield of 10.4 megatons, hundreds of times more powerful than the first atomic weapons, was detonated over the Pacific Ocean by the United States. During the previous three years, the United States and the Soviet Union had conducted extensive series of tests with fission devices, and the United Kingdom had entered the "nuclear club." In August of 1953, the Soviet Union also detonated a fusion device, and the U.S. monopoly in thermonuclear weaponry soon disappeared.

In the absence of international control of nuclear weapons, each major power pursued a program of nuclear-weapons development. The largest thermonuclear devices considered to be practical were tested in the atmosphere. In March 1954, the U.S. tested a 15-megaton device at Bi[illegible] sprinkling Marshall Islanders with dangerous amounts of radioactive fallout. Two weeks later, a Japanese fishing boat, inappropriately named "The Fortunate Dragon," docked in Yaizu Harbor with 23 fisherman sick from radioactive fallout. International attention was focused on the problem of atmospheric contamination from nuclear tests. Representatives of the British Labor Party and the Japanese Socialist Party, Indian Prime Minister Nehru and Indonesian Premier Sastroamidjojo, supported by such distinguished individuals as Albert Schweitzer, urged unconditional cessation of nuclear tests. Pollution of the atmosphere was clearly against the interests of all nations, but those that were uncommitted in the "cold war" between East and West naturally were most strongly opposed. International pressure continued to grow, but nuclear tests continued at an increased rate throughout the next three years.

In 1957, Great Britain became a thermonuclear power after all attempts to establish a ban on nuclear tests had failed. The United States would not consider a test ban without foolproof inspections, and the Soviet Union would not consider intrusion into its territories by international inspectors.

Along with the development of nuclear devices, an applied science had developed concerned with monitoring explosions. Large nuclear detonations emit electromagnetic and acoustic energy that can be detected at great distances, and, of course, the radioactive debris from explosions can be detected and sampled as it drifts through the atmosphere.

By 1958, it appeared to many scientists and politicians that a ban on nuclear tests might be feasible without on-site inspections–that scientific techniques were sufficiently developed to allow supervision of a test-ban treaty from remote-sensing posts. In January 1958, Dr. Linus Pauling sent to the United Nations a petition signed by 11,000 scientists from 49 countries urging the immediate adoption of an international test ban. Political pressure for such a treaty increased throughout the winter, and in April President Eisenhower, in a letter to Premier Khrushchev, suggested that technical talks be held concerning the scientific and political requirements for policing a test ban. Khrushchev accepted this proposal. In July of 1958, a "Conference of Experts" convened in Geneva, attended by scientists and government representatives from the United States, the Soviet Union, the United Kingdom, France, Canada, Czechoslovakia, and Rumania.

Underground Nuclear Testing and Early Attempts at Monitoring

In 1957, the U.S. exploded underground in Nevada a 1.7-kiloton nuclear device, code-named RAINIER. This experiment proved that underground tests were both feasible and useful. This kind of test, moreover, need not release radioactive materials into the atmosphere, and the acoustic and electromagnetic waves emitted are not detectable at significant distances. An underground explosion can be detected only at remote-sensing stations by recording the resulting seismic waves. The questions arose: Could a network of seismic stations detect clandestine underground nuclear tests, or would the seismic records from such tests be obscured by signals from earthquakes? Representatives [illegible] the "Conference of Experts" concluded that a 180-station control network covering the globe could provide tentative identification of underground explosions as small as five kilotons, but that only on-site inspections could unequivocally demonstrate whether a nuclear explosion had or had not taken place. Many scientists expressed doubt concerning these conclusions. They emphasized the uncertainties of the data, the lack of development of the science of seismology, and the scarcity of trained scientists to man such a detection network. It was clear that a small segment of U.S. scientists, previously concerned primarily with the academic study of earthquakes and earth structure, could not provide the technical advice required by the United States Government to enable it to make wise policy decisions concerning such grave matters.

In August 1958, President Eisenhower announced a unilateral, one-year moratorium on U.S. nuclear testing. During the month before the moratorium was to begin, the United States completed 18 nuclear tests, the Hardtack II series.

Four of these were detonated underground. A study of data from the underground tests indicated that the "Conference of Experts" had overestimated the capability of the proposed 180-station network to detect underground nuclear explosions and to distinguish them from earthquakes. The earlier conclusions of the experts had been based upon very few data, and most of the experts had no experience in discriminating between underground explosions of any kind and small earthquakes. These results, obtained during the winter of 1959, forced the United States to reconsider its position in the negotiations then in progress in Geneva. A reduction in the estimated capability of the detecting network meant that a large number of on-site inspections would be required in any year in the Soviet Union. As before, the Soviets were reluctant to allow even a few such inspections.

The Vela-Uniform Program

Early in 1959, President Eisenhower asked that a "Panel on Seismic Improvement" be convened to study ways of increasing our ability to detect and identify underground nuclear explosions and to advance the state of the art in seismology. In March 1959, this panel, chaired by Dr. Lloyd Berkner, reported to the President's Science Adviser, and, in accordance with its recommendations, Vela-Uniform, a large-scale program of research and development in seismology, was initiated under the direction of the Department of Defense. Spurred by the Vela-Uniform program, the university and industrial research effort in applied seismology and related fields was increased tenfold during the next five years. The World-Wide Network of Standardized Seismograph Stations was established, and support for basic research in seismology was begun at a large number of universities.

Many observers have criticized the government for beginning this project so late. Certainly, the nation would have been better served if such a project had existed throughout the 1950's. Let us hope that an important lesson was learned. No significant segment of science can be allowed to lag behind. The government must provide for continuing, well-balanced growth of all basic sciences.

A number of scientific problems that arose during the 1959 negotiations appear to have been solved. Others have not. Underground tests are exempt from the 1963 limited test-ban treaty.

Our newly developed research capability in seismology should not be permitted to decline. The science has been strengthened and many new scientists have been trained as a result of the Vela-Uniform program. The problem of policing an underground-nuclear-test ban is still with us, however. New negotiations are inevitable. The nation must not be placed again in the negotiating position of 1959, when diplomats were forced to act without adequate scientific preparation. After years of searching for effective detection methods, the seismograph still remains the only instrument capable of remote detection and identification of underground explosions.

PEACEFUL USES

Nuclear Reactors

The problem of finding sites that are essentially free from earthquake hazard for the construction of large nuclear reactors has become extremely important. This difficult problem again focuses attention on the national need for a continuing strong program of research and training in seismology and its allied fields.

The United States as a whole must double its electrical-power production in the next 10 to 12 years to keep up with the growing demand. California will need to double its power production in the next 8 to 10 years. It is estimated that by 1980, nuclear reactors will provide about one-fourth of all electrical power in the United States. No fossil-fuel power plants are planned for California after 1972; all new production will be nuclear-powered. Present plans call for the building of about 20 nuclear plants in California by 1977, most of them to be located near the coasts and many in areas that have experienced earthquakes in recent times. However, major geophysical problems have arisen in siting recent nuclear plants in California.

What is the margin of safety required in the design of a nuclear reactor or in the selection of a site for a large nuclear power plant? As larger plants are more efficient, we can assume that public utilities will prefer the largest feasible reactors. But these reactors contain large quantities of extremely radioactive nuclides capable of destroying life in vast areas should they escape. Most reactors now in use contain radioactive iodine, which, if a major accident were to occur, might escape mostly as vapor harmful to life. The damage and loss of life that would result from a nuclear accident involving a large reactor might be great, and the probability of an accident must therefore be reduced to appropriate levels. A dam or a bridge can be designed to withstand a 50-year or 100-year "worst flood" and allow for the possibility that a still-worse flood might exceed design specifications. A large nuclear reactor, on the other hand, must be designed to accommodate the biggest natural disturbance known to be possible at the site.

