APPENDIX 1A

Science Plan for a New Global Seismographic Network

"revised edition"

SCIENCE PLAN FOR

A NEW GLOBAL SEISMOGRAPHIC NETWORK

Prepared by the

INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY

Revised Edition December 1984

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"Global seismic networks are as basic to seismology as the telescope is to astronomy and the accelerator is to physics. Without this instrumentation, seismologists are 'blind' to subsurface earth processes and properties and the very survival of the science would be threatened. Support of a modern global network of seismic stations is clearly in the national interest."

(From *Global Earthquake Monitoring: Its Uses, Potentials and Support Requirements*, Committee on Seismology, NRC/NAS, 1977.)

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

A special feature of seismology is that it not only provides the most detailed information about the structure of the Earth's interior, but it also relates to fundamental problems of economic importance and social well-being."

(From *U.S. Earthquake Observatories: Recommendations for a New National Network*, Committee on Seismology, NRC/NAS, 1980.)

"After considering a wide variety of data problems in seismology, the Panel has identified as the primary challenge in the immediate future the development of a coordinated national effort in the collection, storage, and dissemination of digital earthquake data to assure that our most advanced technology is used effectively in seismological research and engineering applications. Indeed many of the most important and challenging seismological studies of today require both digital data from state-of-the-art instruments and computer facilities capable of analyzing large data sets and modeling the processes that explain the observations."

(From *Effective Use of Earthquake Data, Committee on Seismology, NRC/NAS, 1983.)*

"The rapid development of digital seismographic equipment and the increased availability of computers suitable for processing the digital data have led to demonstrations of the power of digital data for the solution of major problems that have been previously unapproachable. Calculation of the kinematic and dynamic properties of seismic sources and resolution of details of the structure of the earth's interior in three dimensions are two areas in which the use of digital data is already yielding significant new knowledge. These developments make it timely to evaluate the global seismographic observatory system and take remedial actions as needed."

(From *Opportunities for Research in the Geological Sciences*, Board of Earth Sciences, NRC/NAS, 1983.)

"It is essential to maintain a global data base that is uniform for years or even decades. This requires establishing a supportive home environment for [the] G[lobal] S[eismic] N[etwork]."

(From *Seismographic Networks: Problems and Outlook for The 1980s*, Committee on Seismology, NRC/NAS, 1983.)

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EXECUTIVE SUMMARY

Presented here is a plan for a major new initiative in the Earth Sciences. The core of this initiative is a ten year, $80M plan to design, deploy, and operate a global network of some 100 seismic stations, telemetered via satellites to data centers around the world. It is the action plan based on detailed scientific studies conducted by the National Research Council over the past five years to provide the principal facility for global seismological observations until at least the year 2015. This plan is prepared by the Incorporated Research Institutions for Seismology (IRIS), a recently formed group of some 36 independent research organizations with the specific objectives of proposing and implementing the new global network and establishing a national facility for seismic studies of the continental lithosphere.

The management of a project of this size is a complex matter. IRIS was formed for this purpose based on previous experience by similar organizations such as the Joint Oceanographic Institutions, Inc., University Space Research Association, and the Universities Corporation for Atmospheric Research. It is planned that most technical, engineering, and operational aspects will involve subcontracts, with IRIS providing the overall management, direction, contractual support, and scientific advice through its advisory subcommittees. As many aspects of the project will involve close coordination with government agencies, IRIS will provide this liason.

WHAT IS A GLOBAL SEISMIC NETWORK?

- A worldwide deployment of a large number of calibrated seismographs with a central data distribution system.

WHAT DO WE HAVE NOW?

- The 120-station, analog-recording World Wide Standardized Seismic Network (WWSSN), installed 23 years ago, is an example of a global seismic network that has well served the nation's seismological needs.
- Several sparse networks of digital instruments operated by government agencies and universities. These include
  1. Global Digital Seismic Network (GDSN), which consists of:
     a. Seismic Research Observatories (SRO) — 11 installations;
     b. Abbreviated Seismic Research Observatories (ASRO) — 4 installations;
     c. Digital WWSSN (DWWSSN) — 13 installations.
  2. International Deployment of Accelerometers (IDA) — 18 installations, designed specifically to study the Earth's normal modes.
  3. GEOSCOPE — 5 installations, a developing broadband network operated by a consortium of French universities.
  4. Regional Seismic Test Network (RSTN) — 5 installations in North America only with real-time satellite telemetry.

WHY A NEW GLOBAL SEISMIC NETWORK?

- To replace obsolete global analog network with modern, high quality digital instrumentation.
- To upgrade and integrate into the new network existing digital stations
- To ensure operation of a broadband, digital network comparable in the number of stations but better-distributed than the analog WWSSN.
- To improve the resolution of global lithospheric structure, earthquake sources, and structural manefestation of mantle convection patterns
- To improve the timeliness and efficiency of data distribution

WHY NOW?

- Recent results obtained from the analysis of available data demonstrate that significant advances in many problems of fundamental importance to earth sciences could be achieved with the data from a network such as proposed here.
- Technological developments make deployment of such a network operationally and economically feasible.

WHAT ARE THE SCIENTIFIC OBJECTIVES?

- Study of static and dynamic properties of the Earth as a planet
- Global mapping of the lithosphere and deeper lateral heterogeneities
- Resolution of the anisotropy in the lithosphere and deeper parts of the mantle; mapping of mantle flow
- Understanding of the dynamics of earthquakes
- Nearly real-time analysis of large events

WHAT TECHNOLOGICAL ADVANCES MAKE THIS PROJECT TIMELY?

- Application of electronic control methods and digital data acquisition to seismometry
- Developments in digital mass storage methods
- Advances in satellite communications
- Availability of large computing facilities

WHAT WILL BE THE CHARACTERISTICS OF THE NETWORK?

- Approximately 100 stations, 3 components each
- Broadband ~ 10 Hz.
- High dynamic range > 120 db
- Real-time telemetry via satellites

HOW WILL IT BE MANAGED?

- IRIS (Incorporated Research Institutions for Seismology), a non-profit corporation formed by 36 U.S. universities to provide scientists with the large-scale facilities needed for seismic studies of the earth
- IRIS will provide management direction, contractual support, and scientific advice; technical, engineering, and operational aspects will be subcontracted.

HOW MUCH WILL IT COST?

- $80M over 10 years

WHAT IS THE PLANNED LIFETIME?

- 30 years, assuming that the network will be gradually upgraded as new technology develops. In this way, the performance of the network should improve with time.

HOW WILL THE DATA BE MANAGED?

- Archived at national facility
- Distributed to data analysis centers and individual research groups
- Some data analysis at major computational facilities

1. INTRODUCTION

Seismology concerns the excitation, propagation and recording of elastic waves in the earth. The excitation of elastic waves provides the most detailed information about the kinematics and dynamics of the earthquake rupture process, and their propagation is the richest source of information about the composition and state of the earth's interior. To record these waves seismologists are necessarily limited to a finite set of stations at or very near the surface of the earth. The purpose of this science plan is to outline the scientific benefits that would accrue from the global seismic network proposed in this document.

In one of the Academy reports, quoted in the frontispiece, a comparison is made between the global seismic network and a telescope. This comparison is quite realistic, other than the network represents an "inverted" telescope. This is illustrated in Figure 1.1, showing a family of rays of the compressional (P-) waves covering the teleseismic distance range (from 25° to 180° of arc).

This simple picture demonstrates why seismologists need a global network. On the one hand, to determine the velocity distribution as a function of radius, we need stations at all distances for measuring the properties of waves that have turning points at different depths. On the other hand, it is from observations of amplitudes of the waves recorded at different points around the globe that we can study the pattern of radiation at the source and, therefore, determine the location, origin time, and the mechanism of earthquakes.

This need for global coverage of the earth's surface by seismographic stations had been recognized as early as the beginning of this century when the first, very sparse, networks were established. Section 2.1 gives a brief historical account of these developments. The World-Wide Standardized Seismograph Network (WWSSN) installed in early 1960's was by far the largest of the global networks and it has had a profound impact on modern seismology. The key to its success was the fact that copies of records from over 100 stations could be ordered at low-cost from a single central location. This, in turn, led to working arrangements whereby seismograms from many non-WWSSN stations may readily be obtained. Several research institutions within the United States and abroad maintained complete libraries of microfilmed WWSSN recordings. While the impact of the WWSSN was at first the greatest in studies of global seismicity and radiation patterns of earthquakes, hand-digitized analog recordings were used in various quantitative analyses of seismic waveforms and the results provided a strong stimulus for the development of digitally recording stations.

While there are currently some 55 to 60 operational stations that could be considered to constitute the nucleus of a global digital seismographic network, most of them fail to meet the scientific needs of basic research in seismology in a number of important ways. First of all, the distribution is inadequate to provide the global data density required for many of the most challenging and interesting problems of earth structure and source mechanisms. Secondly, the bandwidth of most of the current stations is limited and does not cover the seismic spectrum. They were designed to observe signals within only specific bands of this spectrum, and while their response is appropriate for the objective for which they were designed, the data they produce are not adequate for many applications. Finally, none of the stations has sufficient dynamic range to record on scale, even at teleseismic distances, a great earthquake with magnitude (M_W) above 8. Many, if not most, of the instruments become saturated even for moderately large events ($M_W > 6.5$) at intermediate distances. This prevents seismologists from using the part of the record that contains the most information on the source mechanism. The early part of recordings is also important in studies of lateral heterogeneity, as the information contained in the later orbits of surface waves may be severely distorted by the multipathing effects. Limitations of existing global networks are discussed in Section 2.2.

Despite these limitations, the digital data recorded during the last 7—8 years led to many important results, and there is no question that the existing networks represent a valuable asset for seismology. It is of great importance that these stations be only gradually discontinued, or replaced, as the new stations are introduced. This transition process may take some time, as

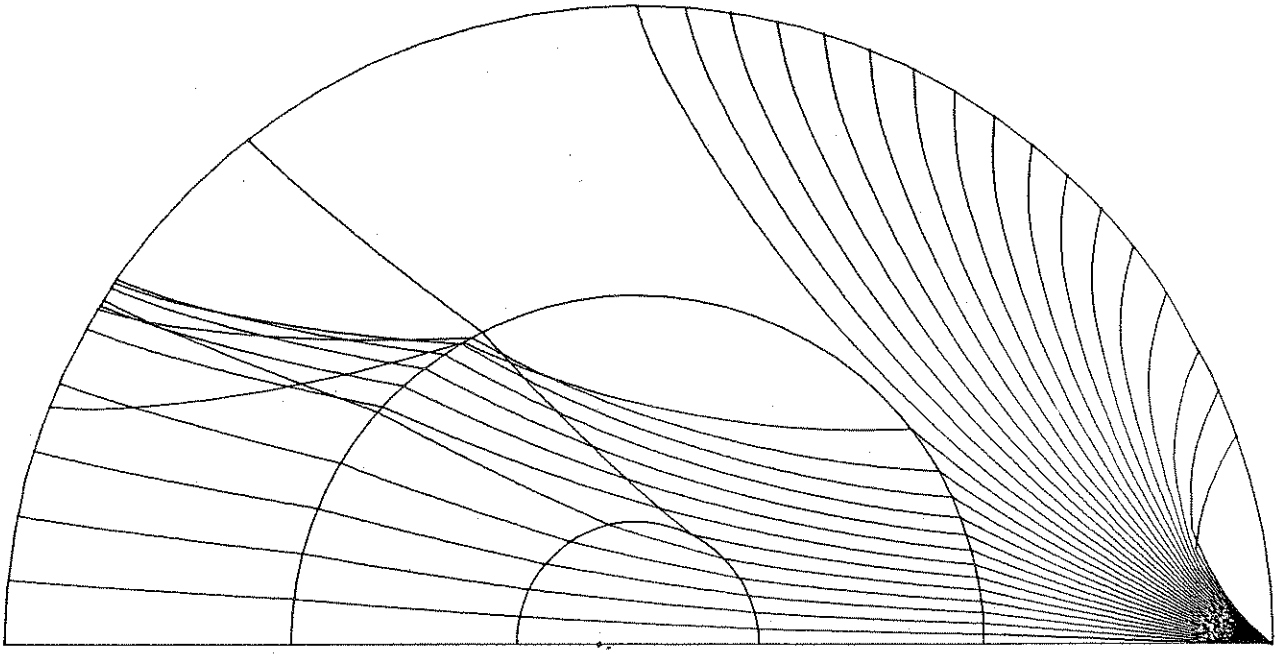


Figure 1.1. The outermost circle is the surface of the earth, the core-mantle boundary is next and the innermost circle has the radius of the inner core; discontinuities in the upper mantle are not shown. The velocity varies as a function of radius. The seismic source is placed at the surface and the rays show paths of the P-waves radiated at incidence angles varying from 0° to 30° with a 1° step. Major perturbations in the ray path occur due to abrupt changes in velocity. The core-mantle boundary, where a change by more than 40% occurs, represents the most dramatic example.

the current plan provides for installation of the new network over a ten-year program.

The value of the existing stations — or digital seismometry in general — is reflected by the fact that most of the research topics discussed in Section 3 have already benefited from digital data. Section 3, Scientific Objectives, represents the principal part of this document. The problems of studying the seismic source and the earth's structure are discussed separately.

The simplest mathematical representation of an earthquake is the "point source," characterized by the permanent change of stress in the source region. While locations of earthquakes have been performed routinely for many decades, the systematic determinations of the moment tensor are relatively novel, and, on a scale of several hundred events per year, would not be possible without digital data.

One can now begin to study the mode of the strain release of earthquakes in particular regions. As an example, it was shown that within the subduction zone of Tonga-Kermadec region, the stress is released within narrow shear bands and that the entire process is characteristic of a plastic flow with the earthquakes representing shear instabilities rather than brittle deformation of a mechanically strong material.

These analyses are well established for the point source and the favorable comparison of results obtained by different research groups, using different subsets of data, gives assurance of reliability of the solutions. However, these analyses are conducted months after the earthquakes occur and what is needed is nearly real-time analysis of the source parameters of major events. The real-time telemetry of global data and the increased dynamic range of the proposed network would satisfy the requirements.

The real-time aspect of the proposed network is important for several reasons. The ability to predict tsunami effects, to assess possible damage in remote areas in order to plan disaster aid programs, to predict the potential of occurrence of damaging aftershocks, are all issues of importance to the society. The ability of scientists to assess rapidly the tectonic significance of a large earthquake in order to inform the public, to plan post-seismic experiments and to make better hazard reduction plans are other valid reasons for real-time data transmission and analysis. The recent large earthquake in Japan (May 26, 1983; $M_W = 7.8$) represents a good example: the source mechanism was not known for several days, even though Japan is one of the countries with the best seismic instrumentation in the world and the level of scientific preparedness is very high (3.2.5).

Derivation of point source parameters is only the first step in earthquake analysis. It is necessary to recover the spatial and temporal history of faulting for a given event to obtain understanding of the physics of the rupture process. In addition to the scientific significance of such studies, they also have practical applications, as the ground motion — and the acceleration, in particular — strongly depend on the heterogeneities in the stress release on the fault surface. The strong motion accelerographs provide the primary data for engineering purposes. But these near-field data, while important in calibration of a particular site, may not be sufficient to reconstruct the faulting process for truly great earthquakes.

The dynamic range, the frequency response and station distribution of the current digital networks are inadequate for studies of this kind. The planned network, however, would remove all the current disadvantages. The broadband response would cover the frequency range from millihertz to several hertz, allowing for much higher resolution in time and space than possible today. The wide dynamic range would guarantee on-scale recording for even the largest events, and the coverage of the 100 proposed stations would be better than that for the existing networks because of more uniform distribution (3.2.2 and 3.2.3).

The recent controversy about the nature of the Mammoth Lakes earthquakes 1978—1980 could have been fully resolved if the data from the planned network were available. The long period data clearly indicate that the overall process of stress release in the main shock of the May 1980 sequence deviates significantly from the double-couple mechanism (plane shear failure). A dike injection of magma or steam was proposed to explain the mechanisms obtained from the analysis of SRO/ASRO data, which contained very little energy at periods below 10 seconds. On the other hand, the analysis of hand-digitized WWSSN records, having better response at short periods, led some researchers to propose a complex mechanism consisting of normal faulting followed, in 6 seconds, by a strike-slip event. The moment tensor obtained by adding these two subevents was essentially the same as the one obtained from the analysis of long-period data. Yet, because of the poor distribution of WWSSN stations for this event and low quality of some recordings, the ambiguity remains. A set of digital broadband records would allow us to answer unequivocally the important question of the nature of the tectonic stress release in this region.

The digital data collected during the last few years has led to the first applications of seismic methods to quantification of volcanic eruptions. The most complete data have been obtained for the Mt. St. Helens eruption of May 18, 1980. The real-time capability of the proposed network would allow rapid assessment of the magnitude of an eruption even in a remote location, which would be useful in predicting its effect on atmospheric processes (3.2.4.2).

Finally, the high quality data of the planned network could be important in studying "exotic" sources such as ultra-low frequency events that escape detection through the usual seismological procedures (so called "silent" or "slow" earthquakes), meteorite impacts and gravitational waves (3.2.4.3).

The anticipated impact of the planned global network will be at least equally important on the studies of the earth's structure. As in the studies of earthquakes, the digital data accumulated over the last few years have been used in studies that demonstrate the potential of high quality digital data.

The problems of the earth's structure are divided, somewhat artificially, into the studies of properties of an "average" earth and investigations of lateral heterogeneity. The former address principally the need for better assessment of change in wave speeds and density near the discontinuities, as the knowledge of the change in these properties at the discontinuities is essential for the unravelling of the radial variations in the chemical composition of the earth's interior.

The structure of the upper mantle, which extends from the base of the crust to a depth of about 700 km, has been the subject of intensive studies for several decades, partly because the properties of this region determine the large-scale dynamics of geological processes observed at the surface. The studies are complicated by the presence of low velocity zone, multiple discontinuities and regions of steep gradient as well as significant lateral heterogeneity. Most likely the progress in studying the fine structure of the upper mantle will be made through deployment of large-scale portable arrays. The global network will be used to identify the anomalous regions. The lateral variations in the radii of discontinuities and the velocity contrast across them, however, can be studied using individual broadband stations.

The structure in the vicinity of the core-mantle boundary is important for better understanding the process of formation of the core and the present-day dynamics of this most dramatic boundary within the earth. The outstanding issues are: fine resolution of the velocity structure up to 400 km above the boundary, mapping of lateral heterogeneities which are known to have large amplitudes in this region, detection of the presence of undulations on the core-mantle boundary and the determination of the velocity gradient below the boundary. These questions could be much better addressed with high resolution broadband data than it is possible using the present-day recordings, and the answers to them are also important for explanation of some key problems in the geodynamo theory (3.3.1, 3.4.3, and 3.4.4).

As an example, recent results on the anomalous structure of the outermost 200—300 km of the inner core brought forward a suggestion that this region is not solid but that it consists of a viscous fluid with the relaxation time increasing with pressure. Availability of the broadband data are essential in testing this hypothesis since, if it is valid, the apparent radius of the inner core should show frequency dependence (3.3.1 and 3.4.5).

Dramatic progress has been made during the recent 2—3 years in studies of lateral heterogeneities in the earth's interior. The potential impact of these results exceeds the interests of seismology itself and promises to provide critically needed data for geodynamics, petrology, and geochemistry. Even with the limited resolution of the initial studies, the three-dimensional pictures of the earth's interior, unbiased by assumptions of continuation with depth of the surface tectonics, illustrated new and unexpected features that caused much excitement within the earth science community. With the current digital network, the half-wavelength of resolvable anomalies ranges from 3500 to 2500 km; in order to make these results more relevant to geological observations, the half-wavelength should be reduced to approximately 1000 km. This could be accomplished with 100 well distributed stations. Additional data, such as the long-period body waves can be included in future analyses and, as the models improve, the frequency content of the analysis could be broadened, leading to higher resolution with depth and, in particular, more detailed global representation of the lithosphere. This would provide the framework for more detailed studies including the use of the portable array (3.3.2.4).

Very low-frequency seismology presents another set of research opportunities. The fundamental approach to studying the earth using the full normal mode (free oscillation) theory, without adopting various asymptotic approximations, provides an important test of the proposed models or approximate solutions. There is, for example, the puzzling observation of the anomalously large splitting of modes that roughly correspond to the P-waves traveling nearly vertically through the earth. The observed splitting is about three times greater than predicted from the ellipticity of the earth and its source has not yet been identified. Accurate measurements of the effect of the coupling between spheroidal and toroidal modes due to rotation of the earth show that this effect is very well predicted at long periods. At shorter periods the coupling due to the aspherical structure becomes important, and significant progress has been made to model these effects. Measurements of attenuation of normal modes remain the principal source of information on the anelastic properties of the earth at long periods (3.5).

The recent results from seismology are having an important impact on research in other branches of earth sciences. For example, the results of inversion for P-velocity anomalies have been used to model the low order geoid field, assuming the perturbations in velocity and densities are proportional. These calculations, which involve a finite viscosity, can lead also to establishment of constraints on the radial distribution of viscosity. Much better correlation with the gravity field is obtained if a tenfold increase in viscosity across the 670 km discontinuity is assumed, then either for a constant viscosity model or for a hundredfold increase. The level of the statistical significance of the hypothesis that the principal source of the gravity anomalies of degree 2 and 3 is located in the lowermost mantle is above 99% (3.6.1).

Seismology is also a petrological and chemical probe. By comparing seismic velocities with laboratory data on various minerals, and correcting for the effects of temperature and pressure, it is possible to discuss the composition of various regions of the mantle. By three-dimensional mapping of velocity anomalies it is possible to make inferences with respect to the depth of reservoirs of mid-ocean ridge basalts and hotspots. The question of the layered *vs.* whole mantle convection could be addressed by investigating the pattern of anomalies on both sides of the 670 km discontinuity. The results so far are inconclusive, but the critical experiments involving simultaneous inversion for the whole mantle have not yet been performed (3.6.2).

The planned network will have major impact on the studies of the lithosphere, particularly in conjunction with the operation of the large portable array. As discussed above, the global array should have a resolving half-wavelength of about 1000 km. This should allow for a broad, global classification of the properties of the lithosphere. The portable array will be used to study in detail the areas of particular interest. The availability of the portable stations will be of great importance to the full utilization of the resources of the global network, as densification of the array may be essential to obtaining certain critical answers (3.7).

Section 4 discusses the technical aspects of the planned network. The technical requirements are developed on the basis of the scientific objectives. Some critical decisions on selection of the instrumentation and station siting will have to be preceded by design studies and experimentation. The real-time transmission of seismic data is entirely feasible from the technical and economic point of view. The only constraints are political. One aspect of these is related to the tariff charges involving the permission to transmit data from a foreign country, the other, simply stated, is that some countries may not wish to permit real-time data transmission. It should be expected that, at least in the beginning, not all sites will be able to use satellite telemetry, even though it would be highly desirable from the standpoint of network monitoring and data management. The issue of data management will require much consideration, particularly in that the expected data flow may be nearly two orders of magnitude greater than that from the present networks. Recent progress in mass storage techniques (optical discs) justifies an optimistic outlook on this issue. Much effort will be devoted to the problem of making the data available to the users, including those who may not have, or may not be able to afford, the access to large-scale computing facilities. The recent revolution in the microcomputer industry should allow us to make the data available on disketts to users with personal computers that can be purchased for a few thousand dollars.

International cooperation (Section 5) is a critical issue in planning a global network. Although it can be expected that the majority of the future sites will be those of the WWSSN, GDSN, and IDA networks, at which there would only be the question of upgrading the existing equipment, there are significant land areas and oceanic islands which would require participation of countries that are not currently involved in those projects. Plans are being made for informing our foreign colleagues about this initiative and we hope that this project will be supported by the international organizations such as the International Union of Geodesy and Geophysics, the International Association of Seismology and Physics of the Earth's Interior, and the Inter-Union Commission on the Lithosphere.

Chapter 6 contains a description of the organizational structure of the Incorporated Research Institutions for Seismology (IRIS), a private nonprofit corporation designed to provide the scientific planning and overall management of the individual programs, of which the global network is only one. In addition to the 18 universities that were the original incorporators, 18 universities have since joined IRIS and it is expected that the membership will eventually include most eligible institutions.

2. GLOBAL SEISMIC NETWORKS

The term "seismic network" can be applied to any grouping of stations used to study a seismological problem, and such networks are conveniently classified according to spatial scale. Local and regional networks, distributed over areas with characteristic horizontal dimensions ranging from ten to several thousand kilometers, are essential for studying the details of seismic activity in tectonic zones and the structure of the crust and uppermost mantle. However, many problems critical to seismology and the other earth sciences can only be approached using global networks; i.e., distributions of seismic stations of truly worldwide coverage. These problems range from studies of very large earthquakes and earthquakes far removed from regional arrays to the structure of the deep interior. Moreover, the data collected by a global network of fixed, high-performance, continuously operated stations can provide the spatial and temporal baselines needed to calibrate and integrate the information collected by local and regional arrays. For these reasons, the new global seismic network proposed here by IRIS (which will be referred to as the GSN) is complementary to parallel proposals by the seismological community to upgrade local and regional recording capability.