Sites can be chosen so as to minimize such hazards as floods and landslides, but the earthquake risk is much harder to define. Protection against earthquakes is the most difficult problem encountered in designing and siting reactors in California. A reactor can be constructed to resist the shaking resulting from an earthquake, but a great problem is the prevention of damage to the reactor caused by motion along a fault directly beneath the reactor. This problem is closely related to that of earthquake prediction; the vital question is not when the earthquake will occur, however, but whether there is even a small probability that significant fault motion will occur at a given site.

Old faults are common geological features in most continental areas. Which of these faults are potentially active? The seismologist, working closely with structural geologists, must share the responsibility of answering this question. Nuclear reactors should be constructed at the safest sites that can be found, and the risks associated with possible reactor sites must be carefully evaluated. We cannot afford to make mistakes in the selection of reactor sites.

Nuclear Explosions for Excavation and Similar Uses

The use of nuclear explosions for peaceful purposes has seemed a possibility for over a decade. The great yield from a small package, in terms of the equivalent in tons of high explosive, makes nuclear devices attractive to the canal and harbor builder, the petroleum engineer who wishes to loosen a "tight" oil or gas reservoir, or to the mining engineer who needs to fracture a large low-grade ore body to recover the metal by leaching.

To use such devices safely, the nuclear engineer must reduce the nuclear radiation to safe limits and he must have the help of the seismologist to make sure there will be no damaging seismic effects.

Large-yield nuclear devices such as those tested in recent years produce earthquakes with body-wave magnitudes in excess of 6 and surface-wave magnitudes in excess of 5. Not only must tests of engineering uses of such devices be planned so as to minimize the direct seismic effects of the shock, but the possibility must also be considered that such an intense and concentrated source will release some of the stored tectonic strain in the vicinity of the explosion. This possibility is now under active study and it must be pursued with vigor if the full benefits of nuclear energy are to be realized. The relationship of these studies to the whole problem of the focal mechanism of natural earthquakes is obvious.

THEORETICAL SEISMOLOGY

The interpretation of seismological observations rests on a set of mathematical results derived from theoretical models of the mechanical behavior of continuous media, both solid and fluid. In this light, theoretical seismology is a special branch of applied mathematics; it depends mostly on classical theories of mechanics and elasticity and also on very recent developments in dislocation theory and in information theory for nonlinear viscous media.

In addition, special methods in statistics, numerical analysis, and high-speed computation are required more and more in the treatment of seismological observations.

The history of the subject shows that theoretical seismology is one of the most fruitful parts of applied mathematics. From the beginning, it has attracted such outstanding mathematicians as Rayleigh, Lamb, Love, and Sezawa. In the areas of probability and statistics, it has stimulated developments by Jeffreys, Tukey, and others. Perhaps nowhere else in geophysics can there be found such an array of physical problems to test the ability and ingenuity of mathematicians.

A few examples of the main lines of present theoretical work are presented in the following sections.

COMPUTATION OF VELOCITIES IN THE EARTH FROM OBSERVED TRAVEL TIMES

One of the fundamental transforms of theoretical seismicity is a form of Abel's integral equation that permits, under certain conditions, velocity-depth functions to be derived from travel-time curves. (More recently, the same technique has been used to derive attenuation functions with depth.) The first solutions were given by Herglotz and Bateman. Recent attention has focused on the limitations of the method (the velocity must vary with depth in an appropriate way) and on the uniqueness of the derived velocity functions, especially in cases where the functions decrease in value through a range of depths. The method has been extended so that not only travel-time functions but also their first derivatives ("slownesses") and second derivatives (amplitudes) can be included analytically. Because of lack of suitable observational material, even for P waves, the full promise of the theory for globally valid solutions is not yet clear; measurements of gradients across arrays have led, however, to a marked increase in precision in the P velocity distribution in the mantle.

ESTIMATION OF THE POSITION OF THE SEISMIC SOURCE

The two main theoretical problems here involve the automatic identification of phases as indicated in seismograms and the development of optimum methods of reducing the variability resulting from measurement errors and path inhomogeneities. Algorithms have been developed and programed for high-speed computers that permit the location of earthquakes in groups by the use of the analysis of variance. These methods take into account the variations in the distribution of available stations through the estimation of station and source adjustments.

FILTER THEORY

The problem of discrimination between underground nuclear explosions and natural earthquakes has led to a great deal of attention in seismology to the enhancement of signal over noise. Problems of this kind in seismic prospecting were previously much studied in the oil industry. The usual approach is to design arrays of a given number (N) of seismometers so that the resulting geometries allow optimum enhancement of signal according to an appropriate stochastic theory. In this work, seismology has drawn heavily on antenna theory developed in communications and radioastronomy.

Recent designs of spatial filters (seismic arrays) range widely; the most modest is the "Geneva-type" array (aperture 2–5 km), which gives roughly a $\sqrt{N}$ improvement in the signal-to-noise ratio. Next in scale is the linear-cross array with arm length of about 20 km, which allows velocity filtering to enhance individual phases. The most elaborate array is the Large Aperture Seismic Array (LASA) of aperture 200 km in Montana. Each of the channels from LASA may be prefiltered and the combined signals from each of the 21 subarrays given time delays; the procedure is equivalent to steering an antenna to receive electromagnetic waves. The operation of these arrays has led to the construction of "maximum-likelihood" filters, appropriate for different seismic phases.

Filter theory is also finding application in other branches of seismology. For example, the precise measurement of the free periods of oscillation of the earth require Fourier analyses of many days of appropriately filtered data; at the other end of the seismic-frequency spectra, periodograms of only a minute or so of signal from a conventional seismograph have been used to estimate the properties of the crust under the recording station.

COMPUTATION OF SYNTHETIC SEISMOGRAMS

Various methods have been developed, some complementary, to produce synthetic seismograms for certain earth models. The two main approaches have been numerical methods of integrating directly the differential equations and analytical methods based on the complex-variable techniques of Lamb, Cagniard, and Scholte. These methods have been most successful in explaining further details of seismograms, such as "leaky mode" waves (e.g., PL) and diffracted seismic waves around the core boundary and along the Mohorovicic discontinuity (e.g., Sn).

The linear theory of mathematical operators is also becoming a widely used mathematical technique in seismology. The frequency function ("wave train") recorded on the seismogram is regarded as a combined effect of separate functions of frequency representing particular physical subsystems (seismograph, crust, mantle, source). By rearrangement of terms and by deconvolution, any one of the functions in the time domain can, under appropriate conditions, be derived.

MODAL THEORY

It has long been known that ground motions can be built up by the superposition of the normal modes of the subsurface geological structure. It has now been clearly demonstrated that high-speed computers make this method a practical one. It has been particularly successful in explaining the longer-period motions on seismograms, especially those recorded at some distance from the earthquake source. Spherical harmonics covering hundreds of orders have been combined in such studies.

The normal-mode approach has also been developed by those interested in the response of soils and alluvium to earthquake waves. The distribution of the intensity of shaking across a region can be computed if sufficient subsurface properties are known. Such predictions are useful to earthquake engineers in their attempts to mitigate structural and other damage during large earthquakes.

SEISMIC WAVES IN STRUCTURED MEDIA THAT DEVIATE FROM IDEAL CONDITIONS

The transfer-matrix methods introduced into seismology so successfully by Haskell for plane-parallel boundaries have been extended to treat the properties of seismic waves on reflection and refraction at interior (spherical) boundaries of the earth.

More recently, other mathematical algorithms have proven successful in analyzing more-complex structural systems. Although the governing differential equations of two-dimensional structures have been known, it has not proven possible to obtain many closed-form solutions that are of practical value. Finite-difference methods are now receiving more attention as a way of obtaining numerical approximations. In these methods, the derivatives in the differential equations and boundary conditions are replaced by difference equations.

A variation of the usual difference methods, called the "finite element method," permits assumptions on plasticity to be introduced through special elastoplastic stress-strain relations. The elastic continuum is replaced by a system of discrete elements that are interconnected at nodal points. This model approximates an infinite-degree-of-freedom system by one having a finite number of degrees of freedom. The partial-differential equations of a continuum are then replaceable by ordinary differential equations. With proper choice of elements there is little restriction on the structural geometry of the region.

THE EIGENVIBRATIONS (OR FREE OSCILLATIONS) OF THE EARTH

A whole new area of seismology has come into being in recent years, particularly following the observations of fundamental motions of vibrations of the whole earth after the 1960 Chilean earthquake. The theory of the free vibrations of an elastic sphere is classical applied mathematics, but complete solutions for realistic earth models required the development of special numerical methods for use with high-speed computers. These solutions involved, in particular, the derivation of energy integrals for the various modes of oscillation and the treatment of the effect of asymmetries in the figure and the physical properties of the earth. Strict mathematical demonstrations have been given for the effect of the earth's ellipticity and rotation on the eigenspectra. The splitting of spectral peaks has been studied, under the name "terrestrial spectroscopy," in order to throw light on the earthquake source mechanisms and the frictional attenuation in the earth.

THEORY OF REPRESENTATION OF SEISMIC SOURCES

Outstanding work concerned with seismic source mechanisms is now under way. Much of the early work on source representations was derived from the theories of Stokes and of Love. This work gave an exact solution for the displacement field resulting from a single force in an infinite elastic medium. A number of methods were devised by Love and others to build up from this elementary form the solutions for dipoles, couples, dilatations, and various combinations of these models. The algebraic results are so complicated that the extensions have been done on a piecemeal basis. In the last decade, a different approach to this problem has been introduced into seismology using the formalism of Somigliana and Volterra. This work provides a general theory for dislocations with arbitrary orientation and for multipolar static sources at any depth in a layered half-space. Much theoretical development remains to be done.

Dynamic sources have also been treated to some extent, and a few comparisons with observations have been carried out. So far, theoretical models appear highly simplified when compared with geological conditions along faults. The analyses have, however, provided useful formulas for estimating average rupture velocities and the partition of elastic energy following the dislocation.

Attempts have also been made to generalize the methods of fault-plane solutions developed on a global scale by Byerly. Rather than reading only first motions, the frequency spectra of P and S (and sometimes other) seismic phases are computed from seismograms written at stations distributed around the globe. These spectra can then be referred back to a focal sphere surrounding the earthquake source. Spherical harmonic analyses then lead to the construction of appropriate source models in terms, say, of a multipolar source.

Like many problems in seismology, the mathematics must account for distribution of measurement errors, so the problem is not a completely deterministic one. Combinatorial statistics are being considered that enable groups of earthquakes in one geological province to be analyzed together in order to [illegible] probabilities.

SURFACE WAVES

There has been a diminution in the amount of seismological research concerned with surface waves, despite the availability of more-extensive observations of surface-wave dispersion and the use of filter theory to estimate the dispersion parameters better.

The main difficulty hindering surface-wave analysis is on the theoretical side. Until now, the inferential procedures used have been based on simplified crustal and upper mantle models with plane horizontal structural interfaces. The importance of dipping layers and transition complexities, between oceans and continents for example, has been recognized. Despite ingenious theoretical work, however, algorithms that give close approximations to the dispersion of surface waves through wedgelike structures have not yet been entirely satisfactory. Theoretical work using finite-element analysis gives some hope of improving on the present methods.

The inference of structure from the observed dispersion is one of the examples of inverse problems in seismology. These problems have received a great deal of attention, with varying degrees of success. In the case of travel times, the inversion of observed travel times to a consistent velocity structure can often be made rather precisely with the Herglotz-Bateman integral method. In the case of surface waves and free oscillations of the earth (which can be represented as very-long-period surface waves), inverse procedures (using linear adjustments based on partial derivatives of the appropriate parameters) have proved successful in only a restricted sense. Monte Carlo techniques to determine the range of possible solutions have been tried. Sharper precision would seem to require the combination of the fundamental and higher modes from both Love and Rayleigh waves using specially derived maximum-likelihood estimators.

SEISMICITY ANALYSIS

One of the oldest concerns of seismology has been the occurrence of earthquakes in space and time. The results that flow from studies of this topic are often of public concern as well, and they must therefore be stated with extreme care. As an illustration, recurrence relations in seismicity are important for engineering purposes and regional planning. The recurrence curves lead to prediction of seismic risk in a given region and to seismic zoning ordinances. On a broader scale, seismicity studies provide crucial information about the present deformation of the whole earth; precision is now such that earthquake patterns have been used to delineate such features as offsets along the mid-oceanic rises.

The statistics of earthquakes on both a global and a regional basis and the properties in space and time of aftershock sequences throw light on the mechanics of earthquakes and on possible triggering mechanisms. The main theoretical interest in this field is in statistical studies. The choice of an appropriate stochastic model is often not clear and the data are often internally correlated, and special tests must be derived.

SEISMOMETER THEORY AND DESIGN

Perhaps the fundamental advance in seismometry following the introduction of electromagnetic coupling by Galitzin came with the inspired work of Benioff in the 1930's. The subsequent modification of the Galitzin seismograph at the Lamont Geological Observatory provided long-period seismographs with highly satisfactory performance. Generally, the theory of the pendulum seismograph has been well worked out, at least for the instruments now in operation. Similarly, an adequate theory for strain extensometers is available.

The broadening of the response of the long-period instruments has drawn attention to theoretical problems connected with earth tilts during the passage of seismic waves. Theoretical work is also being done on more-elaborate types of pendulum seismographs, which provide stable high amplification in certain period ranges. Although the theory of the experimental prototypes is known, no successful routine recording by dilatometer or rotational seismograph has yet been obtained.

TECTONIC PHYSICS—EQUATIONS OF STATE

A number of seismologists have maintained an interest in the equations of state that might apply to various regions of the deep interior of the earth. Theoretical results from solid-state physics must be compared with standard models that come from the derived distributions of seismic waves in the earth. Although no satisfactory theory exists for the physical behavior of complicated compounds, such as silicates, at the temperatures and pressures of the deep interior, certain empirical relations have been derived that involve elastic parameters. Results of deformation measurements and shock-wave analysis carried out in high-pressure laboratories have recently allowed important extensions of these studies. A number of assumptions are made, however, and there is no theory that can be tested by seismological means that provides clear cut results concerning the physics of the interior.