2.1. Historical Development of Global Networks

Progress in seismology, like progress in many of the natural sciences, has often been limited by the quantity and quality of the data available. Each successive generation of improved seismic instrumentation has lead to new discoveries in earth sciences. Modern instrumental seismology has its roots in the last century, but it was not until the first few decades of this century that the global deployment of seismometers yielded reasonably complete catalogs of earthquake locations and a first good look into the earth's interior. The first uniform network of seismographic stations in North America was established in 1908—1911 by the Jesuit Seismological Service and, after 1925, operated by the Jesuit Seismological Association. This network, the forerunner of later networks supported by the federal government, made use of the recently invented Wiechert inverted-pendulum seismographs, which were available in quantity and at low cost. Rapid improvement in instrumentation followed Galitzin's application in 1912 of the electromagnetic transducer and galvanometric recording to the seismograph. Galitzin instruments, especially a version modified by Wilip to improve stability and provide linearity of response, became the primary equipment in many observatories. Other important advances in instrumentation were the Wood-Anderson torsion seismograph (1925), the Benioff quartz-rod strainmeter (1935), the variable-reluctance transducer adapted for seismographic applications by Benioff in 1932, and the development by LaCoste in 1935 of the zero-length spring for recording long-period vertical motions.

By 1940, with the publication of the Jeffreys-Bullen Tables, the basic divisions of earth structure — crust, upper and lower mantles, outer and inner cores — were recognized, and the distributions of elastic-wave speeds were well enough determined to predict the travel times of seismic phases to a few seconds or so. In 1949 Gutenberg and Richter published their classical treatise on the global distribution of seismicity. All of this early work relied on the seismograms collected by a variety of instruments, some with only vaguely known characteristics and many with poor timing, operated by diverse groups of seismologists. Seismological research was very much facilitated, however, by the establishment of the International Association of Seismology in 1905 and the publication, beginning in 1923, of the *International Seismological Summary*, which provided for the collection, editing, and dissemination of seismological data.

The opportunity for a major innovation came as a result of nuclear test ban discussions held in 1958. A panel was formed in the United States to consider research needs for improving the national capability in the detection and identification of underground nuclear explosions. The panel's report, known as the Berkner Report, formed the basis of Project Vela Uniform, a research program managed by the Advanced Research Projects Agency of the Department of Defense (DARPA). DARPA has since been the lead agency in the development of new technology and has sponsored the establishment of most U.S. global networks and arrays. One of the recommendations of the Berkner Panel was for the installation of standardized

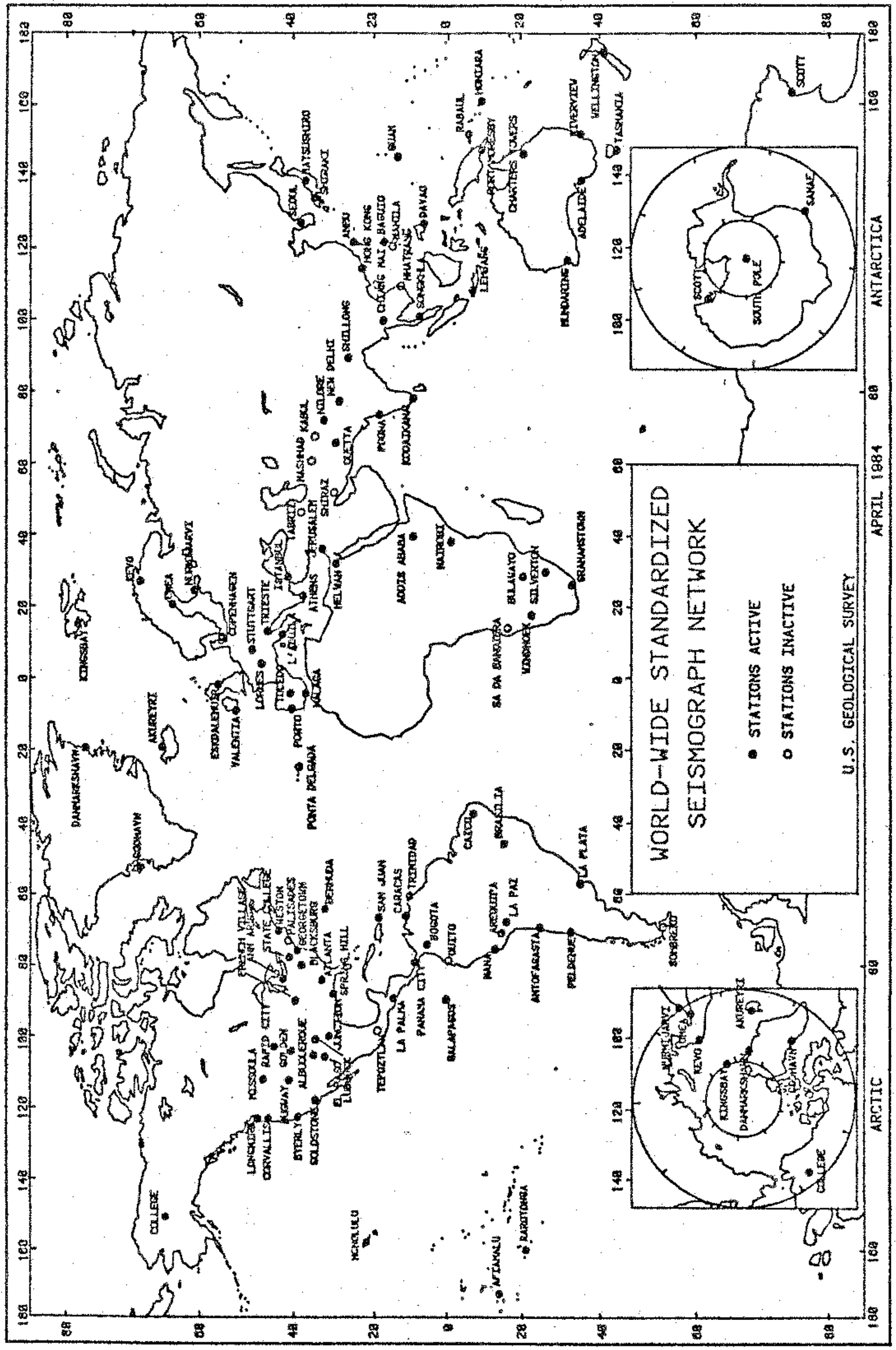


Figure 2.1. Distribution of the analog WWSSN stations, both operational and closed.

seismographs, with accurate clocks, at 100 to 200 existing seismograph stations. The network was not intended for the surveillance of nuclear tests; its role was to produce the data needed for fundamental research in seismology. The recommendation led to the establishment of the World-Wide Standardized Seismograph Network (WWSSN). Between the years 1960 and 1967, 120 WWSSN systems were installed in cooperation with participating organizations in more than 50 countries. These stations (see Figure 2.1) were equipped with six standardized, analog-recording seismographs of well-calibrated response, comprised of three orthogonal long-period components (15-s or 30-s pendulum periods, 100-s galvanometer periods) and three orthogonal short-period components (1-s pendulums, 0.75-s galvanometers). Recording is photographic, with radio-synchronized crystal clocks. Concurrently, facilities were established to copy and distribute the data to research scientists. The WWSSN was a monumental success. The fact that a great majority of the stations are still operating today attests to the splendid international cooperation that has been a hallmark of this program. Today, the WWSSN is managed by the U.S. Geological Survey (USGS), and the distribution of WWSSN data is handled by the National Oceanographic and Atmospheric Administration (NOAA).

The WWSSN quickly became the most widely used seismological research network in the world, by both U.S. and foreign investigators, and it spurred a renaissance in seismological research. Data from the WWSSN played a key role in seismology's contribution to the development and testing of the concepts of sea-floor spreading, continental drift, and plate tectonics. During its first decade of operation the number of earthquakes routinely located, and the precision of those locations, increased by a factor of 3 to 5. The resulting pattern of global seismicity defined narrow zones of activity outlining the stable lithospheric blocks, including the low-level but nearly continuous seismicity of the mid-ocean ridge crests, whose delineation had escaped previous seismicity studies. This discovery gave a major impetus to the hypothesis of plate tectonics.

Similar advances were made in the mapping of radiation patterns from individual earthquakes, providing seismologists with the focal mechanisms that describe the orientations of fault planes and their slip vectors. When the WWSSN data became available, inconsistencies in focal-mechanism determinations dropped from about 20% to 1%, and the large numbers of solutions made possible by this rich new data source were instrumental in the formulation of plate-tectonic concepts and the establishment of the directions of plate motions.

Wave-propagation studies, and the derivation of structural information from them, were also greatly facilitated by the WWSSN, especially in the intermediate-period and long-period bands. Techniques for the analysis of surface waves, developed in the 1950's, were quickly applied to place constraints on crustal and upper-mantle structure in many regions, both oceanic and continental. New theoretical techniques for the numerical calculation of seismic waveforms were developed, and, using these to match observed waveforms, seismologists refined models of earth structure in the mid-mantle transition zone, where the collapse of silicates to denser structures yields discontinuities in elastic-wave speeds, and near the major transitions at the core-mantle and inner-core/outer-core boundaries.

Despite the poor response of the WWSSN at very long periods (> 100s), advanced signal-processing techniques that took advantage of the network's spatial density made possible the measurement of the earth's free oscillations, thus providing a type of data whose collection had been previously limited to a small number of specially equipped observatories. Accurate free-oscillation periods were obtained out to 1500 sec, and these were used to constrain a new generation of earth models which included the radial density distribution, as well as elastic-wave speeds.

In the late 1960's and early 1870's, research on seismic instruments led to the development of a new generation of seismographic stations. Several sparse global networks have been deployed, each designed with specific goals in mind. Stations of these networks are shown in Figure 2.2.

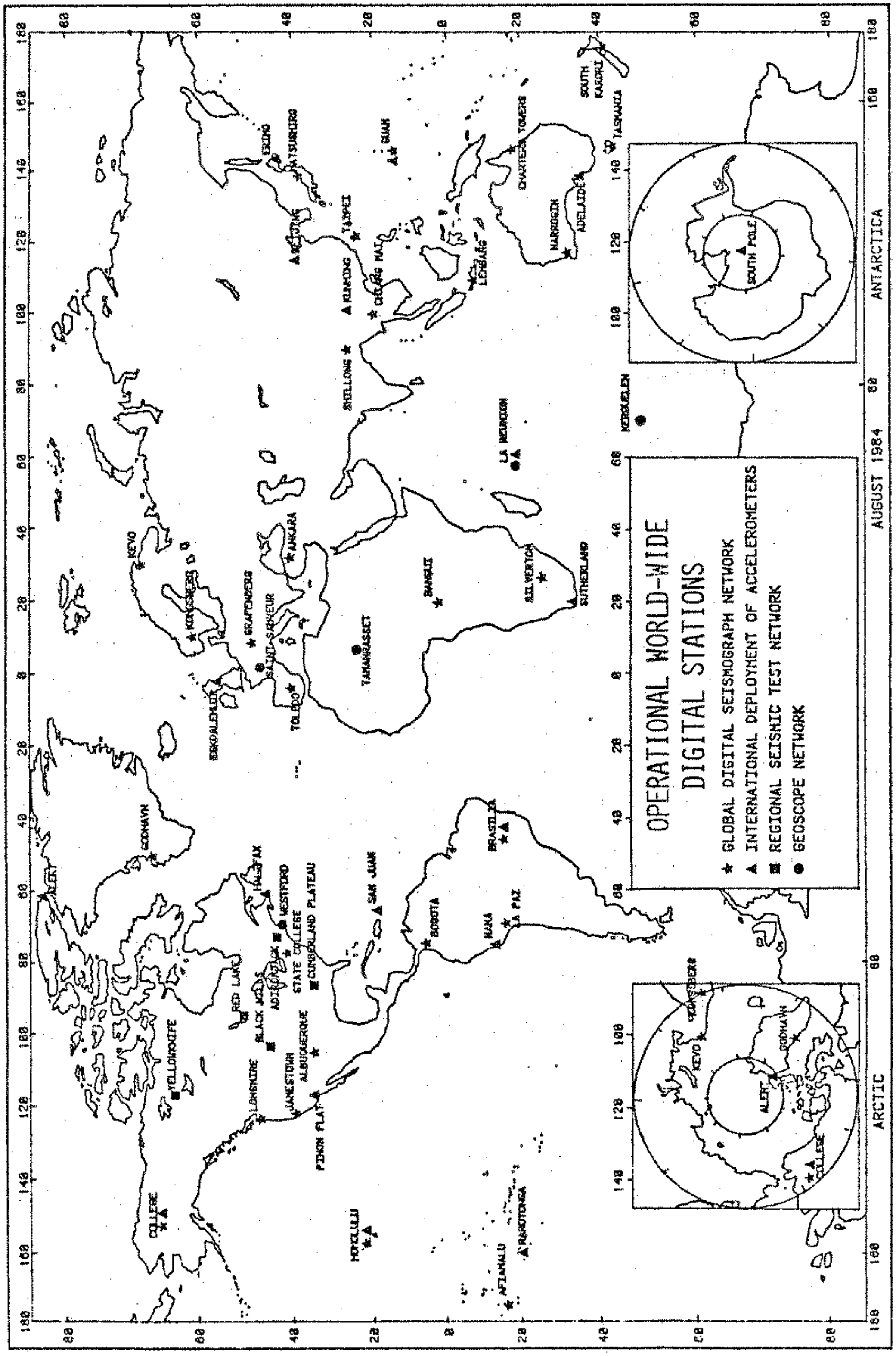


Figure 2.2. Distribution of the operational world wide digital stations.

Research in seismic discrimination indicated that instruments "tuned" to periods of around 30 seconds would be particularly effective in detecting small events. Further, experiments indicated that underground borehole installation of the seismometers reduced quite significantly the background noise that masked signals of interest. This and other research led to the development and deployment of the Seismic Research Observatory (SRO) network and the upgrade of an existing experimental analog network to become the Abbreviated Seismic Research Observatory stations (ASRO). Between them, these networks now include 15 stations worldwide.

Independently, another sparse global network was developed and deployed to a total of 18 stations. This network (Project IDA) was designed specifically to study the earth's normal modes. Its data are confined to the very long period (> 100 sec) waves that are excited by large earthquakes. Only the vertical component of motion is recorded, using converted highly stable gravimeters as the sensors; the data are sampled once every 10 seconds. While acceptable for free-oscillation studies, this rate is totally inadequate to study many of the phenomena recorded well by the SRO and ASRO instruments.

Late in the 1970's, some of the WWSSN analog stations were upgraded by the addition of digital recorders to form the DWWSSN network. The main purpose of this was to provide digital records at places not covered by the SRO/ASRO network. Adding digital recorders provides data of the quality of the WWSSN but saves researchers the tedious task of hand-digitizing the data. The SRO, ASRO and DWWSSN stations are operated by the United States Geological Survey under the name of Global Digital Seismographic Network (GDSN).

Seismic recordings have conventionally been made in two or more narrow frequency bands because of the dynamic range limits of analog records. With digital recording it is possible to use broad-band instruments, to yield higher fidelity data. This approach was pioneered in Europe, at the Graefenberg array in Germany which began operations in 1976. Though not a global array, it should be mentioned because it demonstrated the usefulness of broad-band recordings.

A more recent initiative to install a global network of broad-band seismometers is the GEOSCOPE project, operated by a consortium of French universities. These stations, which include 3-component broad-band instruments and high-dynamic-range digital recording, are in many ways close to those proposed in this plan. At present five have been deployed; the eventual size is planned to be about 30 stations.

In North America a five station regional network (RSTN) has been developed and deployed which features unmanned operation of borehole instruments with the data telemetered via satellite to network recording and control facilities.

As is clear from this outline of the existing digital stations, much development has taken place; most of the technical problems have been solved. What remains, however, is the goal of this proposed program: to forge a unified new global network from our existing base of analog and digital stations. What the WWSSN so clearly demonstrated, the tremendous advantage to be gained in having a global network of standardized instruments, must now be achieved with modern instrumentation in order to provide the science with its major observational tool for the next 25 years.

Besides eliminating the tedious, time-consuming and inaccurate task of hand-digitizing analog records for computer processing, the advent of digital recording has improved the bandwidth and dynamic range over which seismic signals can be recorded. It is now possible to make free-oscillation measurements at periods longer than 1000 sec on single-station recordings of earthquakes with moderate magnitudes; this has led to new efforts to interpret these signals in terms of the structure of the earth and the seismic source. A major drawback of the photographically recorded WWSSN is its low dynamic range, which is only about 44 dB, or a little over two orders of magnitude, so that signals from both very large and very small events are often not usable, even in the center of the instrumental passband. In contrast, modern digital instruments can easily have a total dynamic range of 126 dB, over six orders of magnitude. Borehole installation of the SRO sensors at a depth of 100 m attenuate the effects of wind-

Network	No. of Stations	Channels	Sample Interval Seconds	Resolution DB *	Dynamic Range DB *	Operating Agency	Funding Agency	Comments
SRO/ASRO	15	1 SP	.05	66	126	USGS	DoI	Triggered
		3 LP	1					
DWWSSN	13	1 SP	.05	90	90	USGS	DoI	Triggered
		3 IP	.1					Triggered
		3 LP	1					
RSTN	5	3 SP	.025	56–78	120	Sandia National Labs	DoE	North American Satellite Telemetry
		3 IP	.25					
		3 LP	1					
IDA	18	1 VLP	10	66	66	UCSD	NSF	
GEOSCOPE	5	3 VLP	10	66		IPG	INAG	
		3 BB	.20	66				Triggered

Legend:

SP	Short-Period
IP	Intermediate Period
BB	Broad Band
LP	Long Period
VLP	Very Long Period

Table 2.1
Global Digital Seismograph Networks

*In this table zero-to-peak convention is used.

generated noise, and therefore have ambient noise levels significantly reduced (by 10 dB or more) relative to equivalent near-surface WWSSN sites.

Data from the existing stations have made it possible to determine routinely and quickly the focal mechanism of the two or three hundred largest earthquakes that occur worldwide each year this information is shedding new light on the basic processes of earthquake generation. Computerized analysis of long-period seismic signals has yielded the first global models of the earth's three dimensional structure, and from these models new insights into the convective processes which drive plate motions are being obtained.

2.2. Limitations of Existing Global Networks

Despite this progress, the current configuration and performance of the global seismic networks is inadequate for seismological research in the next decades, a fact that has been repeatedly emphasized in a series of reports by the National Research Council (see *Trends and Opportunities in Seismology*, 1977; *Global Earthquake Monitoring: Its Uses, Potentials, and Support Requirements*, 1977; *Seismographic Networks: Problems and Outlook for the 1980s*, 1983; *Effective Use of Earthquake Data*, 1983). The WWSSN, which continues to provide essential data for seismological research, is based on 25-year-old instrument technology and is limited by its narrow bandwidth, high noise levels, low dynamic range, and photographic recording. Records from the WWSSN must be digitized by hand before numerical processing can be attempted.

The GDSN lacks the spatial coverage needed for research in a number of crucial seismological problems. At the present time it comprises 28 stations, but these are not ideally distributed, they are not standardized, and their instrumental capabilities are limited (Table 2.1). The SRO, ASRO, and DWWSSN stations have three long-period components, but their response is shaped in such a manner that limits their use in waveform and free-oscillation studies. The IDA stations have only vertical components sampled once every 10 seconds, so they are not useful for observing the earth's toroidal free oscillations or other horizontally polarized seismic waves, and their high-frequency response and dynamic range is inadequate for most body-wave studies. Further, none of the stations has, or will have, sufficient dynamic range to record on scale, even at teleseismic distances, a great earthquake with magnitude (M_W) above 8. Many, if not most, of the instruments become saturated even for moderately large events ($M_W > 6.5$) at intermediate distances. This prevents seismologists from using the part of the record that contains the most information on the source mechanism. The early part of recordings is also important in studies of lateral heterogeneity, as the information contained in the later orbits of surface waves may be severely distorted by the multiplying effects.

Another major disadvantage of the current global networks is the length of time it takes to assemble data sets with sufficient coverage to study major earthquakes. For the WWSSN, complete data sets are often not available to the general seismological community for over a year after the event. The distribution time for the GDSN is better, on the order of three months, but this is still too long for the source-mechanism information eventually derived from these data to be of much use in predicting the hazards associated with major aftershocks or to aid in the deployment of portable field instruments for recording these aftershocks. Real-time or nearly real-time telemetry of the data to central recording facilities and remote access to those facilities by research seismologists is essential for these purposes.

3. SCIENTIFIC OBJECTIVES

3.1. Structure of Research Problems in Seismology

Seismologists study both the characteristics of seismic sources--earthquakes, volcanic eruptions, man-made explosions--and the properties of the earth illuminated by these sources; this is the fundamental duality of seismological research. The parameters which describe the seismic source include its location in space and time, its size (magnitude or seismic moment), its mechanism (equivalent dislocation or, more generally, first-order moment tensor), and various higher-order quantities specifying its duration, spatial extent, direction of rupture propagation, and other details of its temporal and spatial history. The structure of the earth through which seismic waves propagate can be described by the mass density, the elastic wave speeds, and the attenuation factors specifying the rate of energy dissipation during propagation. All of these structural parameters vary with position, and the wave speeds and attenuation factors in general depend upon the wave's polarization and its direction of propagation.

3.1.1. Forward Problems

Given a complete description of the source and an exact model of earth structure, it is possible, at least in principle, to compute to any desired accuracy the response of a seismograph at any point on the earth's surface provided, of course, that the instrumental characteristics are also exactly known. This is the *forward problem* of seismology, and formulating feasible algorithms for its solution is a major task of theoretical seismology. Over the past decade, much progress on this problem has been made, spurred by the ever increasing quality and quantity of seismic data and, in particular, by the advent of digital seismometry. The problem is a difficult one and computationally intensive. At present, even the most advanced numerical codes can synthesize complete theoretical seismograms only over limited durations and bandwidths for simplified source and structural models (usually a dislocation or explosion embedded in a spherically symmetric, isotropic earth). Our understanding of wave propagation in more complex models, including fully three-dimensional anistropic structures, continues to increase rapidly. The computing power needed to attack these problems is not available on a routine basis.

3.1.2. Inverse Problems

The retrieval of information about the seismic source or the improvement of an earth model using seismic data is an *inverse problem*; it involves the solution of the forward-problem equations for source and structural parameters in terms of observable quantities. Most inverse problems in seismology are nonlinear (some highly so), and, owing to the incompleteness and inaccuracy of the data sets, their solutions are nonunique. Understanding the fundamental structure of inverse problems, including appropriate mathematical descriptions of the nonuniqueness when the model parameters are continuous functions of one or more variables, is another primary task of theoretical seismology. Here again, the progress in the last decade or so has been spectacular, to the extent that inversion methods first developed by seismologists are commonly employed by scientists in other fields as well. Current research is focused on the basic structure of nonlinear inverse problems and on techniques for handling very large data sets and very large numbers of model parameters. Inverse problems for three-dimensional earth structure where the product of these dimension exceeds 10^{11} are now being attempted, and this capability will continue to increase as computer hardware and software for doing vectorized arithmetic are improved.

All aspects of the seismogram are to some extent affected by both source characteristics and earth properties, so the inverse problems of source retrieval and the inverse problems of earth structure are intrinsically coupled. In the past, seismologists have usually posed these inverse problems in terms of observable quantities that are sensitive only to a subset of model parameters, thus simplifying and stabilizing their solution. Travel times, which are sensitive to source location and elastic wave speeds, but not to source size and mechanism, provide a good example. Given a model of the wave speeds, an event's location can be estimated from the arrival times of various seismic phases. If the network is dense enough, errors owing to inaccuracies in the earth model will tend to cancel, and the location will be more accurate. The travel times computed from this location can then be used to refine the wave-speed model, and the improved model can be fed back into the location procedure. This interactive "bootstrapping" technique for solving these coupled inverse problems usually converges very rapidly. (Indeed, the earth model derived in this manner by Jeffreys and Bullen in 1940 is good enough that it is still employed by the International Seismological Center routinely to locate earthquakes.)

The problem with this methodology is that it ignores most of the information on the seismogram. One goal of seismology is to explain all features of the seismogram, the amplitudes and waveforms of the various arrivals, as well as their travel times. To do this requires that inverse problems be set up for all significant model parameters. When this is done, the coupling among the various inverse problems is invariably increased. For example, owing to attenuation, the elastic wave speeds depend on frequency (physical dispersion); hence, to fit travel times across a broad frequency band requires that we model the attenuation factors in addition to the wave speeds. The amplitudes of seismic waves also depend on the attenuation factors and wave speeds, as well as the size and mechanism of the source. In achieving this goal we make progress on other major goals of seismology, namely the complete description of the structure of the earth's interior and a complete characterization and understanding of the seismic source.

Perhaps the most comprehensive approach to the modeling problem is the technique of "waveform inversion," in which the entire seismogram, or at least a segment comprising many different types of waves, is fit by iteratively adjusting a large suite of source and structural parameters. This technique has recently been applied by several groups of investigators to model complexities of the seismogram not tractable by conventional methods. Examples of the match obtained between observed and synthetic seismograms are illustrated in Figures 3.1 and 3.2. Waveform inversion and other modern algorithms that efficiently utilize information on the seismogram have the potential for improving immensely our understanding of earthquakes and the earth's interior. However, because they couple together the estimation of so many structural and source parameters, they require data from a dense, well-distributed and well-calibrated global digital seismic network.

3.2. Seismic Source Problems

Earthquakes are among the most destructive of all natural disasters, accounting for the loss of more than 800,000 lives and tens of billions of dollars in property damage during the last decade alone, and yet they are perhaps the most poorly understood. Owing in large part to the data collected by global networks of seismometers, the general areas where destructive earthquakes occur have been mapped and, with a few notable exceptions, the basic patterns of faulting are known and interpretable in terms of plate tectonics (Figure 3.3). As the plates move and deform, stresses accumulate along their boundaries and within their interiors, and when the local yield strength of the rocks is exceeded, they are released suddenly by the rupturing of a fault. In detail, however, the physics of this rupturing process is complex and not well understood. Consequently, a physical basis for earthquake prediction does not yet exist.

The proposed Global Seismic Network will provide critical new data for the study of earthquakes, as well as other sources of seismic wave excitation, including volcanoes and explosions. Most of the improvements discussed in this document are quantitative — e.g., higher dynamic range will allow larger events to be recorded without saturation, and distributed stations will permit the location and characterization of lower-magnitude seismicity — but some will be qualitative. The telemetry of seismic data to a central recording facility will allow large earthquakes to be accurately located and their focal mechanisms determined within hours after their occurrence, facilitating the assessment of aftershock hazards, the issuance of tsunami warnings, and the rapid deployment of field instrumentation for post-seismic studies. We anticipate that the enhanced capabilities of the global array will lead to the detection of new phenomena, whose existence is now only theoretical or speculative, and to radically new

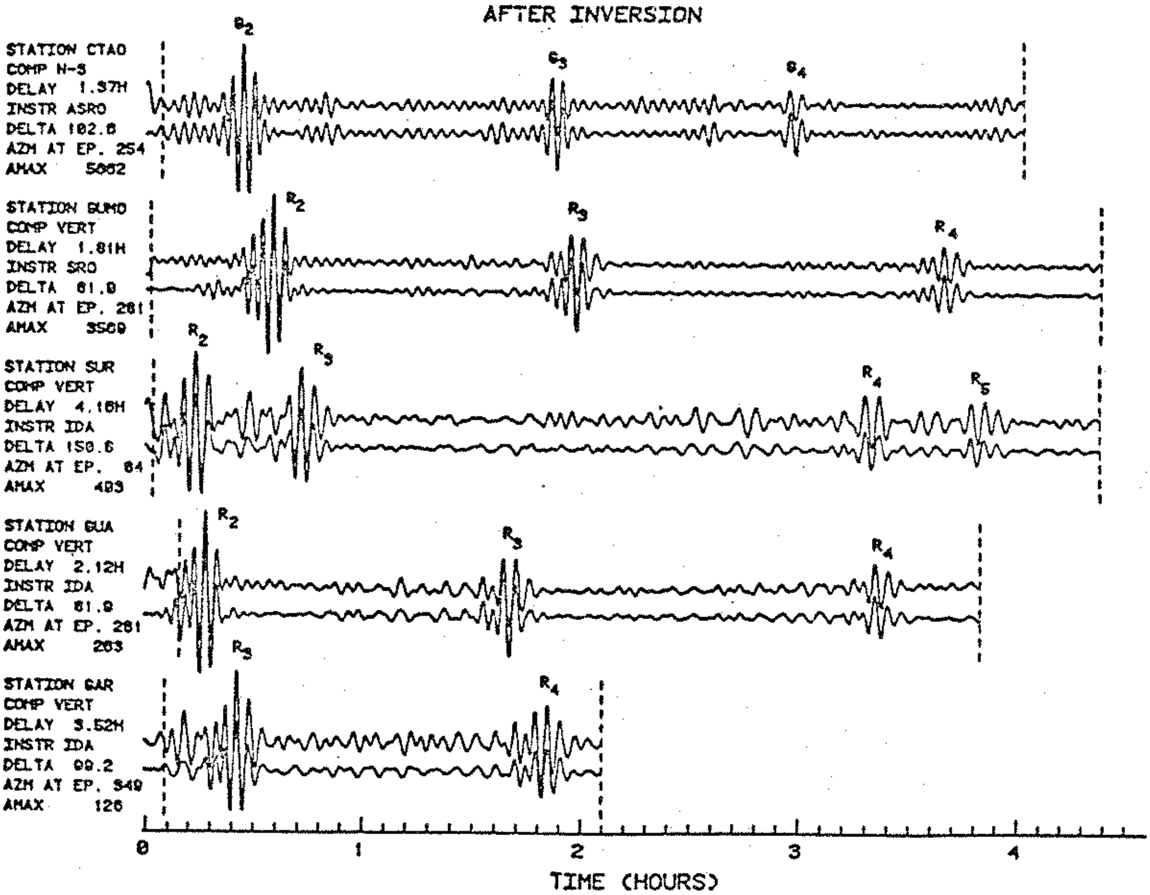


Figure 3.1. Comparison of observed (top) and synthetic (bottom) seismograms for the Eureka, California earthquake of November 8, 1980. Correction for the laterally heterogeneous structure of the upper mantle was used in calculation of synthetic seismograms. (Woodhouse and Dziewonski, *J. Geophys. Res.*,1984)

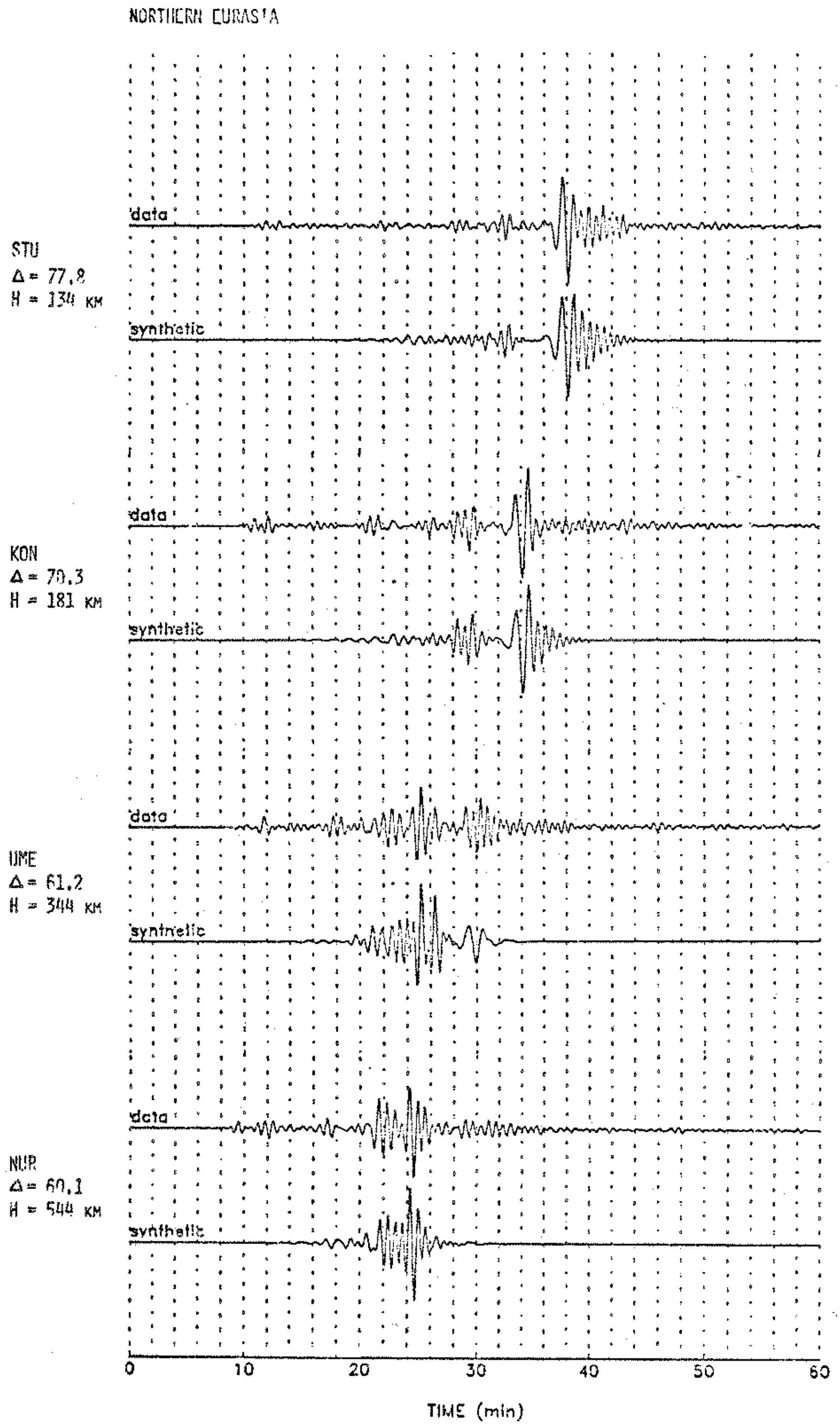
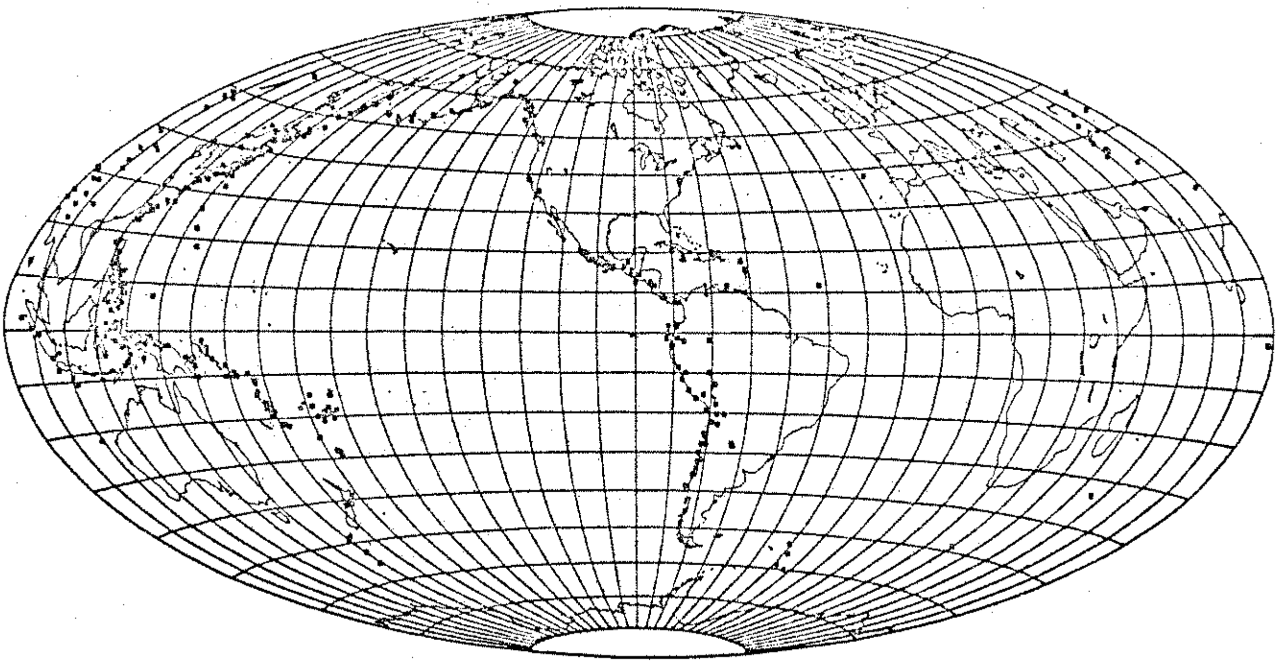


Figure 3.2. Observed (top trace) and synthetic (bottom trace) seismograms for four intermediate and deep-focus events in the Kuril-Kamchatka slab. The data are digitized analog recordings from WWSSN stations situated on the Baltic shield. Each synthetic is the sum of the fundamental and first seven higher-mode traveling-wave branches, which are calculated for a velocity model obtained by inverting cross-correlation functions of synthetic higher-mode branches with the data. Synthetics and data have been band-passed between 30 and 200 second periods. Adequate fits are obtained in both phase and amplitude for all depths, even for the complex interferences observed in the records from deeper events. Studies of these waveforms, which are sensitive primarily to upper-mantle shear-velocity structure, would be aided by the acquisition of digital broadband data from a network as spatially dense as the WWSSN. (A. Lerner-Lam, with permission)



Earthquakes of Magnitude 7.5 or Greater [1897-1974]

Figure 3.3. Global distribution of great earthquakes ($m_b \geqslant 7.5$) through 1974. The major subduction zones encircling the Pacific basin are well-delineated by this seismicity. Zones of more distributed deformation, generally associated with continent-continent plate boundaries, are apparent in the eastern Mediterranean, the Himalayas, and southeastern Eurasia. Mid-ocean ridge and intraplate events occur less frequently at this magnitude cutoff.

observational strategies. For example, the eruption of Mount St. Helens on May 18, 1980, generated low-frequency seismic waves that were globally recorded by the GDSN, yielding the first seismological estimates of the force, duration and energy of a volcanic explosion. Such a study would not have been possible with the previous generation of seismic instrumentation.

3.2.1. Retrieval of Point-Source Parameters

For waves recorded far from the hypocenter whose lengths are large compared to the characteristic source dimensions, the source can be approximated as an instantaneous action over an infinitesimal volume. Such point sources have until recently been parameterized by a time, three spatial coordinates, a magnitude logarithmically related to maximum displacement amplitude, and three constants specifying its mechanism in terms of an equivalent double-couple or fault-model. The magnitude scale and methods for determining fault-plane solutions from first motions were developed in the 1930's. The point-source representation introduced in the early 1970's characterizes an earthquake by its origin time, spatial location, and first-order moment tensor — a total of ten independent parameters, since the moment tensor contains six independent parameters. The displacement field produced by a point source is linearly related to the moment tensor — a decided advantage for inversion studies. The moment-tensor representation also allows for a mechanism more general than a dislocation double couple; e.g., sources involving volume changes, such as explosions or catastrophic phase transitions. If the moment tensor is assumed to be completely deviatoric (no apparent volume change), the mechanism is given by five parameters, and if it corresponds to a pure dislocation, only four are needed, equivalent to the three parameters of a fault-plane solution and the scalar seismic moment. Scalar seismic moment, introduced as a measure of earthquake size in 1966, can be easily interpreted in terms of source kinematics, and has proven to be a more useful parameter than ordinary magnitude.

The point-source representation of earthquakes and other seismic events is critical for essentially all seismological problems. Earthquake catalogs, such as those produced by the International Seismological Centre by applying routine location and magnitude-determination algorithms to global data sets, provide the basic space-time history of the planet's seismic activity, delineating areas of active tectonic strain release and defining regions of anomalous seismicity (or lack thereof) that may be precursory to large earthquakes. Many of these areas are far removed from local and regional arrays of seismic stations, especially in oceanic regions (where most of the world's seismic activity is concentrated), and therefore depend on data from global networks for their study. The same is true for the detection, discrimination and yield estimation of nuclear explosions.

Point-source mechanisms, in the double couple representation, give estimates of the slip vectors and principal stress axes along faults. Slip vectors provide important data for models of plate motions, as well as the relative movements of crustal blocks in zones of distributed deformation separating stable plate interiors. Stress-field determinations from the study of intraplate events provide discriminants for models of plate dynamics (Figure 3.4), and the orientations of stress axes in intermediate and deep focus seismic zones are indicative of the forces acting on descending lithospheric slabs.

Prior to the advent of the GDSN, most reliable point-source mechanisms came from first motions that were hand-collected from the long-period seismographs of the WWSSN, a laborious procedure requiring approximately a full day's effort by a well-trained seismic analyst for each event. Only a fraction of the largest earthquakes recorded in any particular year were processed for this information. Using GDSN data and automated source-recovery algorithms, it is now possible for a single investigator to process many events per day, and, consequently, moment-tensor solutions are routinely published for all earthquakes with scalar seismic moments in excess of about 10^{24} dyne-cm (corresponding to surface-wave magnitudes larger than about 5.3). Comparisons of focal mechanisms determined by several methods are shown in Figure 3.5.

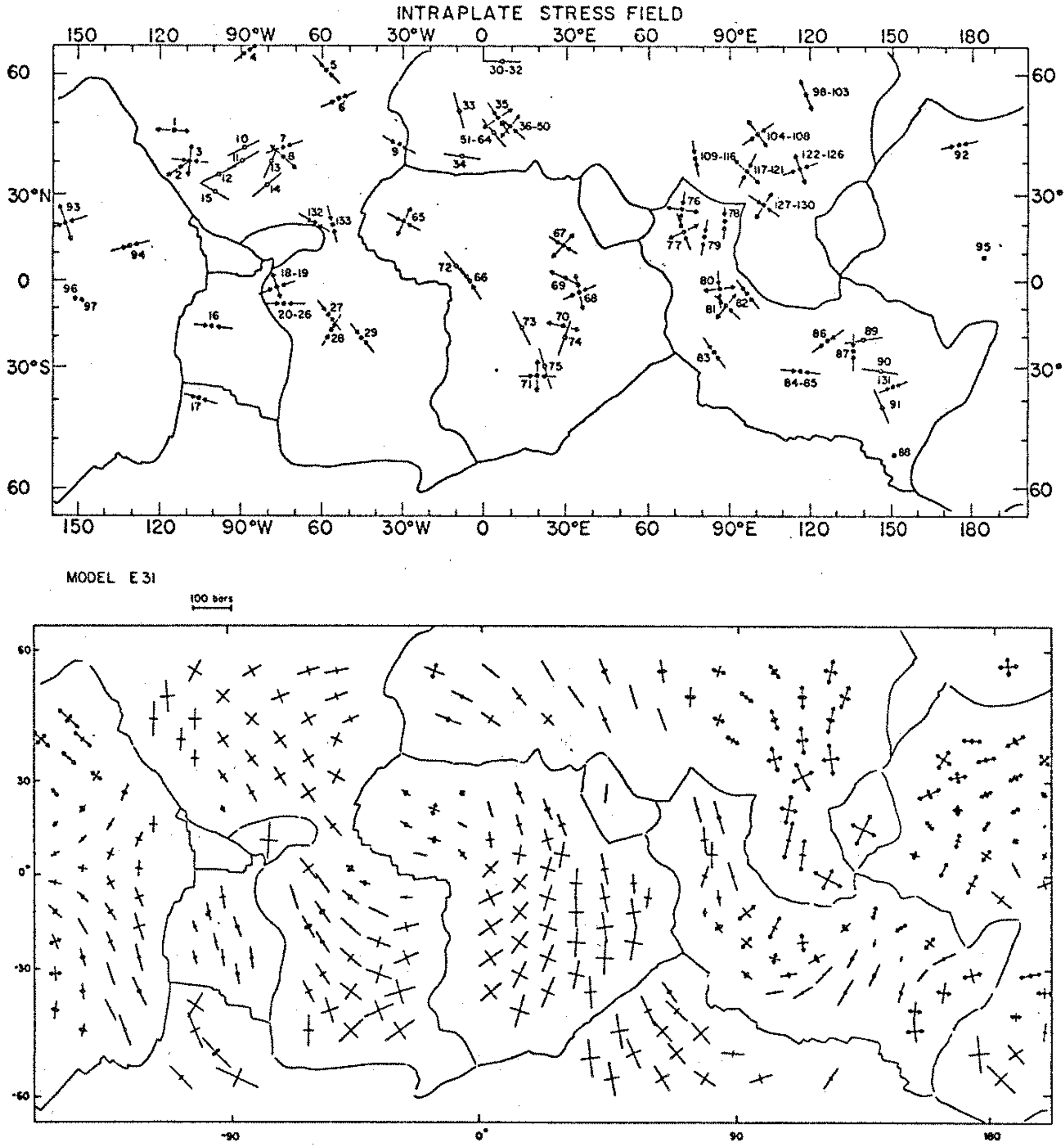
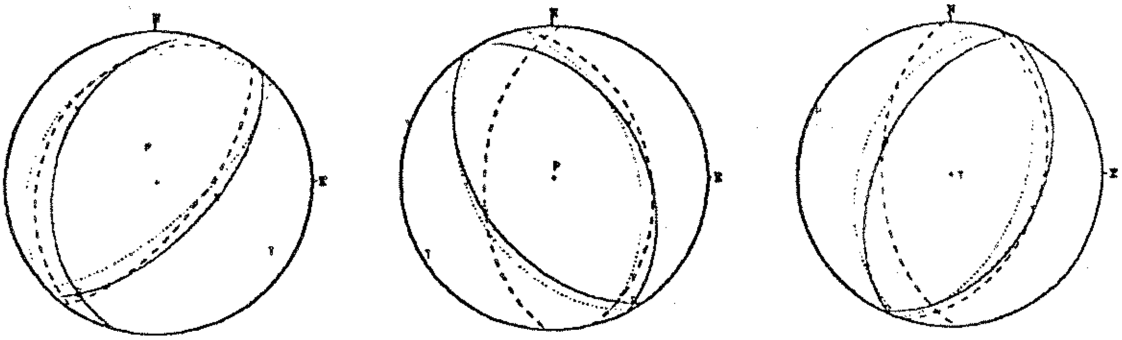


Figure 3.4. a) (Richardson *et al*, 1979, Fig. 7) Summary of observed intraplate stress orientation data. Orientations are obtained from fault-plane solutions, *in situ* measurements, and analysis of geologic structures. The P and T axes for fault plane solutions point inward and outward, respectively. Lines without arrows give the direction of maximum horizontal compressive stress for *in situ* data. Numbers refer to the observations listed in Table 1 of Richardson *et al.* (1979).

b) (Richardson *et al*, 1979, Fig. 23). Principal horizontal deviatoric stresses computed for a finite element model of the lithosphere. The model includes symmetric forces at ridges, continental convergence zones, and subduction zones, and viscous drag forces at the base of the lithosphere. Axes without arrows denote deviatoric compression and those with arrows pointing outward denote deviatoric tension. Relative magnitudes of principal stress are indicated by the length of the stress axes. Good agreement is seen for eastern North America, Europe, Asia near the Himalayas, the Indian plate, South America away from the Peru-Chile trench and western Africa.



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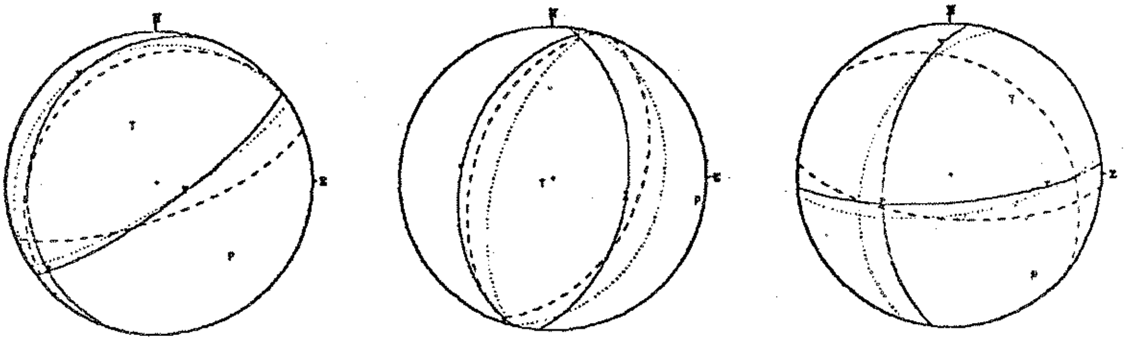

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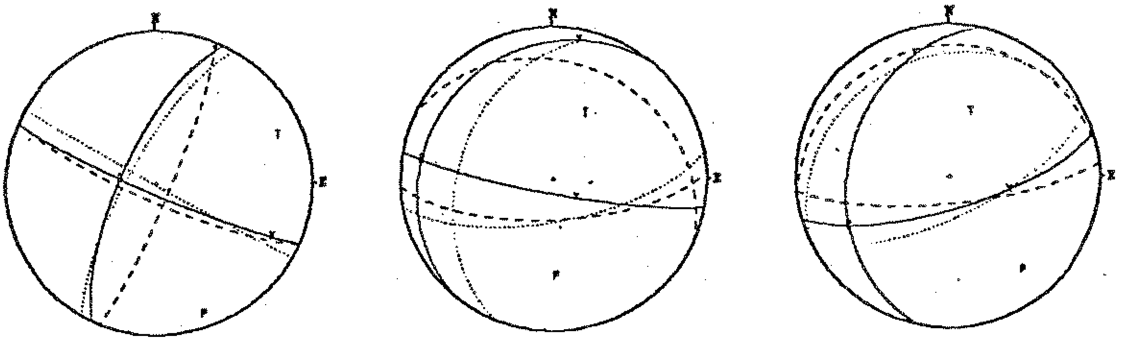


6/24/83 SE. Asia 6/24/83 Taiwan 6/28/83 SE Alaska

Figure 3.5. Fault plane solutions for nine events occurring in June 1983, obtained using data from the GDSN. These events were processed utilizing three routine methodologies: a moment tensor solution (solid line), a centroid-moment tensor solution (dashed line), and a solution derived from first motions (dotted line). The 'best double couples' are also shown for each of the moment tensor solutions. (S. A. Sipkin, with permission)

Not only are the automated analysis procedures more efficient and typically more accurate than hand-derived solutions, but because they use the full moment-tensor representation, they yield more information about source processes; in particular, statistics on the deviations from ideal double-couple behavior. These appear to be significant (Figure 3.6), although the understanding of their theoretical implications is only rudimentary.