SEISMOLOGY AND INDUSTRY

By far the greatest industrial application of seismology is that of the petroleum industry. The effort is huge. Current annual expenditures for exploration and development by U.S. companies amount to some $1.5 billion. Approximately 3,000 professionals, i.e., holders of the bachelor's degree or above, are engaged in this effort. The importance of seismology to the oil industry is fundamental, as most of the costs are for work of a seismic nature. In 1967, the industry paid $1.7 billion to the federal government for leases of offshore areas. The oil company decisions concerning purchase of these leases were based largely on the results of seismic exploration. The figure of $1.7 billion does not, of course, include royalties to be paid subsequently on production from these areas. In 1967, the oil industry paid some $275 million to the federal government in royalties on oil and gas production.

The vast petroleum industry spawns a host of supporting companies, many of which are engaged in construction of the instruments and other tools required for seismological exploration. These companies have grown with time, as seismic-exploration techniques have become more elaborate and more sophisticated in the search for deposits that are more and more difficult to find. The gain-ranging digital field-recording system is one example of a recent development for small-motion recording in the frequency range from below 1 Hz to over 100 Hz with a dynamic range of approximately 130 dB. Such a field system is priced at $100,000-$150,000, and one supplier alone sold 41 of them during a recent 12-month period. The oil-exploration industry spends $50-55 million a year for seismic instruments alone.

The processing of the data obtained by the seismic crews engaged in oil exploration requires the use of large high-speed computers; hence the computing industry has become heavily involved. The total effort, including programming, is difficult to estimate, but is probably in the neighborhood of $40-50 million annually.

The support industries do perhaps $100 million worth of business per year in the seismic phase of their activities in connection with oil exploration.

Seismic exploration has been an important aid to the mining industry, although expenditures for this purpose are dwarfed by those of the petroleum industry. Many of the tools are identical, and it is therefore difficult to separate the expenditures for seismological hardware by the mining companies from those cited above for petroleum. It must be anticipated, however, that the importance of, and expenditures for, seismic exploration for mineral resources will increase steadily with time as the search for minerals becomes more difficult and the need more pressing.

In recent years, a scaled-down version of the seismic technique has been applied with increasing frequency to exploration in relation to sites for construction of highways, buildings, dams, sewers, water-supply facilities, and many other projects requiring shallow subsurface information. The methods are cheap, quick, and reasonably accurate, and often provide very substantial savings over the cost of drilling. Exploration of areas covered by shallow water is included. The work is done largely by construction companies or related small firms or by government agencies. No figures for annual expenditures are readily available, but such expenditures probably come to at least a few million dollars.

The explosives industry, the construction industry, the quarrying industry, and insurance companies have a strong interest in the measurement and control of potentially damaging earth vibration generated by blasting and other sources such as trains, machinery, and pile drivers. Blasting is regularly monitored in populated or built-up areas by specially designed seismographs. A few small companies and parts of various larger companies specialize in this field. Annual expenditures of perhaps some tens of millions of dollars are involved. It is difficult, if not impossible, to estimate the savings that result from efficient use of explosives to minimize or optimize the resulting seismic vibrations, but the amount is undoubtedly considerable. At least two companies in the United States provide specialized instruments for measuring vibrations caused by blasting.

In the field of earthquake or large-explosion seismology, industry provides both instruments and services. Companies supply not only seismograph components but auxiliary equipment such as tape recorders and crystal clocks. Services include the processing and analysis of seismic data and the installation and operation of seismic instruments and auxiliary equipment. This effort is measured in terms of some tens of millions of dollars.

In addition to those discussed above, there are many industries peripheral to the field of seismology itself that derive some business from seismology. The construction of specially designed vehicles to transmit oil company seismic crews through difficult terrain is one example. Construction of special drilling rigs and of unique machines for generating seismic waves are others. There are many more.

Thus, the field of seismology has a very substantial effect on the economy of the United States, an impact far in excess of government expenditures in this field, and the impact on the future is likely to be still greater.

INSTRUMENTATION AND FACILITIES

Measurements that accurately describe the phenomena of interest are the foundation of any of the natural sciences. Hypotheses are formulated and tested in terms of data provided by various kinds of measuring and recording instruments. Man's understanding of his physical environment has grown with the growth of his ability to develop and operate instruments of greater and greater precision and capacity in an ever-increasing variety of locations and environments. Seismology, along with other sciences, has followed this pattern of development.

Basically, the function of seismological instrumentation is to provide measurements of the motions of points at the earth's surface or within the earth relative to the earth as a whole. The motions to be measured may be the effects of earthquakes, explosions (prospecting seismology, nuclear detonations, commercial blasting), tide-producing forces, or industrial operations (vibrations produced by machinery). The range of amplitudes of these motions is large, from inches or feet for large events down to small fractions of a wavelength of light–i.e., interatomic dimensions for certain teleseismic phases and for background noise in some frequency bands.

A complete seismograph system provides a permanent record of the variation with time of the kinds of ground motion being measured (e.g., displacement, strain), with a time scale that permits the determination of the time of occurrence of any recorded event, either with respect to Greenwich Mean Time or with respect to the moment of occurrence of the event The record must be in a form convenient for analysis.

Because seismic-wave propagation is a global phenomenon, effective analysis requires data from observatories distributed widely over the earth's surface. International cooperation in the exchange of seismological data has been traditional since the earliest days of instrumental observations.

SEISMOLOGICAL INSTRUMENTS

Little information of value can be ventured about the origin, nature, and meaning of seismic waves until the wave motion is adequately recorded by instruments. Detailed recording is by no means easy because periods of interest range from 0.05 sec to 54 min (the period of the gravest free oscillation of the earth), and even as much as a day if the tidal response of the solid earth is included. In the same way, the amplitudes of seismic waves of interest may vary from Angstrom units to tens of centimeters, depending upon the magnitude of, and the distance from, the earthquake.

Seismological research requires measurements in three different regions during a seismic event: in the source region itself, in the region of strong motions near a high-energy source, and at points far removed from the source region. The instruments required to provide useful data in each of these regions necessarily differ because the character of the phenomena is different in each region and because different uses are made of the observations. Instruments at large distances from an earthquake must observe motions of the earth's surface that result from the sequential arrival of trains of waves with periods ranging from about 1 sec to 1,000 sec, with amplitudes ranging from a few millimicrons to a few centimeters (surface waves from very strong earthquakes), and coming from completely arbitrary directions. In the strong-motion region, there is a short-duration burst of energy in which wave periods of about 0.01 to 1 sec are predominant and amplitudes are large, ranging from a few millimeters to several centimeters. Instruments covering six decades of frequency, with a dynamic range of 120 dB, are required. No single instrument with this capability has been developed yet.

Within the source region of an earthquake, measurements are needed of slow displacements or strains during the interval before the event, large transient displacements of perhaps a few meters during the event, and permanent displacements or strains after the event. For explosive seismic sources, measurements have been made of large motions and of shock-wave velocities within the close-in region of high stress, encompassing the zone of hydrodynamic behavior as well as the regions of crushing and cracking. Concurrent measurements of other, nonseismic geophysical parameters are also required for a complete understanding of earthquake physics.