One of the most powerful methods for source-parameter recovery is the centroid-moment tensor algorithm which is based on the waveform inversion of complete seismograms. In addition to yielding the moment tensor, this method also provides estimates of the spatial and temporal centroid of an earthquake. Because it is derived from long-period waves which average over the entire source process, the centroid location typically differs from the conventional estimates of hypocenter and origin time obtained from short-period travel times. The latter give values near the initiation of rupture, so the difference between the long-period centroid time and the short-period origin time is a measure of the characteristic time over which the rupture occurs, which is a critical parameter in assessing the rupture process. Estimates of this time difference are shown in Figure 3.7.

In principle, a similar comparison can be made between the long-period spatial centroid and short-period hypocenter, but the errors in these determinations are typically as large as the differences. The focal depths of shallow earthquakes are particularly poorly constrained by conventional travel time studies, whereas they can be accurately determined by waveform modeling (Figure 3.8). Hence, the centroid depths obtainable from digital data should yield new information about the depth extent of seismogenic zones.

Despite the success of many groups of investigators in deriving point-source parameters from the current GDSN, the network's characteristics and performance are far from ideal for source studies. Most modern methods for source recovery depend on the ability to generate realistic synthetic seismograms, and this ability is limited by our imprecise knowledge of earth structure, which can cause bias in the prediction of wave amplitude and phase. In order to average out these errors, it is desirable to have good azimuthal coverage by three-component, broad-band instruments. Unfortunately, the IDA network has poor response at intermediate and high frequencies, no horizontal components, and typically responds nonlinearly to the high-amplitude wave groups arriving in the first few hours after a big event, whereas the DWWSN suffers from low dynamic range and high noise levels. Thus, the data provided by these networks is limited for both large and small events. The characteristics of the SRO/ASRO stations are more suitable for point-source determinations, but given their low density and down-time statistics, the azimuthal coverage of many interesting events is inadequate, and their point-source solutions are correspondingly poor.

The establishment of the global network proposed in this document would remedy these deficiencies and would contribute in a major way to the seismic source problem. It would substantially increase the precision of centroid locations, scalar moment estimates, and mechanism determinations. This is especially important for resolving non-double-couple components of the moment tensor, such as the isotropic (volumetric) part. It has been speculated for over twenty years that deep-focus ruptures are initiated by volumetric changes associated with phase transitions in mid-mantle silicates, but the detection of even a relatively large isotropic component (say, 50% of the total moment) has proven to be a difficult task, despite efforts by several groups of investigators. Large isotropic components were reported some ten years ago for two South American deep-focus earthquakes. These results were obtained using hand-digitized records (45 records in one case, and 165 in the other) from the WWSSN network, but the results of studies employing sparser station sets have been equivocal. The new network would afford a geographical coverage comparable to the WWSSN at a much superior signal-to-noise ratio and bandwidth and should thus be capable of resolving relatively small non-double-couple components, including the isotropic component.

The greater sensitivity, bandwidth and coverage provided by the new network would also extend the reliable determination of complete point-source solutions to events of smaller size, increasing by severalfold the number of earthquakes which could be analyzed each year by

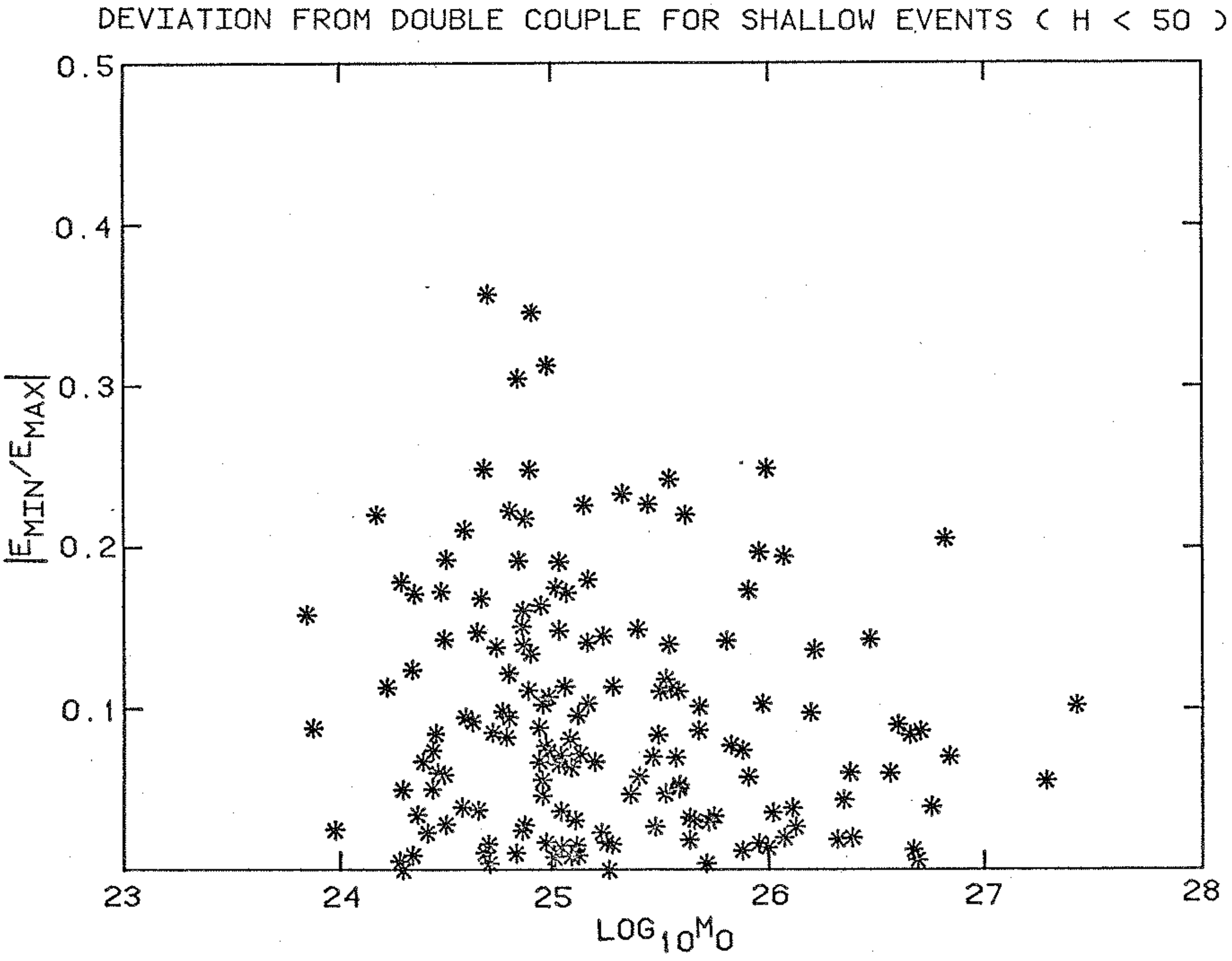


Figure 3.6. Derivation of moment tensor solutions from double-couple mechanism for shallow events. This deviation is characterized by the ratio of the intermediate eigenvalue to the one with the largest absolute value; intermediate eigenvalue is zero for a perfect double couple. (Dziewonski and Woodhouse, *J. Geophys. Res.*, 1983)

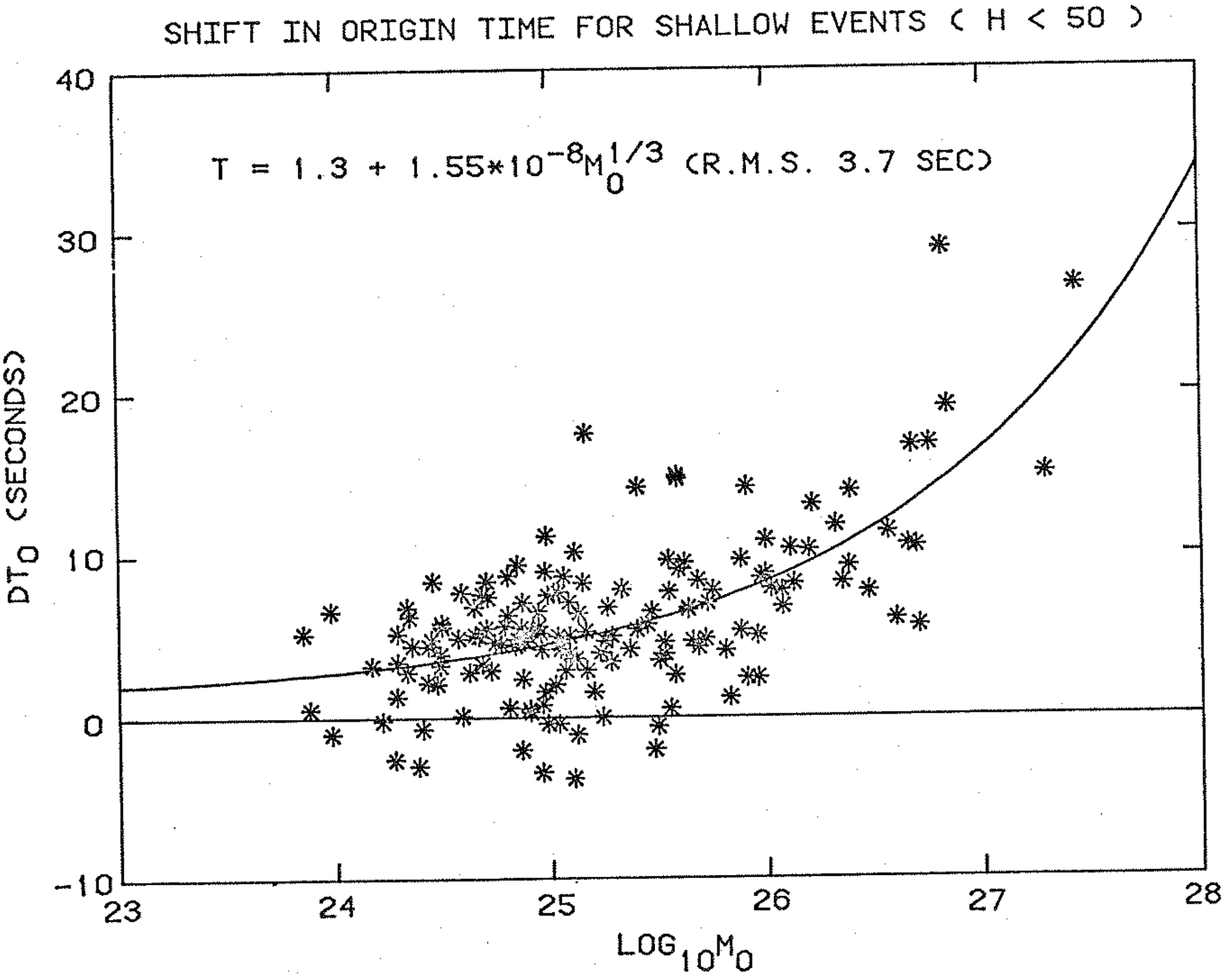


Figure 3.7. Differences between the centroid times and NEIS origin times for shallow events. This difference is equivalent, in theory, to half-duration of a source time function. The solid line shows the least-squares fit of a function proportional to cube root of the seismic moment. (Dziewonski and Woodhouse, *J. Geophys. Res.*, 1983)

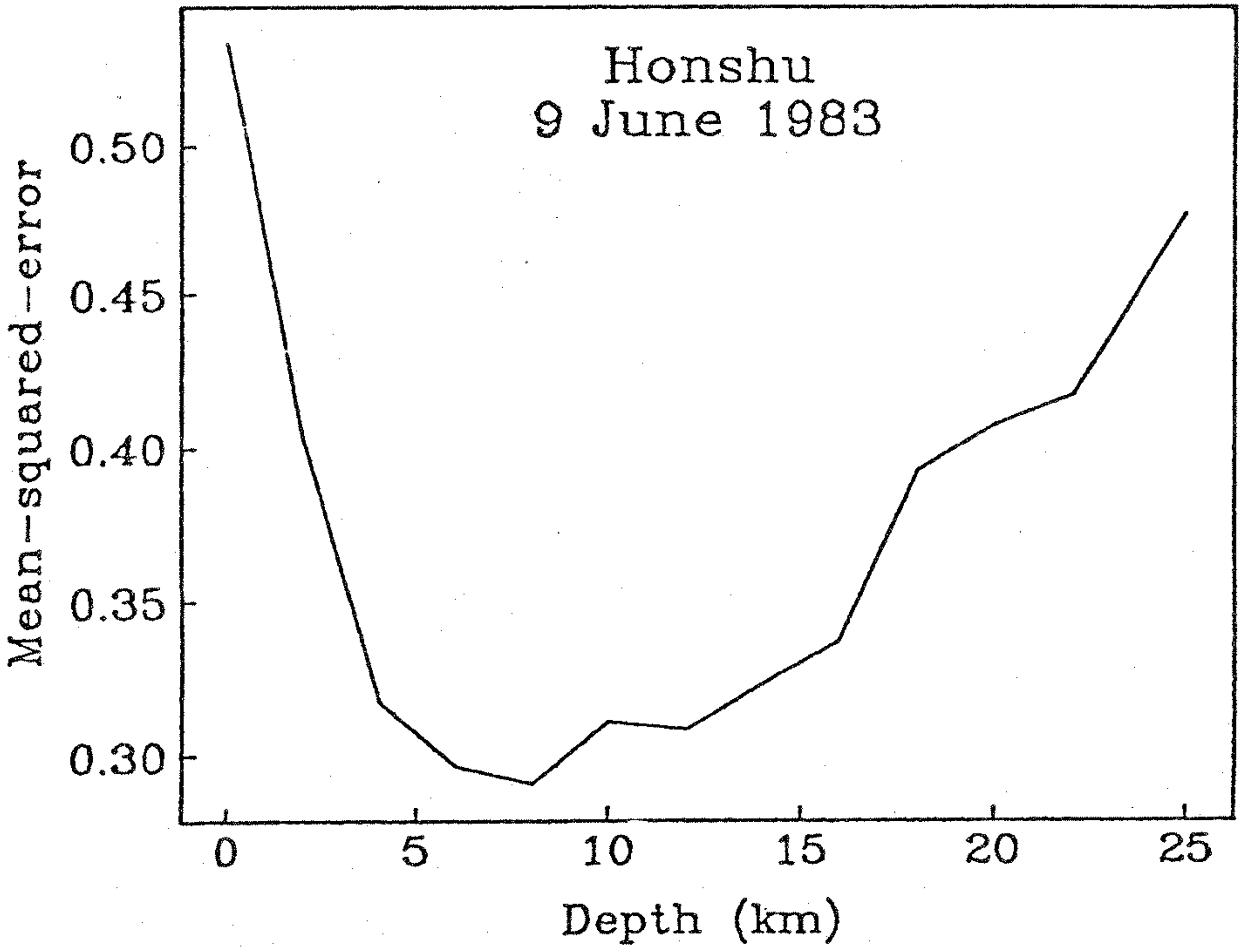


Figure 3.8. Normalized rms misfit of body-wave synthetics to the data as a function of the source centroid depth assumed in the waveform inversion. The event is an aftershock of the large 26 May 1983 Honshu earthquake. The minimum misfit near a centroid depth of 8 km is readily apparent. (S. Sipkin, with permission)

these methods. This is especially important for the study of intraplate tectonics, where the seismicity levels are low and the events are small. For example, unusual clusters of earthquakes have been detected in the south-central Pacific Ocean which appear to be related to the release of plate stresses at isolated zones of weakness; the biggest of these has a moment of only $\sim 10^{23}$ dyne-cm, too small to be studied by the current GDSN, but large enough for a network with 20 or so Pacific and circum-Pacific stations of the type proposed here. Other problems in which a reduced moment threshold would provide significant new data include aftershock studies, foreshock studies and the analysis of deep-focus seismicity, where large events are considerably less frequent than at shallower levels. The temporal behavior of low level seismic activity in seismic gaps can also be monitored. The following is an example of how systematic investigations of the source mechanism can be used to monitor the dynamic behavior of seismicity in a particular region.

Figure 3.9 shows the double-couple representation of moment tensor solutions obtained for the Kurile Islands region for the period from January 1, 1977 through September 30, 1983. These solutions were derived from the digital data provided by the IDA and GDSN networks. The figure shows all events with M_w of 6.5 or greater and it is also complete for $M_w \geqslant 6.0$ from January 1, 1981. M_w is a new measure of magnitude based on the seismic moment, or total energy release. The radius of the "beach-ball" is a linear function of the magnitude. The figure also shows the area of faulting associated with major earthquakes in the past: the events of 1952, 1958, 1963 and 1969. There is a distinct gap in seismicity between the islands of Simushir and Onekotan, covering some 300 km of the trench axis; no major earthquake has occurred in this region since, at least, 1915. The existence of this gap has been recognized for some time.

The major burst of seismic activity occurred as a sequence of large thrust events from March 22 to 24, 1978, with the largest events exceeding M_w of 7.5. The pattern of seismicity following this series seems to be consistent with the hypothesis of stress diffusion along a subduction zone.

The normal fault, outer rise, event on 4/30/81 is consistent with the concept of relaxation of stresses in the subducted lithosphere following a major thrust earthquake. The seismicity migrates towards north-east with a magnitude 6.9 earthquake on 12/31/80 and 7.1 on 6/30/82; the latter event is located on the trench axis and has a rather atypical mechanism dominated by strike-slip. The most recent event illustrated (5/1/83) is a thrust on the south-western edge of the gap itself.

The northeastern end of the gap borders the fault area of the 1952 Kamchatka earthquake. This area has been quiescent since 1977, except for three outer rise events in 1981. Two in the northeast were tensional, but one near the southwestern end was compressive, perhaps diagnostic of the overall high stress in the entire region. Then, in 1983, two thrust events occurred on the southwestern end of the gap: M_w of 6.3 on 2/26/83 and M_w of 6.5 on 4/4/83.

Whether this pattern of migrating seismicity is indicative of an impending major event in the Simushir-Onekotan gap is an open question. Increase of seismicity at the edges of a gap was noted before some major events (1952 Kamchatka $M_w = 9.0$, 1964 Alaska $M_w = 9.2$). What this example shows, and similar pictures for other subduction zones with a significant seismicity during the seven years prior to 1984 seem to indicate, is that one can distinguish spatio-temporal patterns, with the source mechanism being an important parameter. Development of a global telemetered digital network would allow for the real time monitoring of seismic gaps.

3.2.2. Physics of the Rupture Process

Most earthquakes are well described as a shear dislocation across a fault surface. The displacement function (magnitude of the shear dislocation vector on the fault surface) depends on both time and space. Thus, an earthquake is a spatio-temporal process. The earthquake rupture process is defined by the space-time dependence of the displacement function.

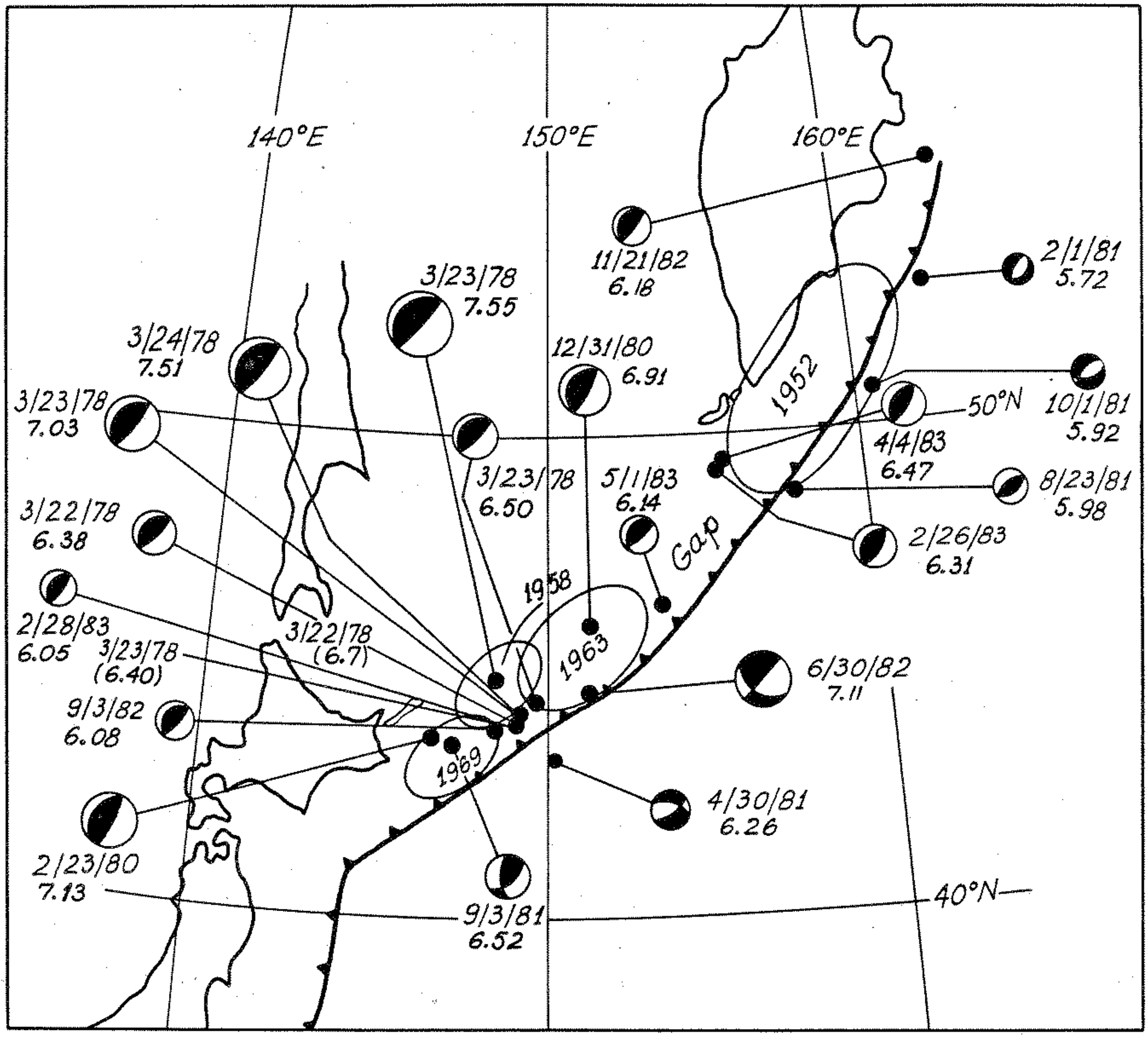


Figure 3.9. Seismicity of the Kurile Islands trench for years 1977-1983. All source mechanism solutions were obtained from analysis of digital data. (Kanamori and Dziewonski, with permission)

A useful quantity for characterizing the earthquake process is the seismic moment: $M_0 = \mu D_0 A$, where μ is the local shear modulus, D_0 is the average value of fault displacement, and A is the fault area. This definition should be viewed as the "static" seismic moment, i.e. M_0 is the value of the seismic moment after the earthquake rupture process is completed. This point is illustrated in the top part of Figure 3.10, where seismic moment, $M(t)$, is plotted as a function of time. Earthquake rupture starts at $t = 0$ and stops at $t = \tau$. Hence, M_0 is the value of $M(t)$ for $t > \tau$. We will now develop the basic concepts for the space-time accumulation of seismic moment. If we consider a small area element on the fault surface, dA, the seismic moment contribution from this element is: $dM = \mu dAD$, where local shear modulus treated as a constant and D is the final value of displacement at dA. Since the displacement depends on time, dM also depends on time. Also, we realize that D varies spatially; hence in general, $dM(t,\underline{x}) = \mu dAD(t,\underline{x})$. This formula is important in that the space-time dependence of the seismic moment characterizes the space-time dependence of the displacement function.

Seismologists study earthquakes by analyzing the seismic waves radiated from the source. Due to the great advances in seismic source theory, we know that seismic wave amplitudes and wave shapes depend on the effective seismic moment rate, i.e., the time derivative of the seismic moment (see lower part of Figure 3.10). Recall that $dM(t,\underline{x})$ is the moment contribution from one area element. The seismic moment function, $M(t)$, is obtained by summing the moment contributions over all of the area elements. The contribution of a given area element depends on the seismic wave type and on the azimuth between the fault surface and the wave path to the station. The azimuthal difference between stations will cause the spatial summation over $dM(t,\underline{x})$ to produce slightly different effective seismic moment functions. The seismic moment rate obtained from the seismograms at each station will reflect these differences in the moment summation. Hence, while the basic time dependence of the moment accumulation is displayed at all of the stations, the space dependence of the rupture process is exhibited as small but systematic variations in the effective-moment rates. We will return to this point later.

A great achievement in quantitative seismology is the development of techniques to determine the static seismic moment of earthquakes accurately. As previously mentioned, the seismic moment, M_0, is the value of $M(t)$ at $t \to \infty$. Clearly, the seismic moment is equivalent to the integral of the seismic moment rate, $\dot{M}(t)$. Note that $\dot{M}(t)$ is zero both before rupture initiation and after rupture termination, i.e., seismic waves are radiated only during the rupture process (see Figure 3.10). An important earthquake parameter is then the time of rupture duration, τ. To determine the static seismic moment, we need to insure that the seismic moment function is well-characterized for time greater than τ (let $t = 0$ at rupture initiation). The easiest way to accomplish this is to use seismic waves with wave periods much larger than τ. Then, they are sensitive only to the final value of the moment function, not to the behavior between $t = 0$ and $t = \tau$. In studying the rupture process of an earthquake, our preference of wave periods is quite different. To learn anything about the moment rate function for $0 < t < \tau$, we must use wave periods that are much smaller than τ. In fact, to obtain a complete picture of the rupture process, we must use wave periods extending from much smaller than τ to larger than τ. Therefore, we must record seismic waves with a broad-band instrument. How "broad" is broad-band?

Consider a typical magnitude 8 earthquake. The characteristic dimension of the fault area is ~ 100 km. with a rupture velocity of 2 km/s, the characteristic rupture duration time would be ~ 50 s. To determine reliably the seismic moment, M_0, wave periods beyond one hundred seconds must be well recorded. To study the rupture process, we must use periods much less than 50 s. How much less? One approach to this question is to consider the desired spatial resolution of moment release. Relative epicentral locations of small earthquakes are generally reliable to less than 10 km. It would be desirable to locate spatial "bursts" of moment time release during a large earthquake to the same accuracy. This is particularly important when considering the asperity, barrier, or other physical models of the rupture process.

As mentioned before, the spatial variation in moment release causes slight variations in the delay time of features in the moment rate function. The azimuthally dependent systematic

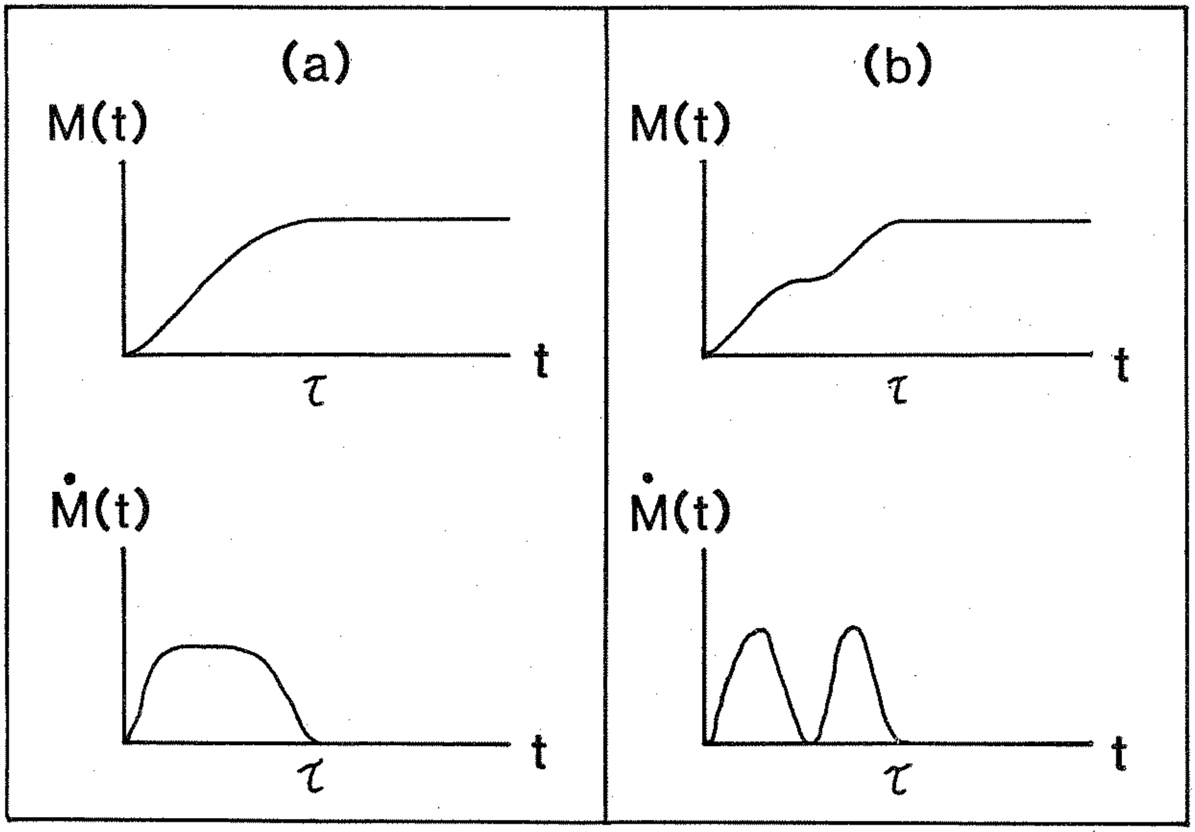


Figure 3.10. Seismic moment function and seismic moment rate for two idealized earthquakes. The upper part of the figure schematically plots the seismic moment as a function of time, the lower part schematically plots the seismic moment rate, simply the time derivative of the seismic moment function. Seismic waves are generated by the seismic moment rate. In (a), a "simple" earthquake is graphed: smooth moment release, a single pulse for the moment rate. In (b), a "multiple-event" earthquake is graphed: sporadic moment release resulting in two pulses for the moment rate. (L. Ruff, with permission)

variation in delay time is referred to as directivity. The maximum azimuthal variation in delay time (δT) is related to the spatial separation as $\delta T = 2p\delta x$, where p is the slowness of the seismic wave and δx is the spatial separation. Although other wave types can potentially be used, most rupture process studies have used P-waves. The typical value of p for a teleseismic P-wave is 0.05 s/km. To obtain a spatial resolution of ± 5 km, we must resolve time variations of ± 0.5 s. Therefore, to study the rupture process we need an instrument that reliably records wave periods ranging from a few hundred seconds down to a fraction of a second, perhaps 0.1 s.

It is important to note that magnitude 8 earthquakes occur infrequently (1 or 2 a year). Many future studies of the rupture process will be concerned with smaller earthquakes, say magnitude 6.5, and consequently a much smaller fault area. To study the spatial moment release of these earthquakes, the requisite time resolution is in the vicinity of 0.1 s.

Since studies of the rupture process place strong demands on the instrument design, notably the band-width and the dynamic range, it is important to point out the importance of these studies. First of all, now that techniques have progressed such that seismic moments can be systematically determined for all earthquakes with M_w above 5.4, the next logical step is to examine how the seismic moment is released. While the point source is a convenient and useful mathematical abstraction, the physics involved in the earthquake process will be exhibited in the space-time history of moment release.

The results from studies of the earthquake rupture process should be interpreted in terms of physical processes. There are two end-member models of earthquake rupture: the asperity model and the barrier model. The important aspect of both of these models is that a fault surface is composed of "weak" regions and "strong" regions. In the barrier model, the largest earthquake in a particular fault segment occurs when the weak regions rupture. In contrast, the asperity model states that the weak regions slip aseismically, thereby transferring stress to the strong regions, and the largest earthquake occurs when the largest and strongest region ruptures.

Aside from the existence of models according to which the rupture process may be interpreted, it is important to realize the variability of this process among different earthquakes. Figure 3.11 summarizes the rupture process of the great 1964 Alaskan and the 1963 Kurile Island earthquakes. The seismograms from these two great earthquakes display a different character, which translates into a dramatically different moment rate function. The Kurile Islands earthquake is a classic example of a multiple event earthquake (Figure 3.10b), while the Alaskan earthquake ruptured a smooth, very large strong region. These differences can be explained by different dimensions of asperities (strong regions).

Certainly, not all aspects of rupture process studies have yet been exhausted. For example, the subject of changes in faulting geometry during the rupture is commonly ignored. The purpose of this section is to state the basic scientific problem, objectives and instrumental requirements. The following are the principal points: (i) seismologists have recently been considering and testing physical models of earthquake occurrence, (ii) following the development of reliable techniques for determining the seismic moment, the next step for quantitative seismology is to study the space-time dependence of moment release, i.e., the rupture process, (iii) recent studies of the rupture process for a few earthquakes indicate there are dramatic differences between earthquakes, which have been interpreted in terms of a physical model of earthquake occurrence, (iv) determining the space-time pattern of moment release for many earthquakes will yield insight into the physics of earthquakes.

3.2.3. Constraining Higher-Order Source Parameters and Detailed Rupture Models

Point-source parameters provide only a spatial and temporal average of the source process, giving no information about the detailed history of rupture required for a complete kinematic description of faulting. Such information is crucial to the development of truly dynamic models of earthquakes and the basic understanding of earthquake physics. More sophisticated parameterizations of source kinematics can be grouped in two classes: those based on a polynomial-

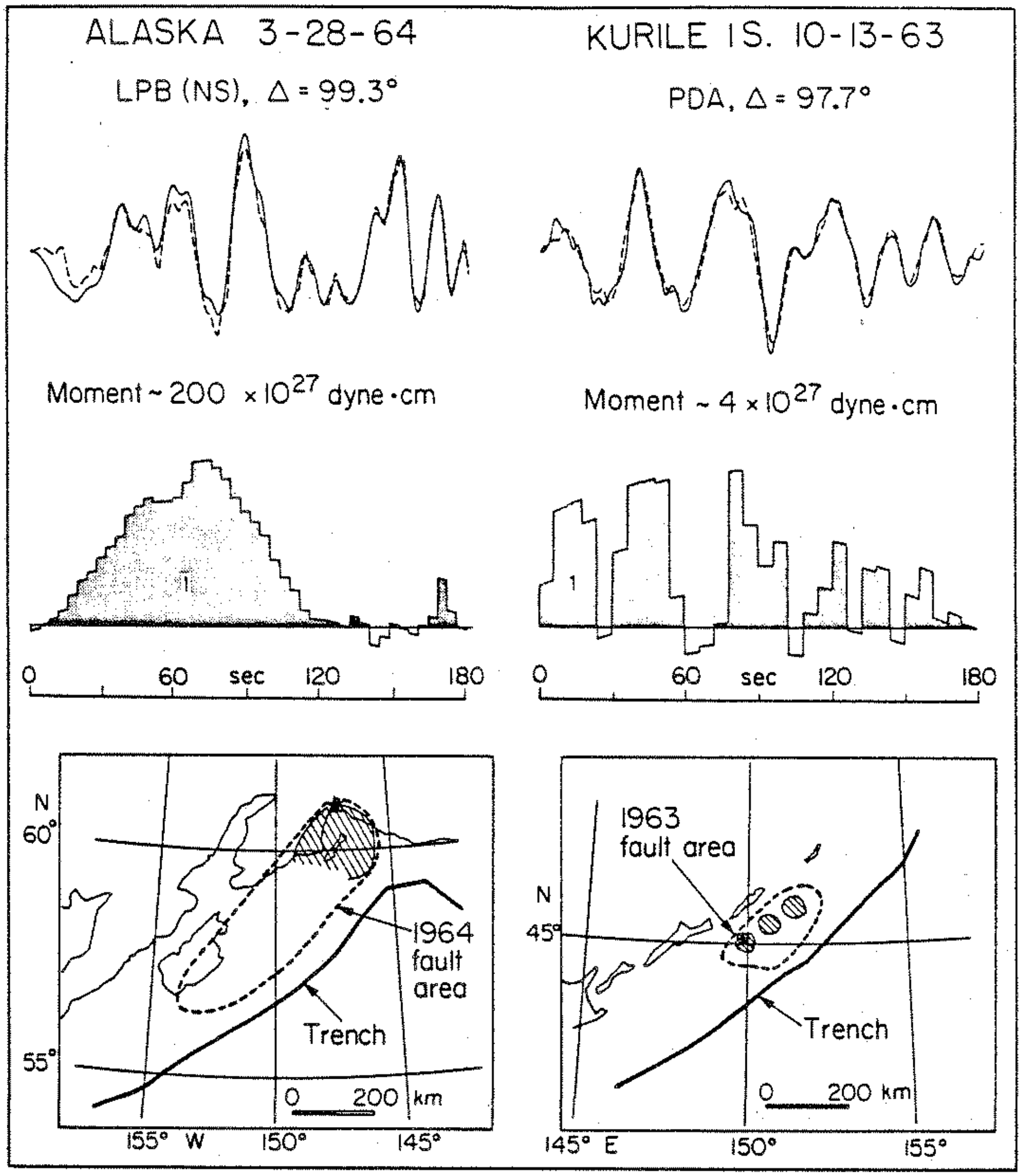


Figure 3.11. The difference in the source time histories and inferred asperity distributions of the 1964 Alaskan and 1963 Kurile Islands earthquakes. The seismograms are shown at top as the solid traces. The dashed traces are the synthetic seismograms corresponding to the deconvolved source time functions shown beneath the seismograms. While the Kurile Islands time function is composed of a multiple event sequence, the Alaskan time function represents a smooth rupture spreading over a large area. Also, notice the large difference in the seismic moments, i.e. scale of the time functions. The epicenters (stars) and fault areas are shown below, and the inferred asperities are indicated as the hachured areas. The Alaskan earthquake occurred in a region of very large asperity length scale. (Ruff and Kanamori, *Phys. Earth Planet. Inter.*, 1983)

moment expansion in both space and time coordinates of the excess stress (stress glut), equivalent to a multipolar expansion of the radiation field, and those based on the representation of the source as an arbitrary superposition of dislocation elements. The former is more general (in fact, completely so), whereas the latter represents more conveniently the complexities of fault rupture, especially the description of asperities and barriers to rupture, and is more easily related to fault dynamics.

Although point-source solutions are now routinely available for most intermediate and large earthquakes, higher-order source parameters and detailed models of rupture have been derived for very few, usually those with good control from local and regional seismographic networks. Waveform-modeling studies have shown, however, that many details of the faulting can be inferred from global broadband networks. For example, the frequency content of a P wave and its azimuthal variations can be used to estimate the duration and directivity of faulting (Figure 3.12). If an earthquake is a multiple rupture comprising several distinct subevents, a common occurrence for large deep-focus earthquakes, then the relative locations, origin times, moments, and sometimes even mechanisms of the subevents can be estimated. As in the case of point-source estimation, a primary problem is the variations in waveforms associated with unknown propagation effects, which can interfere with signals related to source structure.

Again, the current GDSN is inadequate to satisfy the science objectives. The station coverage is too sparse to give good azimuthal control and average out structural complications, and the response characteristics are not suitable to these kinds of source studies. Particularly bothersome is the lack of information in the microseismic band, 0.1-2.0 Hz, which lies in the notch between the short-period and long-period SRO/ASRO channels. Unfortunately, the corner frequencies of many teleseismically recorded earthquakes fall precisely in this band, so that this mid-period information is most diagnostic of the directivity and duration of these sources. Schemes have been formulated to reconstruct broad-band signals from the two channels (Figure 3.13), but the process is laborious, subject to errors, and thus abrogates many of the advantages of digital recording. the direct recording of this information on a single, broadband channel of high dynamic range is a feasible and a much superior alternative.

3.2.4. Problems Involving Other Seismic Sources

Although most signals used to study the earth's interior are produced by earthquakes, there are several other types of seismic sources whose study contributes to important science objectives. Perhaps the most significant of these are nuclear explosions, which can be as large as moderate-size earthquakes (a 150-kiloton underground nuclear explosion has a body-wave magnitude of about 6). The locations and origin times of nuclear explosions can be controlled, and they are efficient generators of high-frequency waves; hence, they aid in the study of body-wave propagation, particularly high-frequency attenuation. Of course, the determination of their source characteristics using teleseismic waves is a subject which impinges on issues of national defense and consequently is a problem that has motivated large research programs in basic seismological research. It is clear that the global network proposed here will increase the observational capabilities of the international seismological community and thus contribute to this research.

It will also contribute to the study of very low frequency sources, which include explosive volcanic eruptions. Although this is a very new area of inquiry -- the Mt. St. Helens event of 1980 was one of the first recorded by global digital networks of sensitive low-frequency seismometers -- it appears to be capable of placing fundamental constraints on the nature of volcanic eruptions.

Finally, there are infrequent or hypothetical seismic sources best described as "exotic". Examples include meteorite impacts and extraterrestrial gravitational waves. Although the probabilities that these particular sources will excite detectable oscillations during the lifetime of a global network appear to be small, they deserve mention because they illustrate the potential payoffs of a tool capable of making qualitatively new, as well as quantitatively improved,

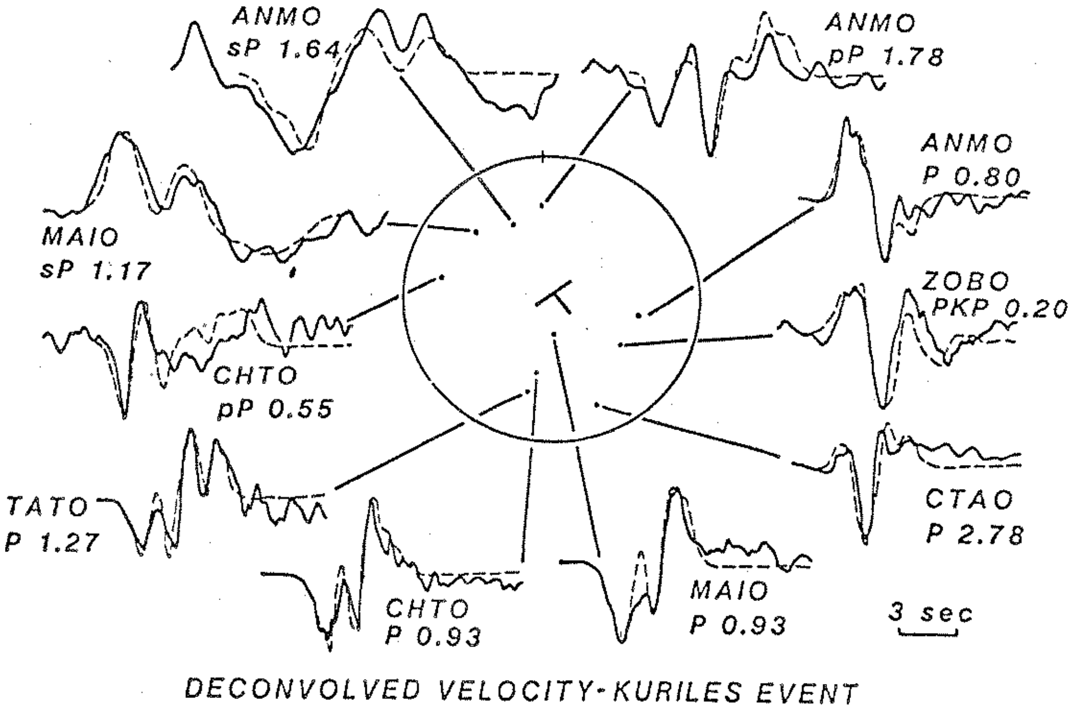


Figure 3.12. Broadband velocity records reconstructed from the GDSN long- and short-period channels for an event in the Kurils ($h = 377$ km), distributed about the local sphere. The fault plane has been rotated to coincide with the plane of the stereonet. Increased high-frequency energy in the P-wave is evident going clockwise in azimuth from ANMO to TATO, a directivity effect. (G. Choy, with permission)

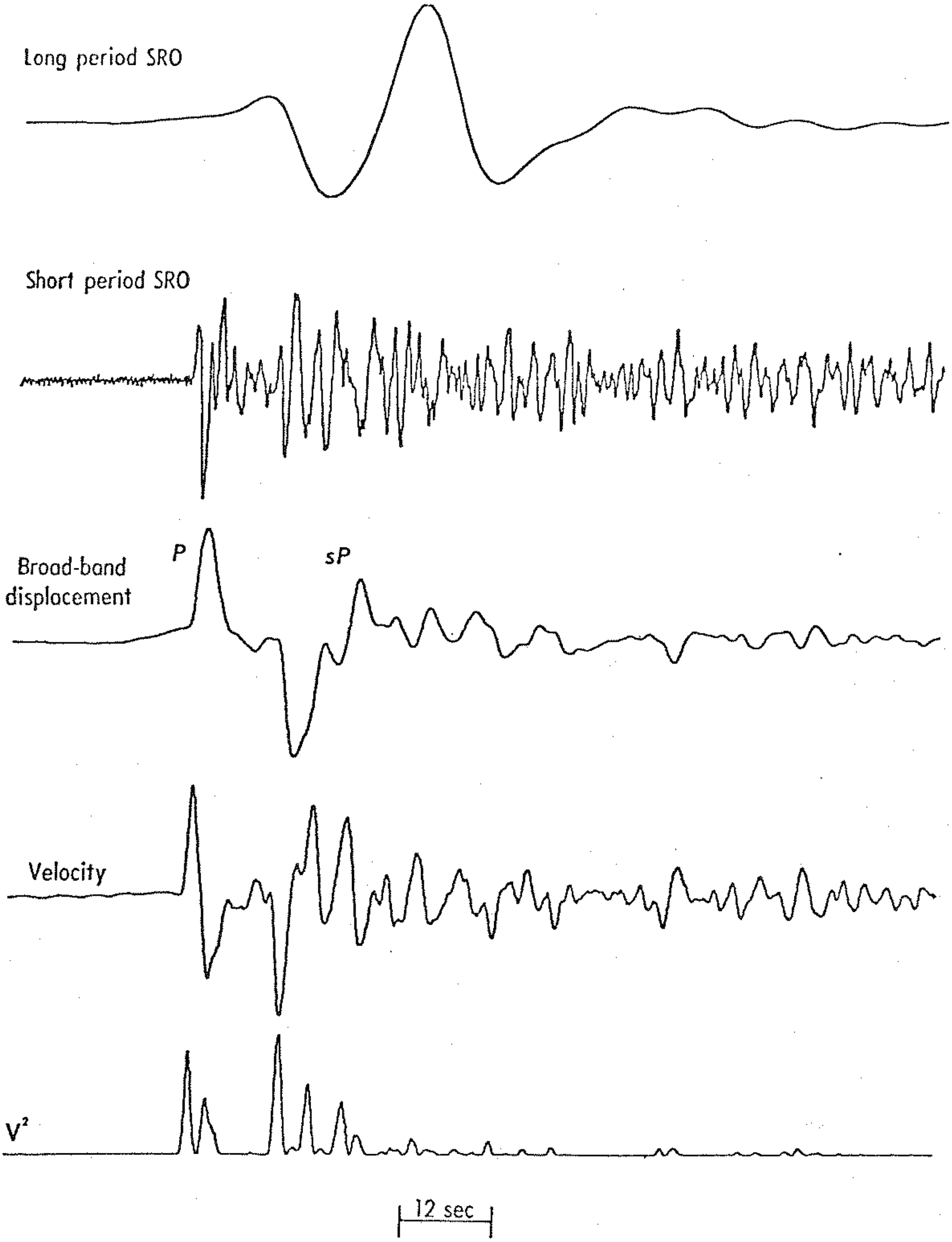


Figure 3.13. An example of broadband signal reconstruction from long- and short-period SRO channels for an event in Japan (m_b = 5.9, h = 38 km) recorded at MAIO (Δ = 63.7°). The top two traces are the raw data channels. The bottom three traces show broadband displacement, velocity, and velocity-squared records. Depth phases can be discerned easily in the displacement record. (G. Choy, with permission)