In the past, few measurements have been possible within the source regions of earthquakes. Because earthquakes are geological events, it is essential that direct observations of large-scale phenomena with permanent aftereffects be made at the place of occurrence. However, the hypocentral regions of most earthquakes are inaccessible, either because they are too deep within the earth or because they are under the sea, or both. Modern hypotheses concerning the source mechanism of earthquakes are based largely on the properties of seismic-wave motion at points distant from the source. Data from observations in the hypocentral zone at the few places at which such observations are possible provide invaluable control for these hypotheses. These data have been obtained through experiments employing nuclear devices as seismic sources. Much of our confidence in the validity of conclusions about the source mechanism, as derived from observations of the seismic signal at a distance, comes from the quantitative understanding of the wave-generating process provided by these experiments.

Instruments for the observation of explosion-generated waves at short ranges have been developed to a sufficiently advanced state that improvements in technology are incorporated quickly. The incentive for instrument development in this area of seismology has been provided largely by the applicability of such equipment to oil-finding. Research related to the detection and identification of underground nuclear explosions has provided an additional motive for improving these kinds of instruments.

Design of Seismological Instruments

The measurement of motion is one of the oldest problems in experimental physics. The measurement of transient ground motion presents some unique problems, however, because the entire environment is in motion. Only two basic quantities have proven applicable to seismic measurements: the motion of an inertial element relative to a supporting frame to which it is loosely coupled (see Figure 12), when the frame moves with the ground; and the change in distance between two points that is associated either with the passage of a seismic wave or with a permanent deformation of the earth (see Figure 13). These two measurable quantities of seismic motions have been recognized since the beginning of the use of modern seismic instruments in the late nineteenth century, and no fundamentally different principle on which to base an instrument has been successfully developed.

In most seismometers, the mechanical energy represented by the motion of the suspended inertial element relative to the supporting frame is used to produce the seismogram or instrumental record. This may be done either by directly coupling the energy to the recording surface through a lever system—mechanical, optical, or both—or by converting the energy into an electrical signal, through a transducer, and then recording this electrical signal. Direct-recording instruments have low sensitivity, and the principal modern application of such systems is for measurements of strong earth motions.

Several physical effects have been employed as the basis for the design of seismic transducers. Electromagnetic induction is the principle most often used, applied either through the motion of a coil in the field of a permanent magnet or through changes in the reluctance of a magnetic circuit. The changes in capacitance resulting from a change in the separation of two parallel conducting plates is also used to detect the relative motion of the suspended mass. The piezoelectric effect on crystals has been used, experimental instruments using lasers as transducers have been built, and experiments with other physical effects are in progress.

When the seismic signal is in the form of a variable voltage, processing of the signal becomes easier. The energy can be amplified, filtered, telemetered, converted to digital form, or otherwise transformed to give the seismologist the information he seeks in a form most useful to him.

Measurement of the change in distance between two points anchored in the earth, the other kind of seismic measurement, is done with strain seismographs, or extensometers. In this method, the two points, marked by "piers" embedded in the ground, are some tens of meters apart and a rigid rod fastened to one reaches almost to the other. A transducer produces a signal that is proportional either to the relative velocity of the two piers (electromagnetic) or to the relative displacement (capacitance). Strain meters equipped with displacement transducers measure strains in the earth caused by the tide-producing forces, as well as secular and abrupt permanent strains. The tidal component is often filtered out, and the instruments are used primarily for measuring transient strains associated with the passage of seismic waves.

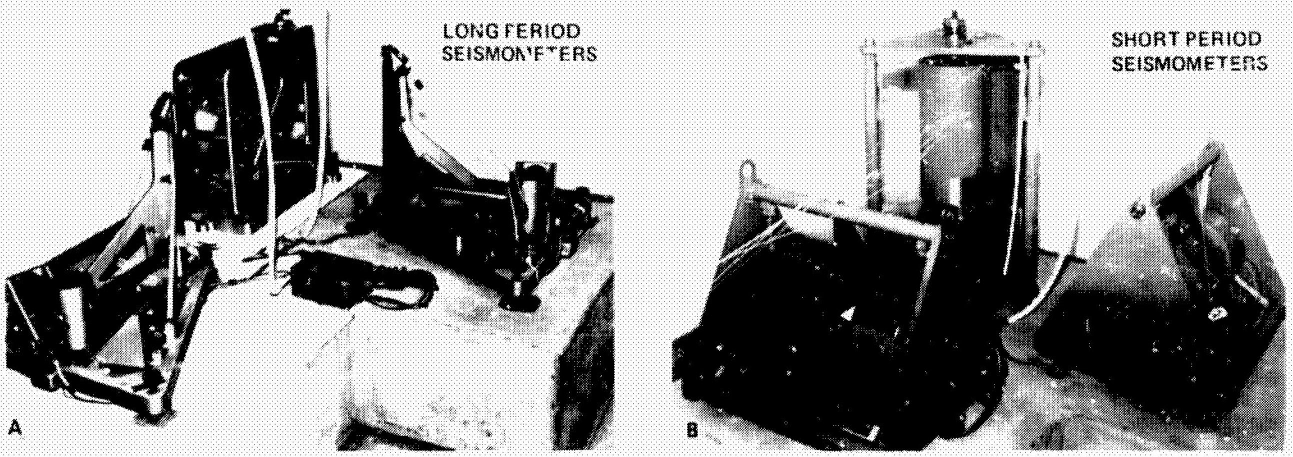

FIGURE 12 Long-period (A) and short-period (B) seismometers. Each photograph shows one vertical and two horizontal seismometers used in World-Wide Standardized Seismograph Stations to detect earthquakes. (U.S. Coast and Geodetic Survey.)

The environment in a seismic observatory must be controlled, especially with regard to temperature and humidity. Instruments for observing long-period signals are especially sensitive to temperature variations. Long-period vertical-component seismographs are sensitive to atmospheric-pressure changes, and either such changes must be compensated for or the instruments must be sealed.

The measurement of strong earth motions presents additional problems. The primary application of this data is to earthquake-resistant design of structures. Both displacements and accelerations of the ground are measured. Because the motions are large, rugged instruments of low magnification are required. The motion to be measured is rich in high frequencies, so a fast chart-speed is needed if photographic or stylus recorders are employed. It is not economical to operate recorders at high speeds 24 hours a day while waiting for an occasional strong earthquake, although this is now being done at certain specially equipped observatories using magnetic tape. Therefore, strong-motion seismographs are equipped with starter devices that are activated by the initial earthquake motion. The onset of the motion is lost in this technique, and while this loss represents little of value to the earthquake engineer, it is a severe one to the seismologist. Even this weakness of the system can be overcome by using a continuously recording magnetic-tape loop in a delay-line arrangement that permits the triggering signal to be recorded—but the cost of strong-motion stations is greatly increased by such additions. The need for additional strong-motion stations in many places in the United States, especially outside the state of California, is great.

Advances since World War II

Important advances have been made in seismological instrumentation since World War II, but these have all involved the application of newly developed technology toward exploiting one of the two basic principles in a better way. Flexible systems of high sensitivity and reliability have emerged through the development of better transducers; stable, low-noise dc amplifiers; low-frequency magnetic-tape recorders with long operating times; and direct digital encoding of transducer outputs. Instruments have been developed that are capable of operating in hostile environments—such as in a bore hole, on the ocean bottom, and on the lunar surface. These instruments are limited in pass-band and dynamic range. Lunar instruments are only now receiving their first tests in their working environment. Ocean-bottom instruments have been operated successfully, but must still be considered in the developmental stage.