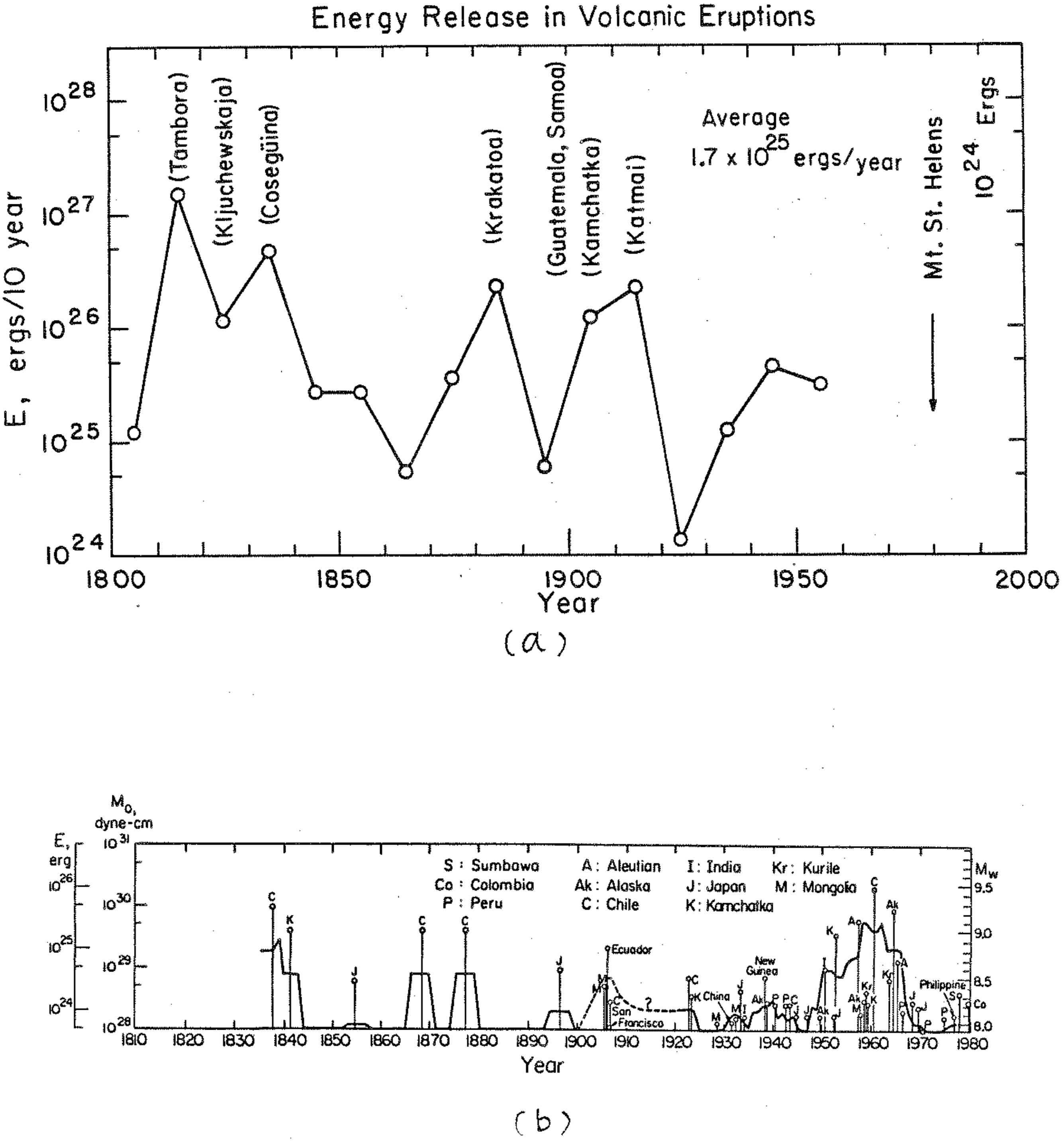


Figure 3.14. (a) The energy release in major volcanic eruptions. Each data point represents the energy released in each 10-year period. The average is 1.7×10^{25} erg/year. The names of the volcanoes which erupted during each period are indicated in parentheses. The estimate of energy is based mainly on the thermal energy carried by the ejecta or lava, and is subject to a large uncertainty.
(b) The energy release in major earthquakes as a function of time. (Kanamori, *Proc. Enrico Fermi School Phys.*, LXXV, 1983)

observations. Perhaps a better example is the so-called "infraseismic" or "silent" earthquake, a hypothetical event whose characteristic source-process time lies well beyond the period range of the seismic waves typically used for event detection (1-100 seconds), but which may still excite low-order free oscillations at levels observable on very low frequency seismometers. At present, too little is known about elastic instabilities within the earth's interior to allow the observational probabilities to be usefully assessed, but some earthquakes are known to be "slow", in the sense that their ratio of low-frequency to high-frequency seismic radiation is anomalously large, and there are no compelling physical arguments to preclude even slower ruptures in the deep interior.

3.2.4.1. Nuclear Explosions

Seismic signals produced by underground nuclear explosions have been extensively analyzed during the past 20 years, yielding numerous advances in our understanding of earth structure. The accurate timing and locations available for most tests, along with the theoretically simple radiation pattern produced by explosive sources, have enabled detailed studies of upper-mantle velocity discontinuities, global velocity structure, lateral variations in attenuation, and structure of the core-mantle and inner core-outer core transition zones. These studies have relied principally on travel-time information, in part because of the many difficulties encountered in modeling signals recorded by high-frequency, narrow-band instruments of the WWSSN and GDSN. Teleseismic body waves from underground explosions are dominated by high frequencies owing to the shallow source depths and the short source-process times of the events. The present separation of short-and long-period recording channels severly limits the mid-period information needed for the quantitative analysis of explosion signals. Availability of broad band data will open doors to complete waveform modeling of explosion signals.

Explosion detection, discrimination and yield estimation are other areas of nuclear explosion seismology that will benefit from a digital network with large dynamic range and good spatial distribution. Such a network will permit locations and depth determinations using complete waveform information rather than just travel times. Broad-band, three-component data are important for many detection algorithms, as well as for the waveform analysis used to discriminate explosions from earthquakes.

3.2.4.2. Volcanic Eruptions

Volcanism is one of the most visible and significant geological processes on the earth's surface. Very crude estimates indicate that the energy release involved in volcanic eruptions is comparable to, or even larger than, that released in earthquakes (Figure 3.14). Many attempts have been made to correlate volcanism, seismicity, and other geophysical parameters. These studies suggest, if not definitely, that the physical processes involved in volcanism have an important bearing on many other geological and geophysical processes, such as seismicity, aseismicity, global climate, and the rotation of the earth. A major difficulty in these studies, however is the lack of physical quantification methods to define the magnitude of volcanic eruptions. For earthquakes, several methods have been established to allow quantitative interpretations of seismicity data. Unfortunately, no analogous quantification system has been instituted for volcanic eruptions. Previous attempts at quantifying the magnitude of eruptions have centered on estimating the thermal, potential, and kinetic energies as estimated from volumes of lava and pyroclastic debris, column heights, and ballistic trajectories of individual fragments. A use of the amplitude of air waves excited by an eruption has been also proposed for quantification purposes.

These studies have contributed greatly towards better quantification of volcanic eruptions. However, some of the parameters used in these studies are somewhat qualitative and subjective. Also, some of the methods can only be applied when detailed on-site field data are available. Many volcanoes are not easily accessible, so that such field data are not always available. It is desirable to have a quantitative and objective quantification method to complement the existing methods.

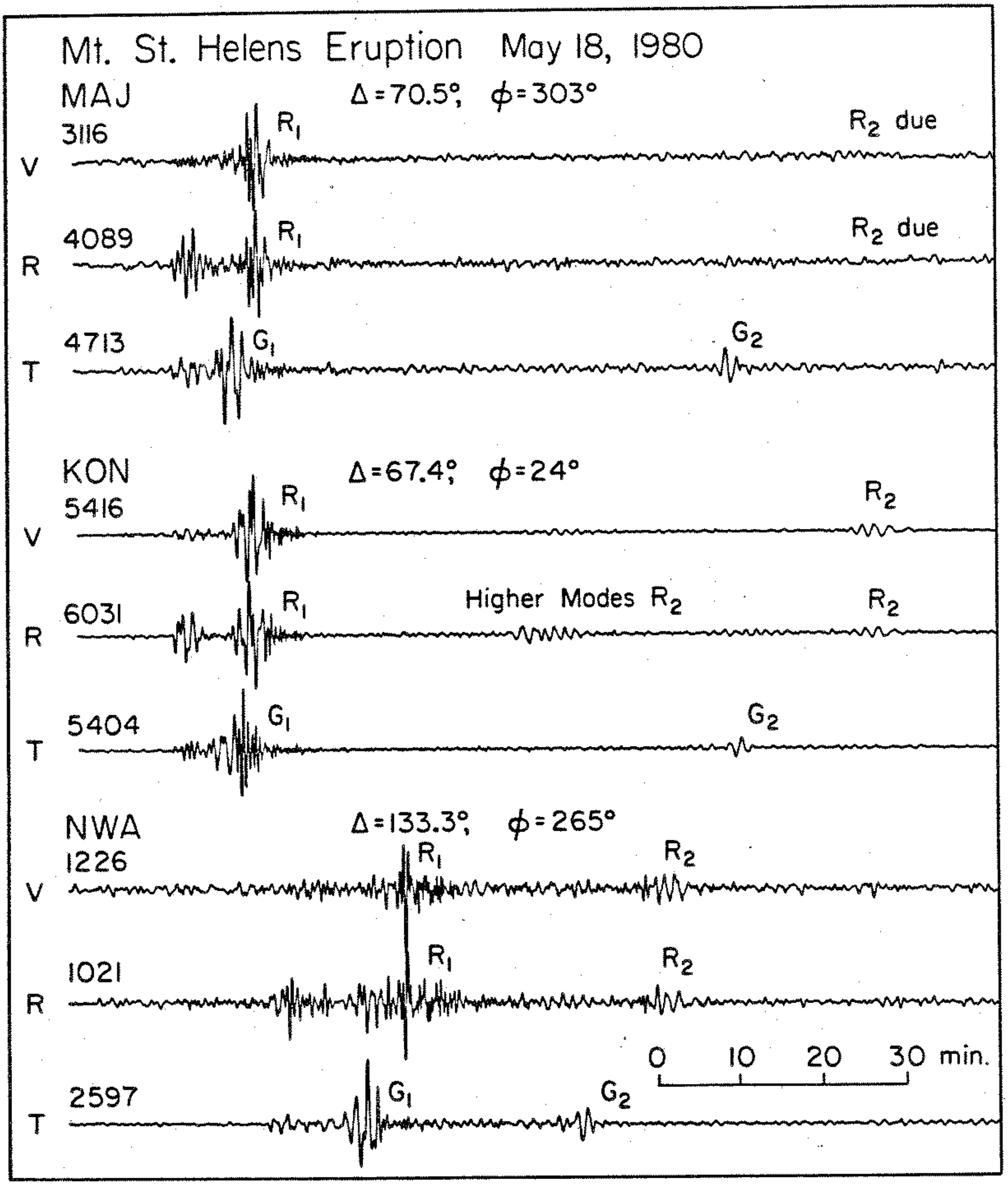


Figure 3.15. Three-component seismograms of the eruption of Mt. St. Helens at MAJ, KON and NWA. Original seismograms are high-cut filtered at 30 sec and rotated to vertical, radial and transverse components. The beginning of the record is at $15^h 32^m 11^s$ GMT, May 18, 1980. The peak-to-peak amplitude is given in digital counts. Note the long-period surface waves, R_1, R_2, G_1 and G_2. (Kanamori and Given, *J. Geophys. Res.*, 1982)

Recent studies on the major eruption of Mt. St. Helens on May 18, 1980 have demonstrated that global digital seismological data can be effectively used for rapid and objective quantification of volcanic eruptions.

The Mt. St. Helens eruption excited very long-period (~ 200 sec) seismic surface waves, body waves, and air waves that were recorded by the GDSN stations as well as the IDA stations (Figure 3.15). These records constitute the first complete global data set ever obtained for a volcanic eruption. From the analysis of these data, the time history and the magnitude of the landslide, and the impulse of the force associated with the eruption could be determined accurately. In these studies, the eruption is represented by a combination of equivalent force systems, and the well-established seismological techniques are used to determine the source parameters.

For example, Figure 3.16 compares the kinetic energy estimated by seismic methods for several recent eruptions. The energy is also expressed by the corresponding magnitude scale. Through this type of analysis, we can rank volcanic eruptions and compare them with earthquakes on a rigorous physical basis.

The seismic signal excited by volcanic eruptions is too small to be detected by standard analog seismograph networks. The GDSN is adequate for recording only the very largest of eruptions. However, the relatively sparse distribution of these stations and their narrow bandwidth hamper the use of seismological methods for the study of all large eruptions in the world. Implementation of the new global seismic network would enable seismologists to establish a quantitative data base for the study of explosive volcanism.

With the real-time capability of the network, it would be possible to determine immediately the explosivity and the duration of an eruption. This information is useful for assessing the effect of the eruption on global climate and other atmospheric processes.

Records of the airwaves associated with an eruption provide additional information on the processes involved. For this reason, digital barographs at a limited number of stations would be very helpful.

3.2.4.3. "Exotic" Sources

The source spectrum of most earthquakes can be defined by 2 parameters, the seismic moment M_0 and the corner frequency f_c. For a frequency range from 0 to f_c, the spectrum is essentially flat with the amplitude proportional to M_0. At frequencies beyond f_c, the spectrum falls off as f^{-2}. However, some earthquakes are known to have anomalously large amplitude at the low frequency end of the spectrum indicating that their source process involved an anomalously slow motion. These earthquakes are often called "Slow Earthquakes" or "Silent Earthquakes". In some cases, the slow motion seems to have preceded the main rupture. Examples are the 1960 Chilean earthquake, 1970 deep Colombian earthquake, 1978 Izu, Japan earthquake, June 6, 1960 Chilean earthquake, 1896 Sanriku earthquake and 1946 Unimak Is. Aleutian earthquake. In case of the last two examples, the evidence for the slow process time came from the anomalously large tsunamis excited by these earthquakes. If the slow displacement is precursory to the main rupture, detection of such slow displacement may provide a useful means for short-term earthquake prediction. Many mechanisms for slow earthquakes have been suggested: slow rupture propagation, slow viscoelastic fault motion, phase changes, landslides, etc. Unfortunately, in many of these cases, the data were very limited mainly because of inadequate long-period response of the instrument, and the mechanisms are not fully understood. The dense spatial coverage and the broad bandwidth of the proposed new global network would be adequate for the study of these slow earthquakes. The physical mechanism of slow events may provide an important clue to the mechanism of precursory deformations associated with earthquakes.

High-quality digital data can also be used to study other exotic seismic sources such as meteorite impacts and gravitational waves from pulsars. For the Siberian explosion of June 30, 1908, seismological methods have been effectively used to resolve some of the details of the

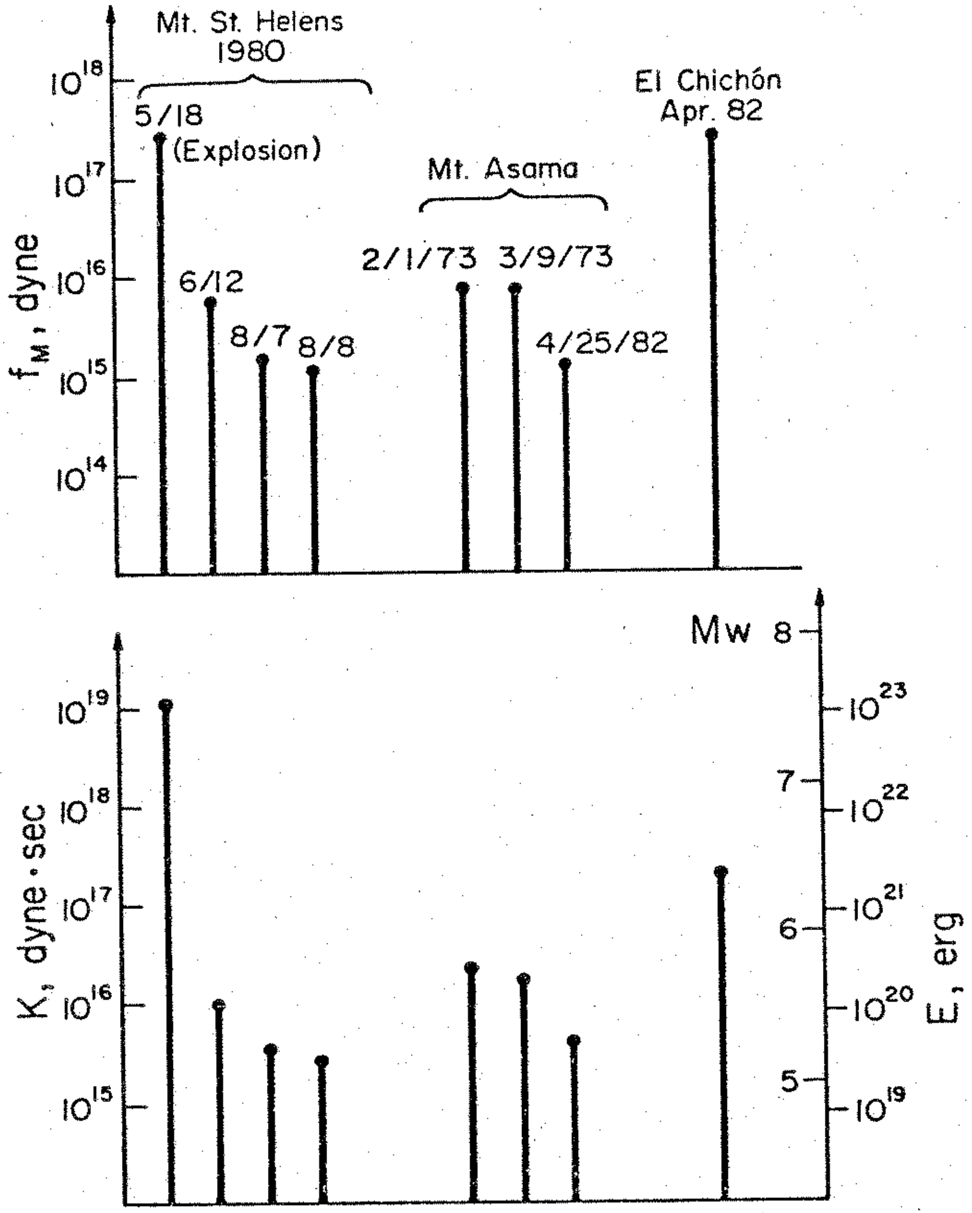


Figure 3.16. The magnitude of the force, *fm*, impulse *K* and energy *E* associated with several recent eruptions determined from global seismological data. (Kanamori, with permission)

impact source. As a result of these investigations, the source is believed to consist of a combined action of an atmospheric explosion and a ballistic wave.

Attempts to detect seismic response of the earth to gravitational waves have been made by several investigators, but the results so far are inconclusive mainly because of the insufficient signal-to-noise ratio. At present it is unclear whether seismic excitation by gravitational waves is strong enough to be detected by any seismographic instrument. However, the enhanced capability of the proposed new global network would provide seismologists with a much better opportunity to study this type of problems than before.

3.2.5. Real-Time Aspects

Real-time transmission of the digital seismic data through satellites is an important aspect of the proposed network. For the first time, it will allow seismologists to analyze the source mechanism of large events within one hour or so of its occurrence. This has implications both for science and for society.

3.2.5.1. Tsunami Warning

The damage caused by tsunamis is very extensive. It is widely known that most, if not all, large tsunamis are caused by sea-bottom deformations associated with large earthquakes. Although many factors such as the magnitude, the depth, the location and the mechanism (dip-slip or strike-slip) of the earthquake determine the magnitude of a tsunami, the magnitude of the earthquake is the most critical.

Since the height of tsunamis at coastal areas is influenced by many factors such as the strength of a tsunami at the source, effect of the propagation path and, in particular, the local topography near the observation site, no simple straightforward relation between the magnitude of a tsunami and that of the earthquake can be expected. However, the observed maximum amplitude of tsunami wave H observed at various sites is correlated fairly well with the magnitude of the earthquake, M, measured by very long-period waves. This correlation is shown by Figure 3.17. Although the scatter is considerable, primarily because of the local coastal effects around the site, this figure clearly indicates that the long-period magnitude, M, is a very useful measure of the tsunami potential of the earthquake.

The earthquake magnitude is among the most important parameters used by the present tsunami warning system. However, the magnitude of large earthquakes has been traditionally determined by using 20 second surface waves (surface-wave magnitude M_s). It is known that the surface-wave magnitude, M_s, saturates beyond a certain limit (about $M_s = 7\ 3/4$) and is thus not a very reliable measure of the tsunami potential of the earthquake.

Furthermore, the magnitude alone is not quite enough to evaluate the tsunami potential of an earthquake. Since tsunamis are primarily excited by vertical motion of the sea bottom, an earthquake with a substantial dip-slip component is more likely to be tsunamigenic than one with primarily strike-slip mechanism. Unfortunately, the earthquake mechanism is not considered in the present tsunami warning system. Owing to the advance of source mechanism studies during the past decade, it is now possible to determine important earthquake source parameters (location, mechanism, source duration time etc.) very rapidly from the existing GDSN data.

Several methods have been developed that can determine earthquake source parameters within 10 minutes after the seismograms from 10 to 20 widely distributed stations have been collected. The new global seismographic network with its real-time capability will provide a tsunami warning system with far more quantitative and reliable information on the tsunami potential of an earthquake than is available now, thereby reducing tsunami hazards.

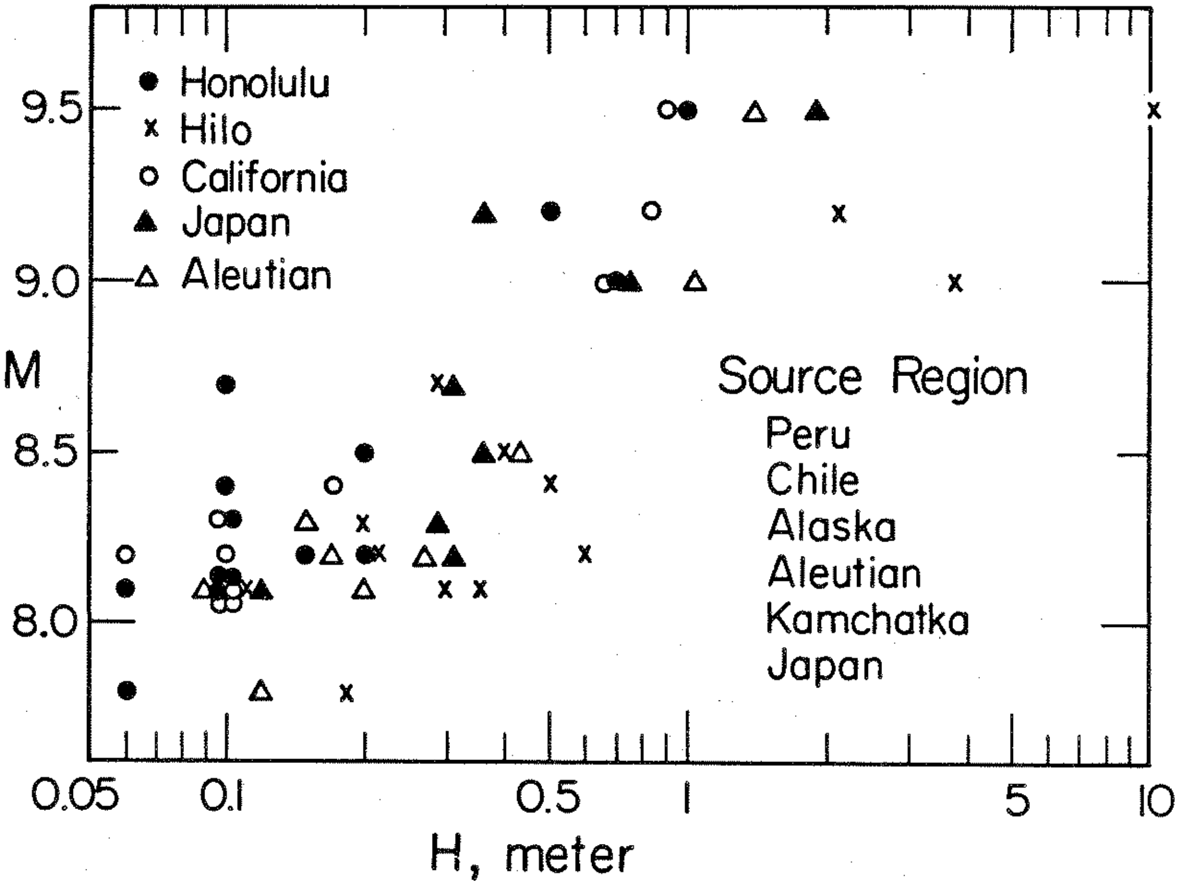


Figure 3.17. Relation between magnitude and the observed maximum amplitude H of tsunami waves for selected earthquakes. (Abe, *J. Geophys. Res.*, 1979).