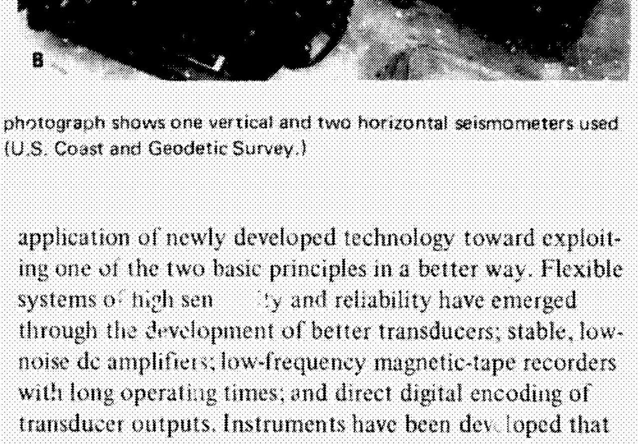

FIGURE 13 Strain meter—a quartz tube (Q) suspended between two concrete piers. The relative motion of the tube and pier, measured at B, is a direct measure of strains within the earth. (U.S. Coast and Geodetic Survey.)

Groups of instruments have been combined to form seismic arrays. An array, taken as a whole, is in a sense a single instrument with capabilities exceeding those of the individual elements of which it is composed. When combined with computer control and processing of the outputs of the array elements, an array is a powerful tool for seismological investigations.

The use of telemetry to permit recording, at a central observatory, of the signals received from remote seismic detectors has led to new precision in seismological research.

The important advances in instrumentation outlined above pertain mostly to instruments for recording short-period ground motions (1 sec and less). Stable instruments with high sensitivity in the very-long-period range (longer than 100 sec) have not been developed. Very-long-period motions have been detected, but only as an effect of infrequent, very strong earthquakes.

Instrumental Needs for the Future

Experience in the physical sciences has taught that the ability to make measurements in previously unexplored environments or in a previously unexamined range of values of a physical parameter almost invariably leads to important new discoveries or to the drastic modification of earlier hypotheses. Extrapolation into regimes beyond the range of observation is always uncertain in view of the limitations of man's knowledge of the behavior of matter. But such extrapolation is often the only way open to the investigator. Subsequent measurements may show that theory was indeed far ahead of experimental capability, or, conversely, that theory when applied to untested regions led to conclusions not in accord with nature.

As applied to seismology, this experience dictates that future development of instrumentation be directed toward an increased capability to emplace and operate instruments in locations other than the land surface of the earth, and ward improved response characteristics, especially in the very-long-period part of the spectrum.

The importance of ocean-bottom seismographs capable of providing routine data in the same way that land stations now do is immediately evident from a glance at a map of the world showing the distribution of epicenters and seismological observatories. Most seismic energy is released around the perimeter of the Pacific Ocean. There is, therefore, always at least one quadrant in the intermediate range of distances in which no observations are available from the present global network of observatories. Both research into the earthquake mechanism and routine determination of epicenter locations will benefit from a network of ocean-bottom instruments.

The study of micro-earthquakes is still in its early stages. Results thus far indicate that these small events can reveal important facts about the seismicity of a region and may prove useful for earthquake forecasting. Results of micro-earthquake research can be extended to ocean basins only if high-sensitivity ocean-bottom instruments are developed. A high-sensitivity ocean-bottom network, along with major facilities on the Mid-Atlantic Ridge, would undoubtedly produce data of great value.

The potential scientific value of seismological observations on the moon and other planets is large. It is important to know whether seismic events occur on these bodies, for if they do, they will provide new knowledge about the internal structure and composition of the planets and about the history of our solar system. Even instruments limited in passband and dynamic range will yield some information. This information may shed further light on the internal constitution of the earth itself; our understanding of the earth's interior and of its physical evolution may have to be modified in the light of the new knowledge gained through planetary seismology.

The need to place instruments within the source regions of earthquakes has been emphasized above. Here, the emplacement of the instruments is a much harder problem than their development. In only a few places, such as along the San Andreas fault in California, does the source region extend to the surface of the earth. Much of the research effort aimed at gaining a better understanding of the physics of earthquakes is now concentrated in such places. Although other seismogenic structures similar to the San Andreas fault are known, it is not known whether the physical processes of such sources are typical of all earthquake sources, and to what extent conclusions based on observations in such places can be transferred. The ability to place sensors at great depths in seismogenic regions will be of inestimable value. Quantities to be observed include not only strains and displacements but also such related parameters as heat flow, geomagnetic variations, and changes in electrical conductivity of the rocks. Only through data provided by instruments within the source region can the full power of our knowledge of physics and chemistry be brought to bear on the question of the earthquake mechanism. Such fundamental information as the energy budget of a natural earthquake, now well-understood for buried artificial explosions, cannot be obtained with the data now available.

Another area in which additional work is required is in the development of recording media and methods of presentation of data. In this field also, the exploration seismologists have played a role of leadership. For example, the presentation of reflection seismograph data in variable-density displays is enormously suggestive to the interpreter. The same information is contained, of course, in other forms of presentation, but the variable-density display gives the seismologist special aid in discerning features of interest. Such techniques have not been adequately employed in studying earthquakes.