3.2.5.2. Rapid Determination of Source Parameters

When a major earthquake occurs in a densely populated area, there is a strong demand among local seismologists and government officials for quick information on the nature of the earthquake. The present global network can provide information on the approximate location and the size (magnitude) of the event; however, as our experience with many earthquakes in the past demonstrates, more detailed information than currently available is clearly desirable not only for thorough scientific investigations of the earthquake but also for taking necessary measures for prevention of possible post-seismic hazards. In what follows, we describe several notable examples.

1) Akita-Oki, Japan, Earthquake (May 26, 1983, $M_w = 7.8$)

This earthquake occurred on the Japan Sea coast of the island of Honshu. Since most large earthquakes in Japan occur on the Pacific side of the island, the occurrence of an earthquake this size on the Japan Sea side was a great surprise to seismologists. Because of the very unusual location of this event, it was crucial to quickly determine the size and the mechanism of this event for a better understanding of its tectonic significance. Although hundreds of seismographic stations are in operation in Japan, it is difficult to determine accurately the mechanism and the seismic moment of very large nearby events because most seismographs are driven off-scale. For the Akita-Oki event, the mechanism remained unknown for a few days after the earthquake during which period a normal-fault mechanism was suggested on the basis of incomplete data. It was not until data from several European stations have been added a few days later, that the correct mechanism (thrust fault) was obtained.

If a global real-time system were operating, this critical information would have been given to the local seismologists quickly enough for them to inform the public of the tectonic significance of this event, to plan various scientific experiments to be conducted during the post-seismic period, and to make better overall post-seismic hazard reduction plans.

2) Tangshan, China, Earthquake (July 26, 1976, $M_w = 7.4$).

This earthquake was one of the most disastrous earthquakes in this century. About 15 hours after the main shock a large aftershock with $M_s = 7.2$ occurred, near the city of Tangshan, to the northeast of the main shock epicenter. This aftershock caused substantial damage in the city.

A source mechanism study conducted later revealed that the main shock has a right-lateral strike-slip mechanism on NE-SW trending fault. The geometry of the main shock and the aftershock suggests that the aftershock was triggered by the tensional stress resulting from the right-lateral movement of the main shock. There are many other similar examples in which aftershocks caused serious damages to the buildings that had been already structurally weakened by the main shock.

Although it is not always possible to accurately predict the occurrence of such large aftershocks on the basis of the mechanism of the main shock alone, it is helpful to know the mechanism and the size of the main shock immediately after its occurrence. Such information together with the knowledge of regional fault geometry would enable seismologists to assess the likelihood of such triggered events, and to take necessary measures for prevention of further damages.

3) Mauna Loa, Hawaii Earthquake (Nov. 16, 1983, $M_s \sim 6\frac{1}{2}$)

On Nov. 16, 1983, a magnitude 6½ earthquake occurred near Mauna Loa, Hawaii. The occurrence of this event caused some concern about the possible eruption of Mauna Loa, because, in 1950, a similar $M \sim 6\frac{1}{4}$ earthquake was followed in a few days by a major eruption. Indeed, the 1983 event was also followed by an eruption but this time not for several months. Although the causal relationship between the earthquake and the eruption is not fully understood, it is desirable to determine the nature of the event in real time so that the significance of the event can be evaluated quickly in the light of the past sequence.

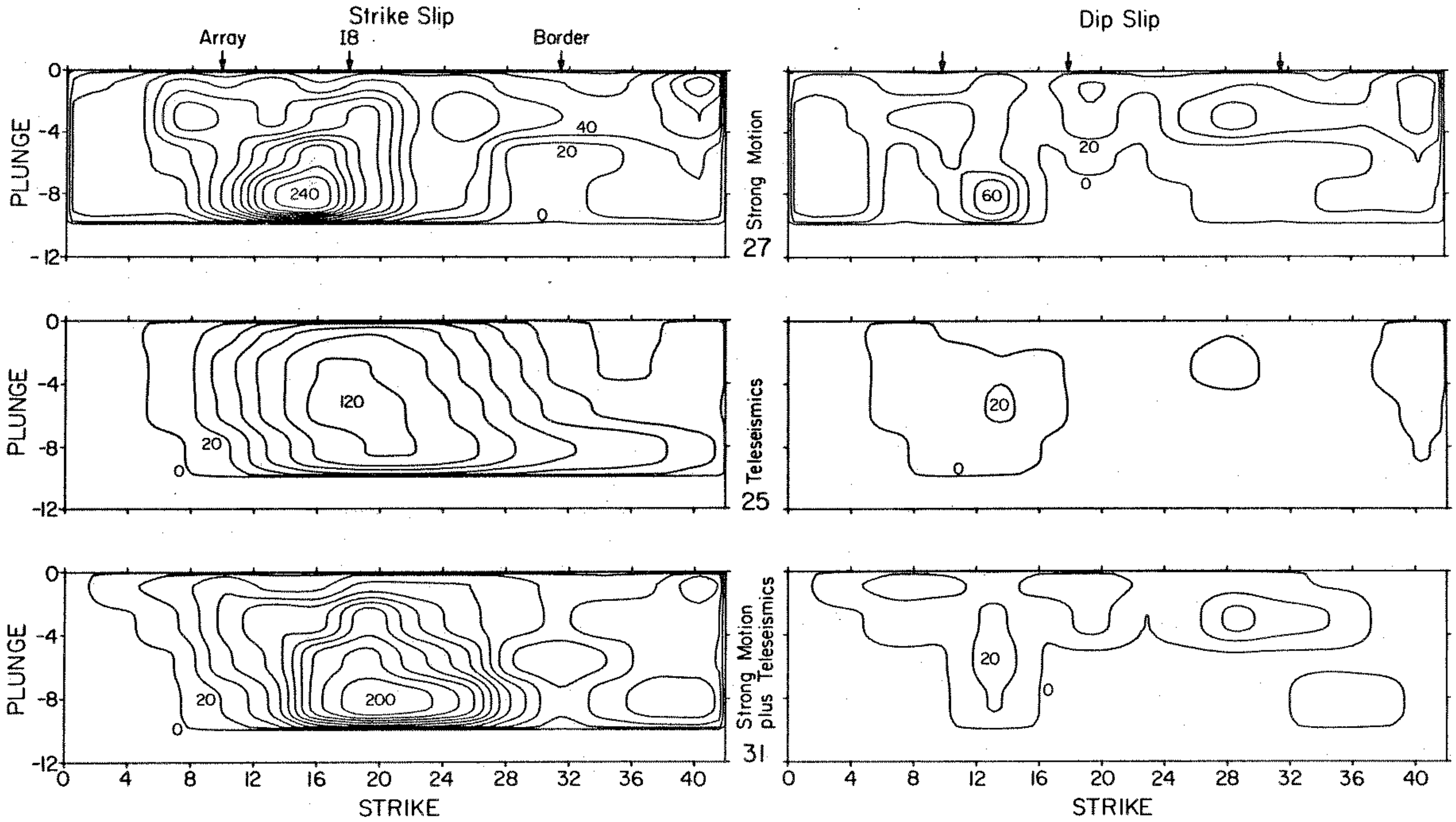


Figure 3.18. Contour of dislocation (cm) on the Imperial Valley fault plane for the 1979 Imperial Valley earthquake as inferred from inversion of: i) strong motion data alone, ii) long-period teleseismic body waves alone, and iii) combined data sets of teleseismic body waves and strong motion data. (Hartzell and Heaton, *Bull. Seism. Soc. Am.*, 1983)

As these examples demonstrate, the capability for real time determination of source parameters would significantly contribute to overall reduction of hazards caused by earthquakes. Also, quick retrieval of quantitative information on the main shock would provide adequate guidance for various scientific experiments to be conducted during the post-seismic period. The proposed global network provides this capability.

3.2.6. Relationship to Local and Regional Studies

The estimation of seismic source parameters with broadband global data provide data complementary to several types of investigation traditionally termed local or regional studies. The addition of real-time monitoring from teleseismic range offers the new possibility for directing such studies into areas of interest otherwise unseen. In seismically active areas not served by local ($\Delta < 10°$) seismographic networks, the source parameters derived from the proposed global network data will provide first-order descriptions of seismicity patterns and general seismic tectonic relationships. Time-varying patterns of local seismicity or source parameters (depth, mechanism, stress drops) can be monitored teleseismically above, roughly, a magnitude five threshold (see Section 3.2.1 and Figure 3.9). Most of the world's great earthquakes occur in seismographically remote areas, and the higher order source properties, fundamental to techniques for predicting strong motion, will be available only through the analysis of the proposed global network data.

Source parameters estimated from teleseismic data represent predominantly radiated seismic wave energy at frequencies less than 2 Hz. Local network data are in the 2–20 Hz range, while regional data are typically of less than 10 Hz bandwidth. Source results for the same event are often contradictory, pointing up shortcomings in modeling methods (e.g., the Mammoth Lakes earthquakes of 1980). Interpretation of the proposed global network data with local and regional data can provide better constrained source parameters for earthquakes and explosions.

Many local and regional source studies require the use of large mobile arrays of portable seismographs. The real-time monitoring feature of the proposed global network offers a level of guidance for efficient deployment of the large mobile arrays of up to several hundred elements planned for aftershock sequence studies on intensive earthquake prediction investigations. Rapid evaluation of the source parmeters is important not only to seismic studies of post-earthquake effects, but also for geodetic measurements (*Geodetic Monitoring of Tectonic Deformation — Toward a Strategy*, NRC/NAS, 1981).

One of the more important current problems in seismology is the estimation of ground motions during damaging earthquakes. Although near-source accelerometer recordings provide the primary data source in this field, many important damaging earthquakes are not well recorded in the near-source region. This has particularly been true for very large subduction zone earthquakes and for earthquakes located away from recognized plate boundaries. These earthquakes include both the largest (1960 Chile, $M_w = 9.5$, 1964 Alaska, $M_w = 9.2$) and the most damaging earthquakes (1976 Tangshen, 500,000 deaths) in recent history. In recent years there has been growing concern that the northwestern U.S. may be susceptible to great subduction zone earthquakes and that the eastern U.S. is susceptible to potentially devastating intraplate earthquakes. Because near-source recordings of these types of earthquakes are rare, seismologists have turned to careful studies of teleseismic waves observed for these earthquakes. Since earthquakes radiate energy in all directions it is necessary to have information at many azimuths and distances to completely characterize the seismic source, even if near-field data are available.

Since teleseismic waveforms contain information in the frequency band of interest to structural engineers, important constraints on the nature of strong ground motion can be derived from teleseismic records. Of course it is important that these teleseismic records be consistent with meaningful interpretations of earthquake sources that have been well recorded in the near-source region. Figure 3.18 shows detailed source models of the 1979 Imperial Valley earthquake as inferred from both strong motion recordings and teleseismic body waves

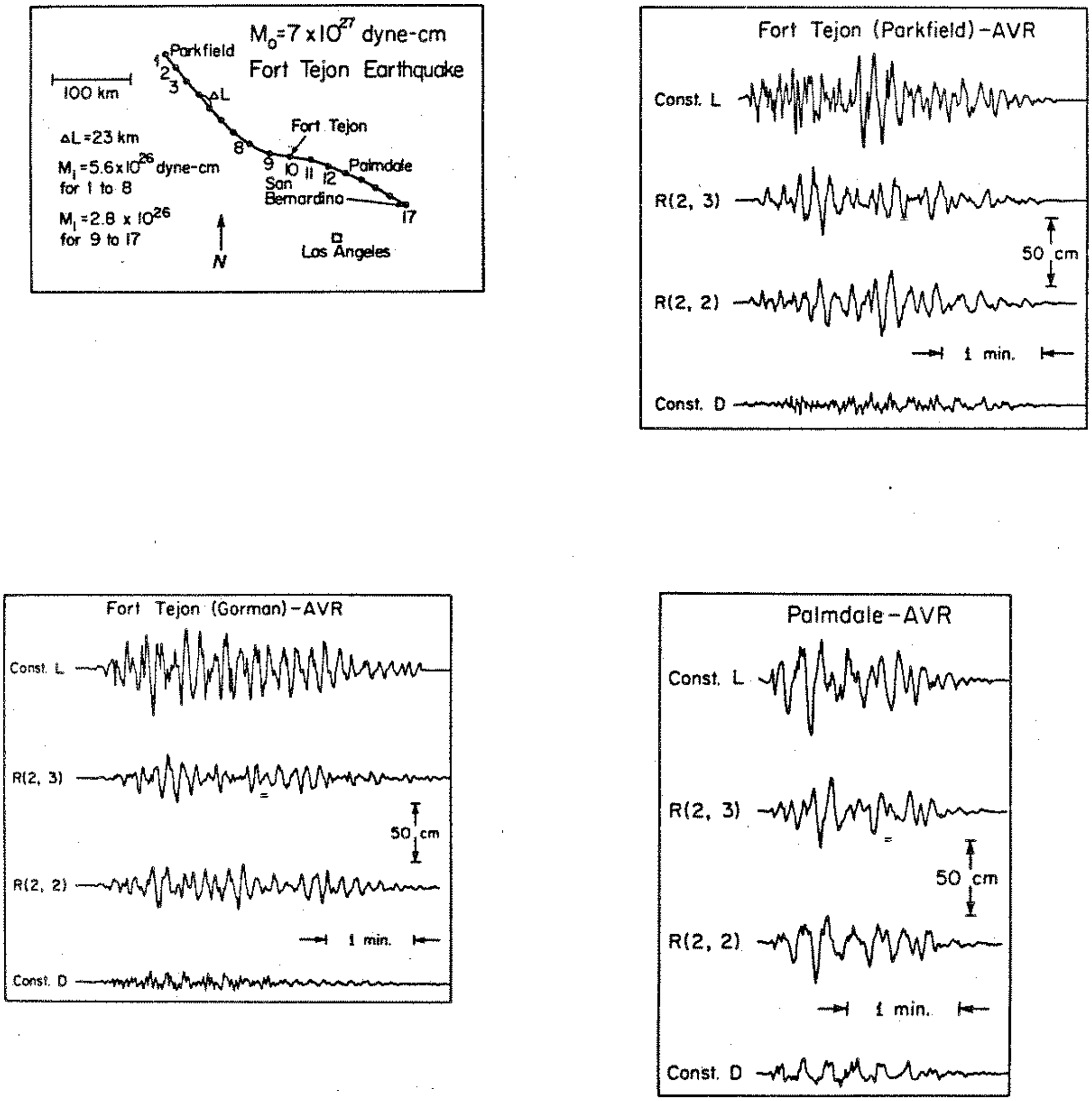


Figure 3.19. Simulation of strong ground motions in metropolitan Los Angeles from the repeat of an 1857-type San Andreas earthquake. The model is based on a characterization of the source complexity for the 1976 Guatemala earthquake as inferred from the study of teleseismic body waves. (Kanamori, *Bull. Seism. Soc. Am.*, 1979)

recorded on WWSSN long-period seismometers. This study demonstrates that source characteristics important to the estimation of strong ground motion can be recovered from teleseismic waveforms.

In a related, but different type of study, the nature of strong ground motion to be expected in the metropolitan Los Angeles region due to the expected repeat of an 1857-type great earthquake on the San Andreas fault has been estimated. The nature of source complexity to be expected from great strike-slip earthquakes has been inferred from teleseismic recordings of the 1976 Guatamala earthquake, another great strike-slip earthquake. This characterization of source complexity was, in turn, used to construct the synthetic strong ground motions that might be expected from a great San Andreas earthquake. Figure 3.19 shows the assumed source geometry and resulting ground motions.

Although this type of study is still relatively new, it shows great promise for inferring the nature of strong ground motion from great earthquakes. Having broad-band, high-dynamic-range teleseismic recordings of important earthquakes will greatly enhance our ability to understand characteristics of seismic sources that are relevant to strong motion estimation.

In the last decade, several studies have suggested that earthquake stress drops vary systematically with tectonic setting. It appears that shallow subduction zone earthquakes have average stress drops of about 15 bars, whereas interplate strike-slip earthquakes may have average stress drops of about 30 bars, and earthquakes removed from plate boundaries may have average stress drops as high as 60 bars. In most models of the seismic source, the amount of high-frequency radiation is controlled by stress drop. This implies that strong ground motions of earthquakes occurring away from plate margins (such as might be expected in the eastern United States) may be surprisingly intense. Although this is an important problem, there are still many uncertainties involved in the calculation of stress drop. These uncertainties will be removed only by careful analysis of broad-band teleseismic waveforms.

Another problem of great importance is the estimation of temporal variations in seismic risk. The notion that earthquakes occur in seismic gaps has received general acceptance in the last decade. In principle, the seismic gap theory allows us to identify times of higher risk by recognizing temporal variations in seismicity. Unfortunately, actual application of the seismic gap theory to the real earth often leads to severe ambiguities. The identification of gaps requires a good knowledge of the source dimensions of adjacent earthquakes. Furthermore, the identification of temporal variations in seismicity is greatly complicated by temporal changes in the way in which world-wide earthquakes are recorded and quantified. A well calibrated system that records ground motion over a broad band is essential if we are to make further progress in the problem of identifying spatial and temporal patterns in the occurrence of earthquakes along plate boundaries. Indeed, as stressed in the NAS report, "Effective Use of Earthquake Data," 1983

> "It is clear that with the development of high dynamic range, broadband digital seismic systems, the distinction between strong-motion recording and sensitive high-gain seismic recording is disappearing. This means that earthquake engineers and seismologists soon can share a common seismic data base for their respective applications ..."

3.3. Earth Structure Problems

Approximating the Earth as a spherically symmetric body has been very successful in satisfying a large body of geophysical data. Division of the Earth into shells of distinctly different properties is one of the major accomplishments of seismology, but — in the conceptual sense — identification of the principal regions in the earth's interior was almost completed in the late 1930's with the discovery of the inner core by Lehman, publication of the P- and S-wave speed profiles by Jeffreys, and derivation of density models by Bullen. An important exception was the elucidation of the fine structure of the upper mantle presented in the 1960's. What has taken place since can broadly be described as a process of refinement. Other results, however, such as the studies of attenuation and anisotropy, have added a new dimension to our image of the Earth's interior. Derivation of density profiles through inversion of normal mode data provided an independent confirmation of the validity of the assumption of adiabaticity for most of the lower mantle and outer core.

Delineation of the structure near major discontinuities is particularly important for understanding of the petrology and dynamics of the Earth. The major questions are those of the chemical and thermal regimes, both relevant to addressing the problems of the scale and driving forces of geodynamic processes. Interpretation of the structure in the vicinity of these regions from seismic data is particularly complex because the most commonly used asymptotic approximation of seismology, the geometrical ray theory, either breaks down or is impossible to apply. Quantitative use of waveforms is the only way to achieve progress. While there have been significant developments in the methods of construction of theoretical seismograms, the lack of sufficiently good data, both in coverage and in breadth of the frequency response, has limited full application of these methods.

Another complicating factor, particularly in studying structure of the upper mantle, is the effect of lateral heterogeneity. Indeed, the lateral heterogenity in the outermost regions of the Earth is so significant that a radially symmetric model must be considered a mathematical abstraction, and interpretation of the data must allow for the fact that the radial earth structure varies as a function of position.

The study of lateral heterogenity is one of the principal reasons for the establishment of the new global network and development of a large number of portable digital seismometers. Seismology offers the highest resolving power of all geophysical methods and, consequently, the greatest potential for delineating the details of the internal structure of the earth. This, for instance, accounts for the leading role of seismology as a commercial exploration tool as well as being the only technique that allows us to resolve the structure of the inner core. This example indicates the range of scale for which seismological experiments may be designed.

There are two principal reasons for studying lateral heterogeneity. One is related to the needs of seismology itself: the earth is an imperfect lens which distorts the image of a seismic source. By correcting for the effect of lateral variations, one obtains a better estimate of the source parameters. Although seldom stated explicitly, the other principal goal amounts to an attempt to map convection in the mantle. Comparison of recently derived models of lateral variations in velocity at relatively shallow depths (~100 km) and the surface tectonic features indicates that velocity and temperature are well correlated. From comparison of the low-order velocity anomalies in the lower mantle and the corresponding coefficients of the geopotential field there is an indication that perturbations in velocity and density are proportional to each other. Thus, by mapping in three dimensions the velocity field, we may be delineating the instantaneous pattern of convection in the mantle. Even if the image is somewhat inaccurate, it should provide very important constraints on the pattern of flow. With a large set of high quality data it is even possible to map anisotropy in the mantle. This will be an additional powerful constraint on convection.

Since most of the inverse problems in seismology are nonlinear, the imaging of lateral heterogeneity requires a good starting model. Lateral heterogeneity is then treated as a first order perturbation problem. These perturbations are evaluated with respect to a spherically symmetric Earth model. The solutions, in addition to the terms describing the lateral heterogeneity, also allow for a spherically symmetric perturbation to the starting model. In this way, the studies of lateral heterogeneities and the spherically symmetric structure are closely linked; this may be the only procedure which will allow us to obtain an unbiased average structure.

3.3.1. Average Earth Model

Figure 3.20 shows variations with depth of the seismic wave speeds and density in a recent average Earth model. This model was derived by inversion of nearly one thousand observed periods of free oscillations of the Earth and several hundred thousand body-wave travel times from ten different branches.

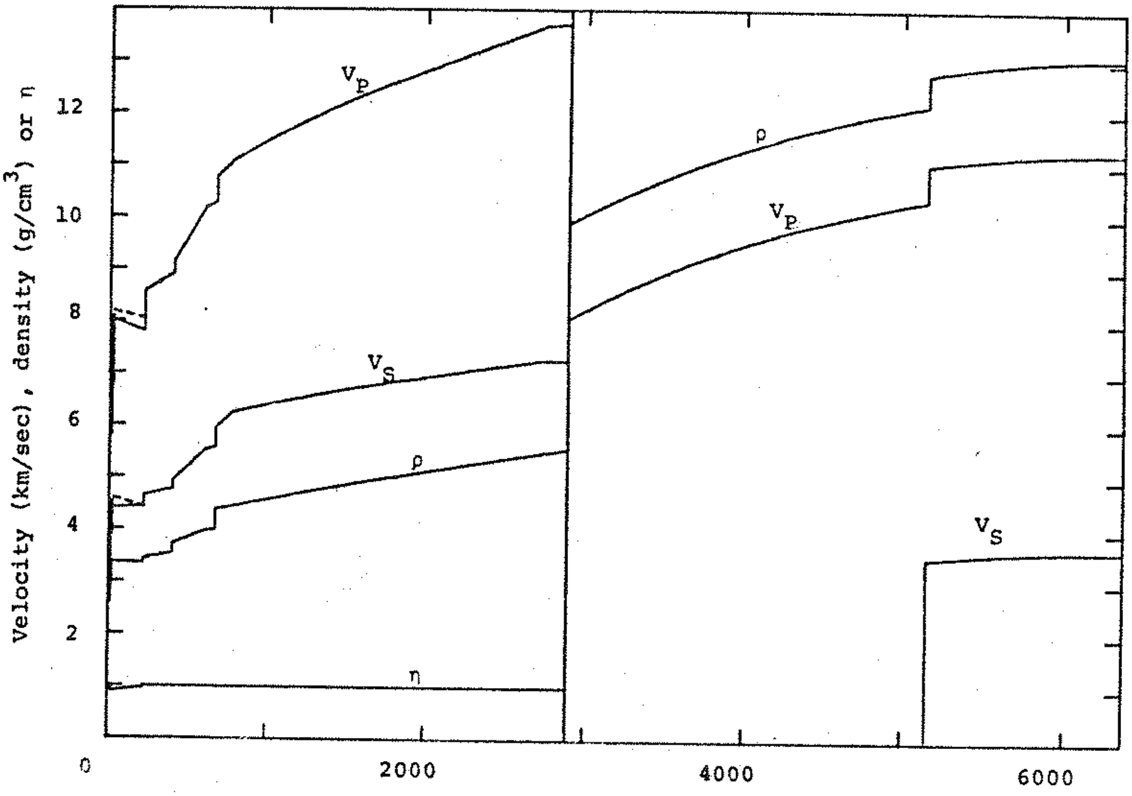


Figure 3.20. The PREM model. Dashed lines are the horizontal components of velocity. Where η is 1 the model is isotropic. The core is isotropic. (Dziewonski and Anderson, *Phys. Earth Planet. Inter.*, 1981)

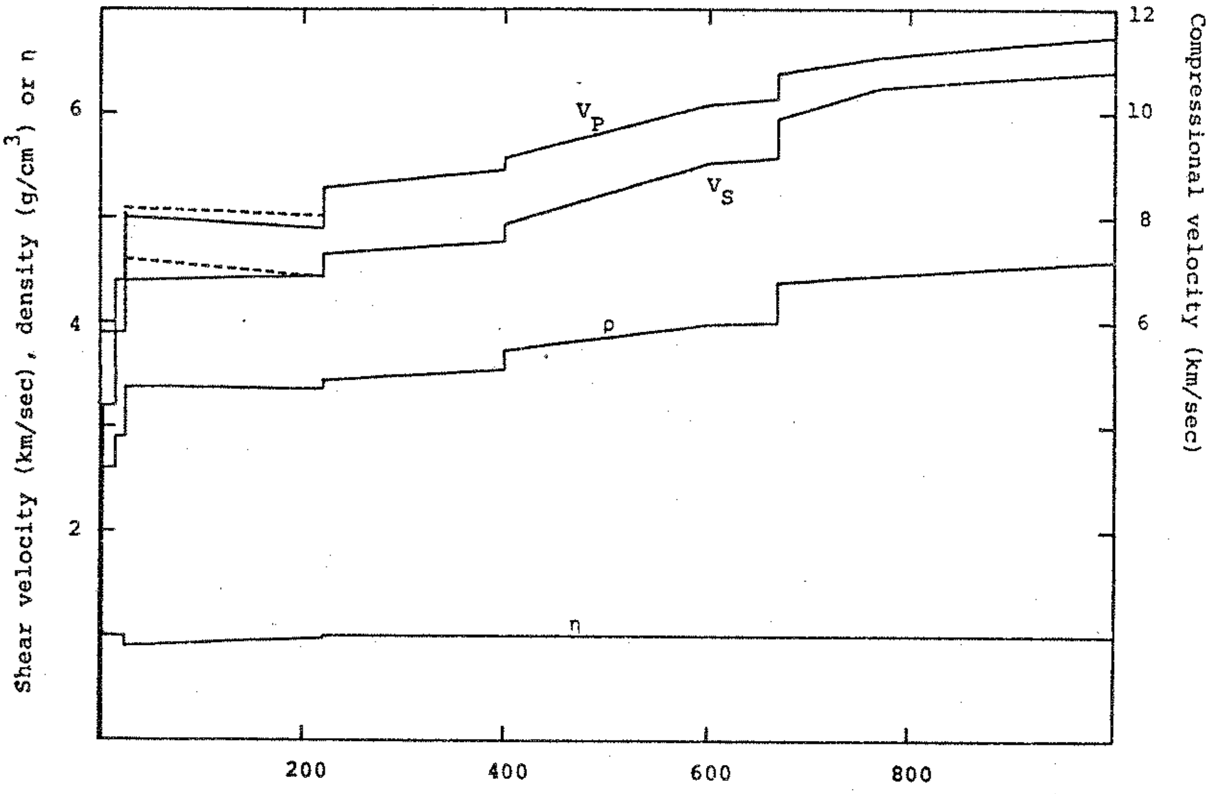


Figure 3.21 Upper mantle velocities, density and anisotropic parameter η in PREM. The dashed lines are the horizontal components of velocity. The solid curves are ν, ρ, and the vertical, or radial, components of velocity. (Dziewonski and Anderson, *Phys. Earth Planet. Inter.*, 1981)

The outermost 700 km of the Earth--the crust and upper mantle--shows the highest degree of complexity; this region is shown in an expanded scale in Figure 3.21. Understanding the fine structure of the upper mantle is important in determination of the thermal regime, chemistry and mineralogy of this region. Petrology, geochemistry and mineral physics are capable of providing additional constraints.