Direct digital recording is now used extensively in ex-

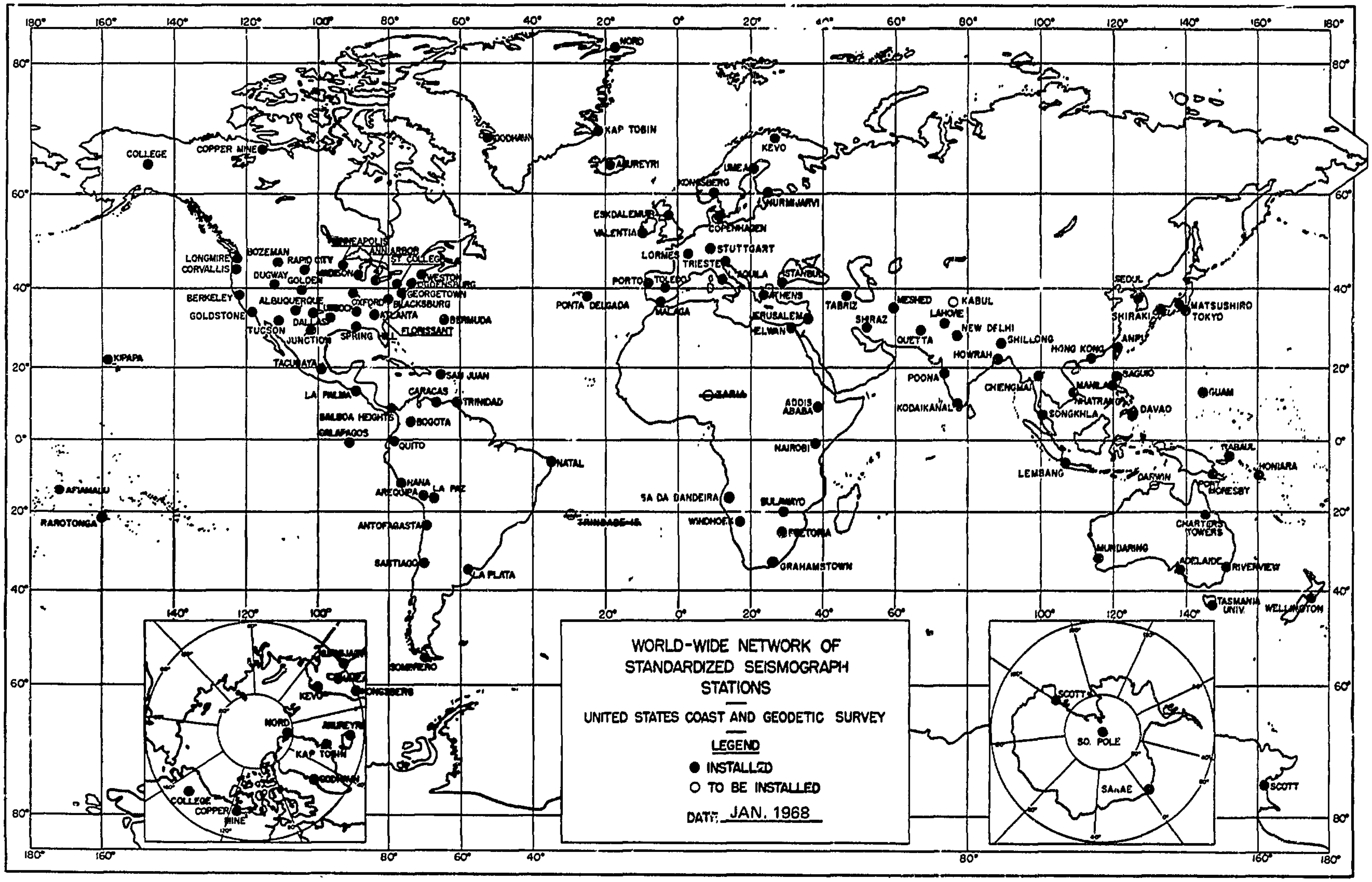

FIGURE 14 World-Wide Standardized Seismograph Network established as part of the nuclear-test-detection program. (U.S. Coast and Geodetic Survey.)

ploration seismology, but in only a few earthquake observatories. The routine application to earthquake records of powerful techniques, such as time-series analysis carried out by machine computation using detailed amplitude in addition to time information, is feasible where data are available in digital form. This is not to suggest that digital recording should replace analogue recording, but it provides an important supplement.

FACILITIES

To make the most effective use of the instruments of seismology and of the skills and efforts of seismologists, various kinds of facilities are essential. These facilities range from single instruments to networks of permanent observatories throughout the world. They include facilities for the storage, processing, analysis, and communication of data, patterned arravs of instruments at a single location, and laboratories for such things as model studies and simulation of conditions in the earth's interior.

With regard to observational seismology, facilities requirements can be examined in terms of the sequence of steps leading from initial ground-motion measurements to the final interpretation. Details of the procedures will differ, depending on whether the observations are for research use or for routine monitoring of seismic activity and whether the problem is one in exploration seismology or in earthquake seismology, but the main features are the same. The steps are detection of motion, data transmission and recording, data analysis, and interpretation.

Networks

Seismology is inherently worldwide in character. Continuous belts of seismic activity encompass the earth. The seismic waves generated by an earthquake of only moderate size penetrate the deep portions of the earth's interior and spread with detectable amplitudes over the entire surface of the earth without regard to political boundaries. Thus, a network for collecting data on seismic events must be of worldwide extent. The earthquakes of a given country cannot be studied effectively using data from instruments in that country alone, nor will data from only those countries with areas of high seismicity suffice. The need for worldwide international participation in the establishment of a huge seismic-data-collecting network is readily apparent. Similarly, there are other phases of the science of seismology that require investigation on a worldwide scale. The relationship between earthquakes of one area and the geology of that area takes on true significance only in the light of comparable information from related areas throughout the world. To understand the San Andreas fault and its environs is one thing. To understand that fault along with similar faults such as the Denali fault of Alaska, the Alpine fault of New Zealand, and the Philippine fault in the light of a common mechanism is more basic and fundamentally more important.

At present, seismology's lifeblood is the observational data from about 800 seismographic stations around the world. Many belong to national networks, such as those of the USSR (about 100 stations) and of Canada (about 21 stations). Of primary importance is the Worldwide Network of Standardized Seismograph Stations (WWSSN), a network of 116 standardized stations in 61 countries (see Figure 14). This network was established under the auspices of the U.S. Coast and Geodetic Survey, Department of Commerce, and began its activities in 1960. It is the direct descendant of the global networks of Milne and the Jesuits. Each of the WWSSN stations has a three-component set of calibrated Benioff short-period seismographs and a three-component set of long-period seismographs. The network has the special value that the instruments are the same at every observing point and that frequent calibration checks are made in a standard manner so as to hold the response characteristics within narrow tolerances. This standardization makes the seismograms obtained from this network of vastly greater usefulness when quantitative comparisons of ground amplitude are being made. Without this standardization of a large number of observations on a worldwide basis, many of the advances of seismologic knowledge of the past four years would have been impossible.

The data obtained by WWSSN include time-of-arrival readings, sent promptly to the National Earthquake Information Center (NEIC), Rockville, Maryland, for use in the epicenter program, as well as seismograms, which are sent to the ESSA National Geophysical Data Center in Asheville, North Carolina. There, the records are copied and made available internationally to all who require them for research. The ready availability of these data at one location is in itself one of the major advances in seismology in recent years.

A number of more-elaborate seismological observatories have also been established at various points around the world (see Figure 15). Many of these observatories are research centers as well, and many of them operate specially designed instruments, some in deep holes or mines in order to avoid surface-enhanced microseisms. Some of these observatories monitor very small nearby earthquakes (micro-earthquakes), earth strain, ultralong seismic waves and tides, perturbations of gravity, and large ground displacements and accelerations. Others, particularly those under government auspices in the United States and the United Kingdom, consist of large arrays of seismographs designed to record small seismic signals at large distances from the sources; at these, research is usually aimed at discrimination between underground explosions and earthquakes. A group of observatories is especially concerned with the rapid detection of large submarine earthquakes that might be generators of damaging tsunamis. Another group of stations, in the western United States, Alaska, and several countries of South America, records

FIGURE 15 Vault for WWSSN instruments at Bogota, Colombia, operated by the Geophysical Institute of the Colombian Andes. (U.S. Coast and Geodetic Survey Photo.)

strong-motion-seismograph data from nearby earthquakes.

In addition to their seismological research and teaching activities, many universities operate seismographic networks partly as a public-service activity. Many of the routine reports of local earthquakes come from these networks, and their reports are the primary basis upon which seismicity and seismic-hazard maps have been constructed for large areas of the United States. The University of California at Berkeley, for example, routinely operates 16 widely dispersed seismographic stations in central and northern California; the data from 10 of them are continuously telemetered to Berkeley. Similarly, the California Institute of Technology operates 21 stations in southern California, seven of which telemeter data to Pasadena. These two long-established networks provide the primary basis for our knowledge of seismicity patterns in California. In our attempt to gain a better understanding of seismic hazards, it is essential that these kinds of seismographic networks continue to be supported, whether they be operated by the universities or by state and federal agencies.

In addition to the types of seismic work normally performed at the universities, many universities have taken on the special responsibility of collecting and analyzing seismic data for their local geographic regions.

The vision of a global network held by the founders of seismology is now nearly fulfilled, although it was an extra-seismological stimulus that provided the WWSSN stations and permitted modernization of a number of other seismological observatories. The need to improve the network is great. Much experimental design remains to be done; moreover, the distribution of stations is largely bound by the continents and, within the continents, to the more populated and technically advanced regions. More-complete scientific arrangements, involving stations on the floors of the oceans and in the more inaccessible land regions, are vital tasks for the future.

Supporting Activities

Machine computation of hypocenter locations is now routine. It is conceivable that a continental network of seismic observatories will evolve that is controlled directly by a computer. Rapid determination of earthquake locations would then be available as an aid to the tsunami-warning service and to agencies involved in seismological investigations that require installation of equipment in an epicentral region as soon as possible after an earthquake.

Additional facilities for processing seismic-wave data with respect to both time and frequency will be required. Research into all aspects of seismology, including such large topics as the mechanism of earthquakes and the internal constitution of the earth, requires such facilities. These facilities will be built around high-speed digital computers and large-capacity analogue devices. As computation devices of increased capacity and speed are developed, steps must be taken to make them available to seismologists in all branches of the subject.

The associated data-assembling and data-dissemination facilities are as important as the network of observatories. Continued research concerning the application of new developments in communications technology to the transmission of seismic data should be conducted. Systems with greatly increased information-carrying capacity will be forthcoming, and their application to the rapid handling of seismic data must be provided for. Continental or intercontinental networks connected by high-speed data-transmission channels to central data-processing facilities can reduce routine hypocenter-location efforts to an on-line process.

Arrays

The individual seismometer is and will remain the basic building block of a seismic observing system. However, a group of seismometers arranged in a pattern becomes an array, in effect a new instrument with capabilities beyond those of the individual elements of which it is comprised. In an array, the seismometers are interconnected so that the outputs of the individual elements are combined to give the desired system response. The Large Aperture Seismic Array in eastern Montana is a successful first-generation major array (see Figure 16).

Continued research concerned with array design should be supported. The choice of array geometry is now largely empirical and should be put on a rational basis. Studies should be carried out to determine what operating characteristics are best for seismometers used in arrays designed for specific seismological investigations. Selection of sites for new arrays must be done carefully. The need for an adequate data-transmission system becomes increasingly apparent, as does the need for a data-processing system of sufficient capacity and flexibility to permit optimum treatment of the array output. Data-handling systems must be designed so as to permit the widest simultaneous use of the array output by many investigators, even though they may be interested in different seismological problems. (See Figure 17.)

Laboratory Facilities

Laboratory studies play an increasingly important role in seismological investigations. Improved and expanded facilities are needed for investigating the properties of earth materials under higher temperatures and higher pressures than those yet obtained. Studies must be conducted not only of the properties of these materials in ambient conditions simulating the earth's interior but also of the mechanisms by which they fail when subjected to nonhydrostatic stress.

Laboratories capable of performing model studies of seismic phenomena have demonstrated their value in elucidating difficult problems. Improved facilities incorporating new techniques for detecting motions and strains in the interiors of models, and techniques for applying realistic earthquake-like loading to these models, should be developed.

DISCUSSION

The need for cooperation on an international scale has been apparent in seismology since the very beginning of the science. Systems for transmitting and exchanging information at a rate which, if not ideal, was adequate for an earlier era were devised during the first part of the twentieth century. With some modifications and improvements, these are the systems that prevail today.

Additional facilities of substantial proportions will be required to sustain the growth of research, application, and education in seismology at a rate satisfactory to meet the needs of the United States. As new research programs emerge and as new applications are discovered, specific facilities to meet the needs of these programs will have to be developed. Speculation about the special requirements of individual projects before their conception is not likely to be fruitful. However, the general need for new and expanded facilities can be anticipated in the light of the outlook for the growth and development of the science.

The continued development of seismology, and the very nature of earth science, requires that facilities, especially research facilities, be located so that seismologists are brought into intimate contact with their colleagues in related sciences—for example, geology, geodesy, geomagnetism, and oceanography. The creative seismologist performs at his best in an intellectual atmosphere in which he can exchange information and ideas with specialists in these other areas.

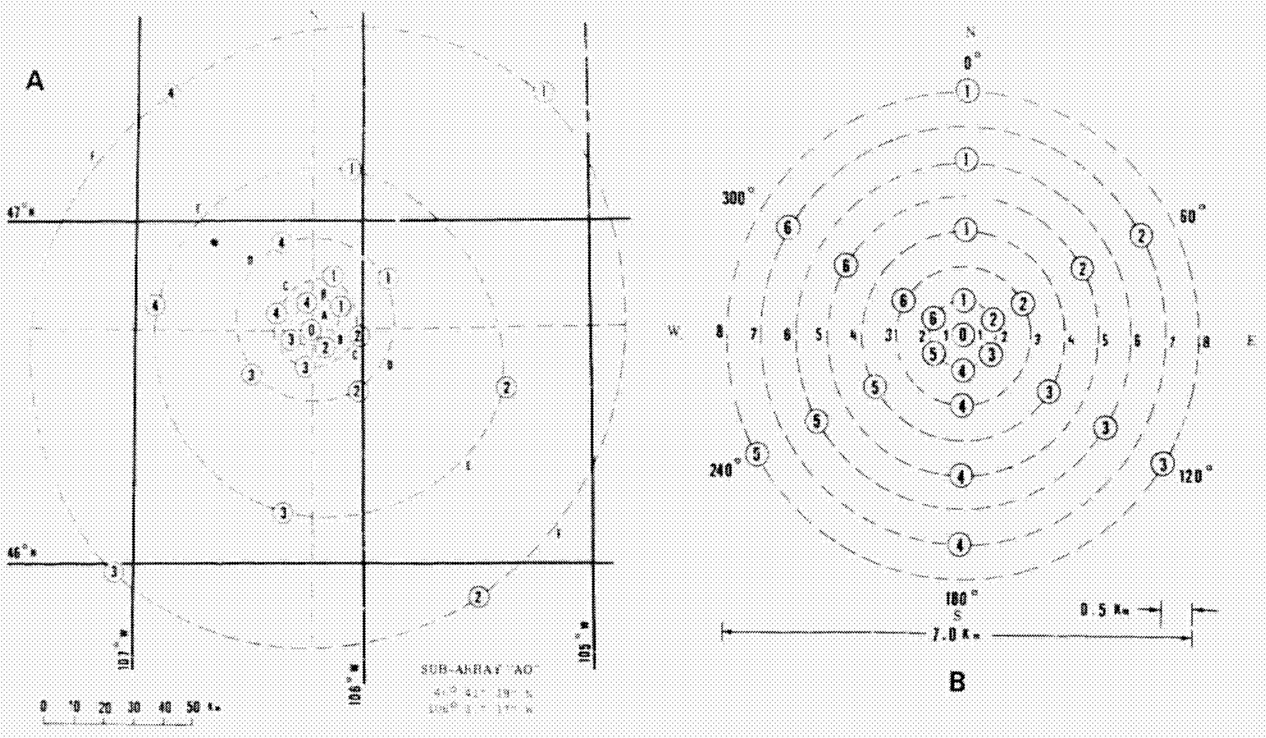

FIGURE 16 (A) Plan view of Large Aperture Seismic Array located at Miles City, Montana. Each small circle on (A) designates a sub-array with 25 seismometers (B). There are 21 such sub-arrays. Total diameter of LASA is 200 km. (Diagram by Lincoln Laboratory, MIT.)

FIGURE 17 Interior of LASA Data Center at Billings, Montana, where all signals from the 525 LASA sensors are brought together for automatic processing. The Center, nearly 150 miles from the array center, serves as a research facility where scientists and engineers from many organizations can conduct independent research. (Photograph from Lincoln Laboratory, MIT.)

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