Despite the relative proximity of this region to the Earth's surface, resolution of its structure represents one of the greatest challenges to seismology. There are two primary reasons. First, low velocity zones and discontinuities, or regions of very steep gradient, cause complications in the pattern of wave propagation. In particular, waves with turning points in these regions are generally later arrivals and, as such, are difficult to interpret. The features in a record vary rapidly with distance and dense coverage is necessary to identify the branches correctly and to determine their cusp points. Second, this region of the earth is characterized by strong lateral heterogeneity. This means that, for a fixed source, one must be not only concerned with variation of seismic parameters with depth, but also as a function of distance between the source and receiver. It is likely that major progress in elucidating the fine structure of the upper mantle will come through deployment of portable arrays. Examples of results obtained from data collected by dense regional arrays, such as the Caltech/USGS network in Southern California, demonstrate the potential resolving power of this tool.

While detailed models of the upper mantle should be derived through special experiments, the sparse — in terms of the range of distances involved — global network can be used to verify their applicability on a global scale and to identify anomalous regions.

The broadband instruments of the proposed global network will provide the data needed to determine the radii and sharpness of discontinuities through observations of "underside" reflections and converted phases. Some spectacular results of this kind have been obtained from the broadband stations of the Graefenberg, Germany, array. More detailed discussion of the experiments mentioned here can be found in Section 3.4.

The lower mantle in a depth range from 800 to 2600—2700 km can be modelled by smooth variation of parameters, not inconsistent with the expected behavior of a chemically and mineralogically homogeneous material under adiabatic conditions of temperature and pressure. P-wave speeds are much better known, because of numerous travel-time measurements, than are S-wave speeds. The last 200 km or so above the core-mantle boundary, region D'', is anomalous both in the wave speed gradient of the average model and in the level of lateral heterogeneity. The broadband data from the global array will be most helpful in identifying the anomalous regions and special studies carried out using the portable array array may allow us to determine the radial and horizontal extent of the heterogeneities. From the standpoint of the evolution of the Earth, it is important to know whether the D'' region is chemically or mineralogically distinct or if its anomalous properties are related to a thermal boundary layer at the base of the mantle.

The properties of the Earth's core are not known as well as those of the mantle. One reason is that the outermost 1000 km of the core represents a low velocity zone to P-waves entering the core from the mantle (see Figure 1.1). The first entering P-waves are refracted downward. This region can only be studied using converted S-waves (i.e., SKS, SKKS). Measurements of the travel times of these waves are not very numerous and the available data show inconsistencies. There is an open question regarding the velocity gradient at the top of the outer core. This has important bearing on the question of whether convection in the core is layered. With adequate data the questions of heterogeneity and convection in the outer core can be solved.

Another important observation related to the vicinity of the core-mantle interface is scattering of the waves near this boundary. While this effect has been recognized for some time, relatively little quantitative interpretation has been proposed because of the lack of broadband data. In particular, it is not yet clear whether the primary source of the scattering is the core-mantle boundary itself or the D'' region. Also, relatively little is known about the size of the scatterers. Answers to these questions would be important for better understanding of the process of the formation of the core and the present-day dynamics of this most dramatic boundary within the Earth. The possibility of km-scale undulations of the boundary cannot be addressed with current data.

While the principal features of the structure of the solid inner core and liquid outer core have been obtained using assumptions of the geometrical ray theory, it is clear that further progress will depend on interpretation of waveform data and that broadband data are most needed for this purpose.

An important illustration of the outstanding problems in this region of the Earth is the question of the nature of the inner-outer core boundary and the properties of the outermost 200—300 kilometers of inner core. It has been demonstrated recently that this region is characterized by extremely high attenuation of compressional waves and that there is a steep gradient in the P-wave speed. These findings have led to a suggestion that the inner core, or at least its outermost region, is not solid but it consists of a viscous fluid with the relaxation time increasing with pressure. This hypothesis could be tested by investigating whether the radius of the inner core is frequency dependent. Again, broadband data are needed for this purpose: the most precise current estimates of the inner core radius were obtained using reflections from this boundary recorded by very narrow-band short-period instruments.

It was stated earlier that the model shown in Figure 3.20 was derived in part by using observed periods for nearly one thousand normal modes. There are two principal reasons why these data are important. First, they provide the only independent constraints, other than the mass and moment of inertia of the Earth, on the density distribution as a function of radius. Second, these data are sensitive to the structure of the Earth in regions which are poorly sampled, in terms of horizontal coverage, by the direct path body waves (P, S). In addition, the frequencies of normal modes are sensitive to effects which are not readily identifiable in terms of body waves. For example, the finite shear modulus of the inner core significantly affects certain observed modes, while the J-phase remains elusive. The weakness of the normal mode data is that, unlike high frequency body waves, they cannot resolve the details of the radial structure. For example, the upper mantle discontinuities shown in Figure 3.20 could be smoothed out with, essentially, no degradation of the fit to the normal mode data.

The top 200 km of this model is represented by material characterized by transverse anisotropy. While the details of this representation may undergo modification in the future, it is important to recognize that introduction of this feature allowed for a conceptually important change in representation and interpretation of the low velocity zone. A more general anisotropy may be present.

Most of the currently available free oscillation data were derived more than ten years ago from manually digitized records of the Alaskan earthquake of 1964 and the Colombian event of 1970. Availability of digital data has resulted, so far, only in improvement of the estimates of periods for the fundamental mode branches and relatively few other modes. Application of advanced techniques to the analysis of seismograms from the new network will result in much more accurate data covering a large set of modes.

Observations of attenuation of normal modes forms the basis for the global models of anelastic properties of the Earth at long periods. The most accurate data now available are for the fundamental modes and the gravest radial modes. The dominant effect in attenuation of normal modes is due to the effect of dissipation of the shear energy, although it can be shown that compressional energy must also be dissipated at a finite rate. Resolution of the variation of Q_K with radius will be difficult, since Q_K is at least one and possibly two orders of magnitude greater than Q_μ and the frequency dependence of the latter may not be negligible even in a period range from 100 to 3000 seconds.

Significant improvements in resolution of Q_μ, particularly in the lower mantle, could be achieved through measurements of attenuation of overtones. Current progress, reported in Section 3.3.2 on global resolution of the large wavelength lateral heterogeneity, should be an important element in improving our ability to obtain reliable estimates of Q of overtones, by allowing the application of phase equalization procedures. Other aspects of attenuation of seismic waves in the Earth are discussed in Sections 3.3.3 and 3.4.

3.3.2. Modeling of Lateral Heterogeneity

The surface expression of the earth's dynamics is known in detail, and the overall pattern is well explained by the theory of plate tectonics. It has been concluded that on the time scale of some tens of millions of years the material of the earth's mantle behaves as a convecting fluid, and that the behavior of plates at the surface reflects, in some way, the motions in the interior. The understanding of the nature of the flow in the mantle must be considered one of the primary research goals in the Earth Sciences — to discover the internal workings of our planet.

The inaccessibility of the interior below a depth of some 10-15 km necessitates the inference of conditions in the deep interior from observations at the surface, and of all methods available in the Earth Sciences, seismological techniques have potentially the greatest resolution for the remote sensing of *in situ* material properties.

In recent years the mapping of lateral velocity variations in the earth's interior has become one of the key research areas in geophysics. The long term goal is to provide direct seismic evidence for tectonic and convection processes. Recent studies indicate that this goal is indeed achievable. An essential ingredient of this research is a dense and spatially well-distributed data set of body and surface wave seismograms.

A first step in mapping the lateral velocity variations may be the inversion of the travel times of various phases. This inverse problem has recently been termed tomography because of its similarity to medical X-ray imaging. In the next two sections, two tomographic studies are briefly discussed as examples of this type imaging. Tomographic techniques can be applied to a variety of wave types, geometries and scales.

The next logical step is to invert the amplitude information contained in the seismograms. The final step is to do waveform matching of the entire seismogram. These last two steps would require broadband digital data of the type proposed by the global array. The resulting models provide constraints for the next generation of convection modelling. Large computing facilities will be required for these final steps.

3.3.2.1. Tomographic Inversion of Regional Travel Times

As an example of mapping fine-scale lateral velocity variations with array data, we show a travel time inversion in Southern California. Teleseismic body waves (P, PKP, and PKIKP) recorded on the 200-station Southern California Array have been used to determine the upper mantle velocity structure. The inversion is done by back-projecting the travel time delays along the ray paths. An image of the anomalous regions is formed by compositing approximately 10,000 rays. The blurring of the image that results from non-uniform and non-isotropic ray coverage is substantially reduced by deconvolution with an empirically determined point spread function.

The results show a slab of high velocity material (3% fast) beneath the Transverse Ranges that extends to a depth of 250 km (see Figure 3.22). This anomaly is evidence for the tectonic interpretation that the Big Bend of the San Andreas Fault has been a zone of lithospheric convergence for the last 5 million years. This is the first detailed report of an aseismic slab. It should be stressed that only teleseismic data were used in the analysis.

3.3.2.2. Global Tomographic Inversion of Travel Time Data

As an example of mapping velocity anomalies on a global scale, some preliminary results of global tomographic inversion are given. The lateral velocity variations of the mid- and lower-mantle are determined from teleseismic P-wave delay times. The data are the P-wave arrival times assembled by the International Seismological Centre (ISC) for the years 1971—1980. In all, nearly 25,000 events are used, yielding a ray set consisting of 1.7 million rays in

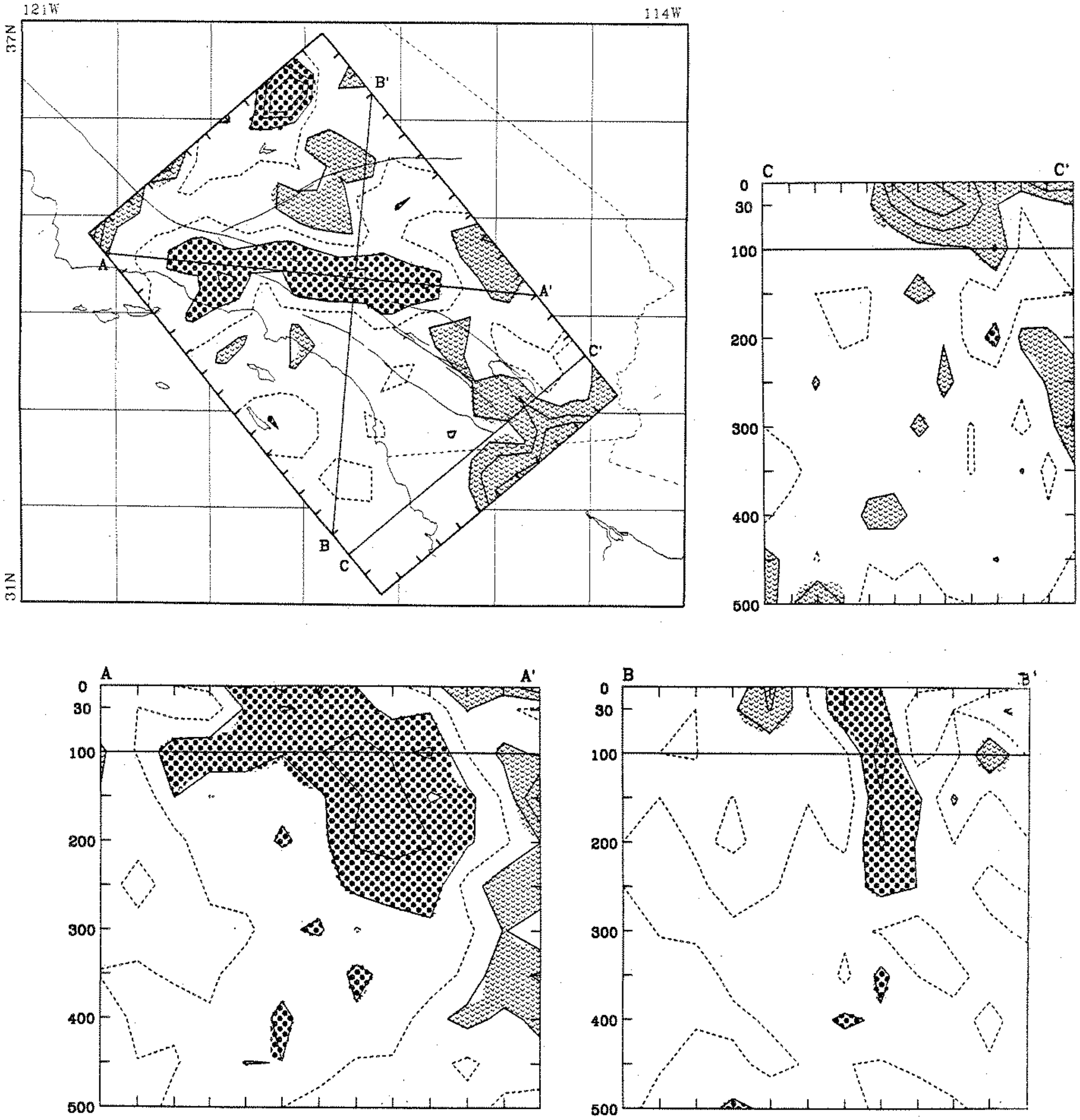


Figure 3.22. Results of the inversion of teleseismic P-delays. In the upper-left panel a horizontal section at a depth of 100 km is shown superimposed on a location map of Southern California. The locations are shown for the three cross-sections (A-A', B-B', and C-C') that are displayed in the other panels. The tick marks surrounding the horizontal section show the locations of the bin centers used in the inversion. All panels are displayed with no horizontal or vertical exaggeration. The contour interval is 1.5% relative velocity deviations with > 1.5% indicated by dotted areas and < -1.5% by the hatched areas. The zero contour is dashed. In the lower-left panel a W ≥ E cross-section (A-A') through the Transverse Range anomaly is shown. In this projection the anomaly appears as a wedge-like feature that is deeper on the eastern side. A S ≥ N cross-section (B-B') through the Transverse Range anomaly is shown in the lower-right panel. The anomaly appears as a slab-like feature that dips slightly to the north. In the upper-right panel a SW ≥ NE cross-section through the Salton Trough anomaly. The anomaly is about 2-4% slow and extends down to 75-125 km. (Humphreys et al., *Geophys. Res. Lett.*, 1984)

the distance range 25—100 degrees.

The inversion method is an adaptation of the Algebraic Reconstruction Technique (ART) used in medical X-ray imaging. The travel time delays are back-projected along raypaths are determined by reference velocity model (the Jefferys-Bullen model in this case). A composite of all the rays forms an image of the anomalous zones. Synthetic examples indicate a high-resolution image can be obtained in many areas of the mantle. The Pacific Ocean at mid-mantle depths, and the south pole near the core-mantle boundary are notable exceptions.

An example of the inversion is shown in Figure 3.23. The results indicate the largest velocity anomalies occur near the core-mantle boundary. Another interesting feature is a region of low-velocity material at 1100 km under the Mid-Atlantic ridge.

3.3.2.3. Waveform Inversion of Low-Frequency Data

The accumulation of long period digital seismic data from the IDA network and the GDSN over the last 6 years has led to rapid advances in our ability to map the Earth's interior. Such studies provide a strong motivation for the creation of a greatly improved digital network.

Significant in this discussion is the question of resolution. Each long period seismogram corresponds to a particular source — receiver combination and yields information about the great circle path which joins them — both the major and minor arcs. By making use of a large number of seismograms one hopes to achieve a dense average of the globe by paths, and it is this density of coverage which governs the amount of detail which can be inferred in the global model. Because the distribution of seismogenic zones is fixed, the achievable resolution depends mainly upon the distribution of seismometers in the global array.

In the construction of the aspherical model to be described here, mantle wave data from both existing networks and 53 large earthquakes were used, yielding some 2,000 seismograms. Although many more events could be selected, they would usually occur in close proximity to one of the original events and would thus give largely redundant information if the network remained the same. This data set represents, therefore, a significant fraction of all available information on mantle wave propagation in the chosen frequency band ($f < 1/135$ Hz).

Data of this kind are sensitive principally to variations in shear wave velocity in the upper mantle, and it was found to be possible to construct a global model expanded up to degree and order 8 in spherical harmonics, and expressed as a cubic polynomial in depth, for the upper 670 km of the earth's mantle. This corresponds to average lateral and vertical resolving lengths of the order of 2,500 km and 150 km, respectively. The model is, thus, a highly smoothed representation of true mantle structure.

Figure 3.24 shows a map of shear wave velocity variations at 100 km depth. Notable here is the extent to which it corresponds with our expectations based upon surface tectonics. All major shield areas are fast: Baltic-Siberian, South African, Australian, Canadian, Brazilian and Antarctic. Slow areas follow the major ridge systems, and the areas of strong back-arc activity of the W. Pacific. It is important to recognize that no prior information is incorporated into the model; the pattern arises purely from the analysis of digital seismograms.

The map of Figure 3.24 corresponds to a single level of the model, and similar maps can be drawn for any depth in the upper mantle. The close correlation with surface features begins to diminish below 200 km. At 250 km many portions of ridges are underlain by high velocities; notable in this respect is the Southeast Indian Rise south of Australia. The back arc regions of the west Pacific are fast at this depth. At 300—400 km depth, ridges are no longer apparent, except for those of the South Pacific and the low velocity anomalies tend to localize in the neighborhood of major hot spots: Red Sea, Kerguelen, Hawaii, Iceland, Tristan da Cunha, together with a low velocity anomaly centered on New Zealand. One of the few linear features remaining at these depths is approximately aligned with the Emperor Seamount chain of the North Pacific.

At greater depths (450—650 km) the model shows little or no resemblance to surface features, and is dominated instead by two large plateaus of high velocity — one encompassing

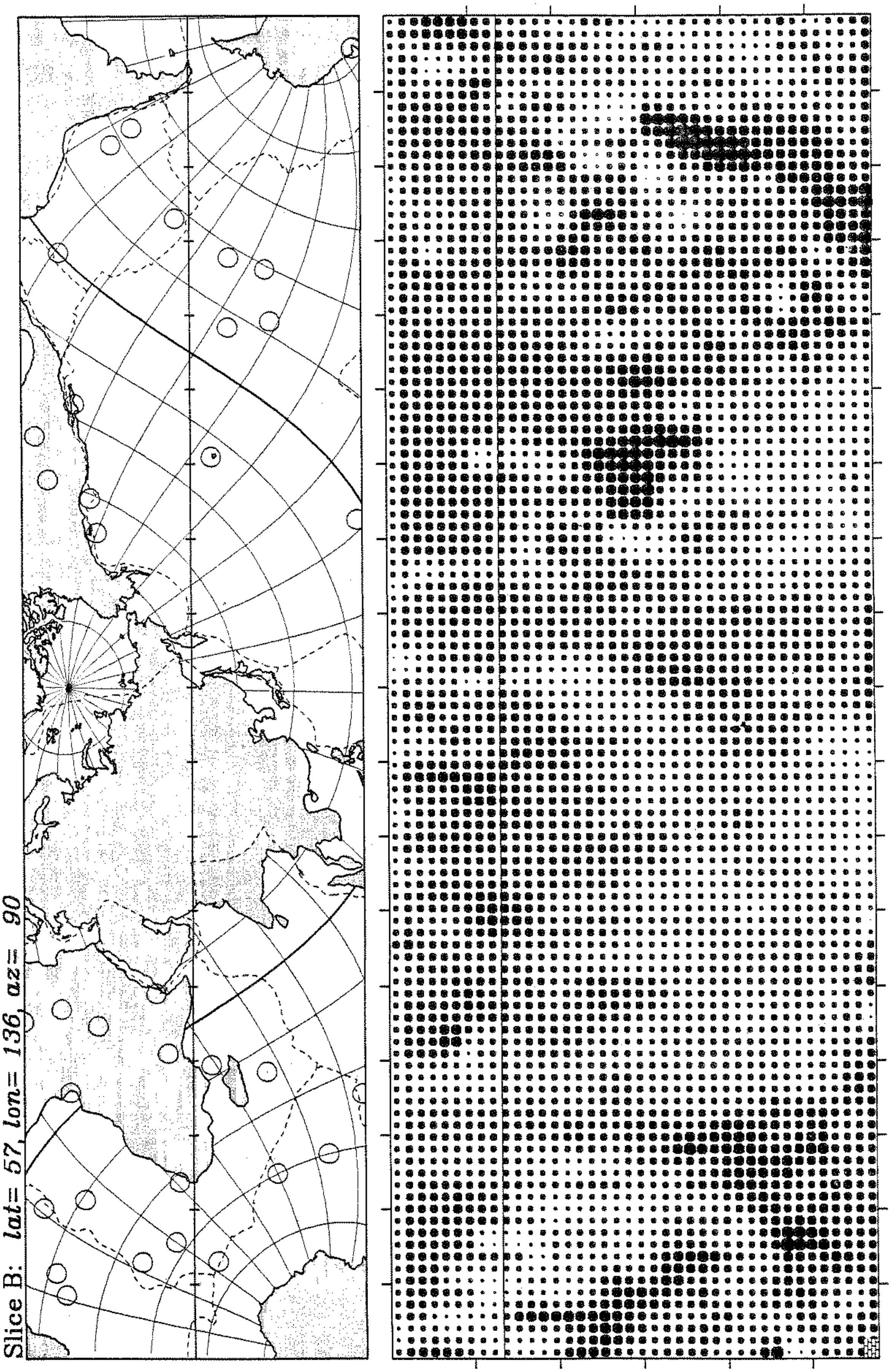


Figure 3.23. Results of the global tomographic inversion of the ISC travel time data. The display is a cross-section of the mantle along the great circle path shown on the map. The top and bottom of the section are the earth's surface and core-mantle boundary respectively. The tick marks on the vertical axis are 500 km apart. The light regions indicate fast velocities, and the dark regions are slow velocities. The open circles are hotspots. (Clayton and Comer, with permission)

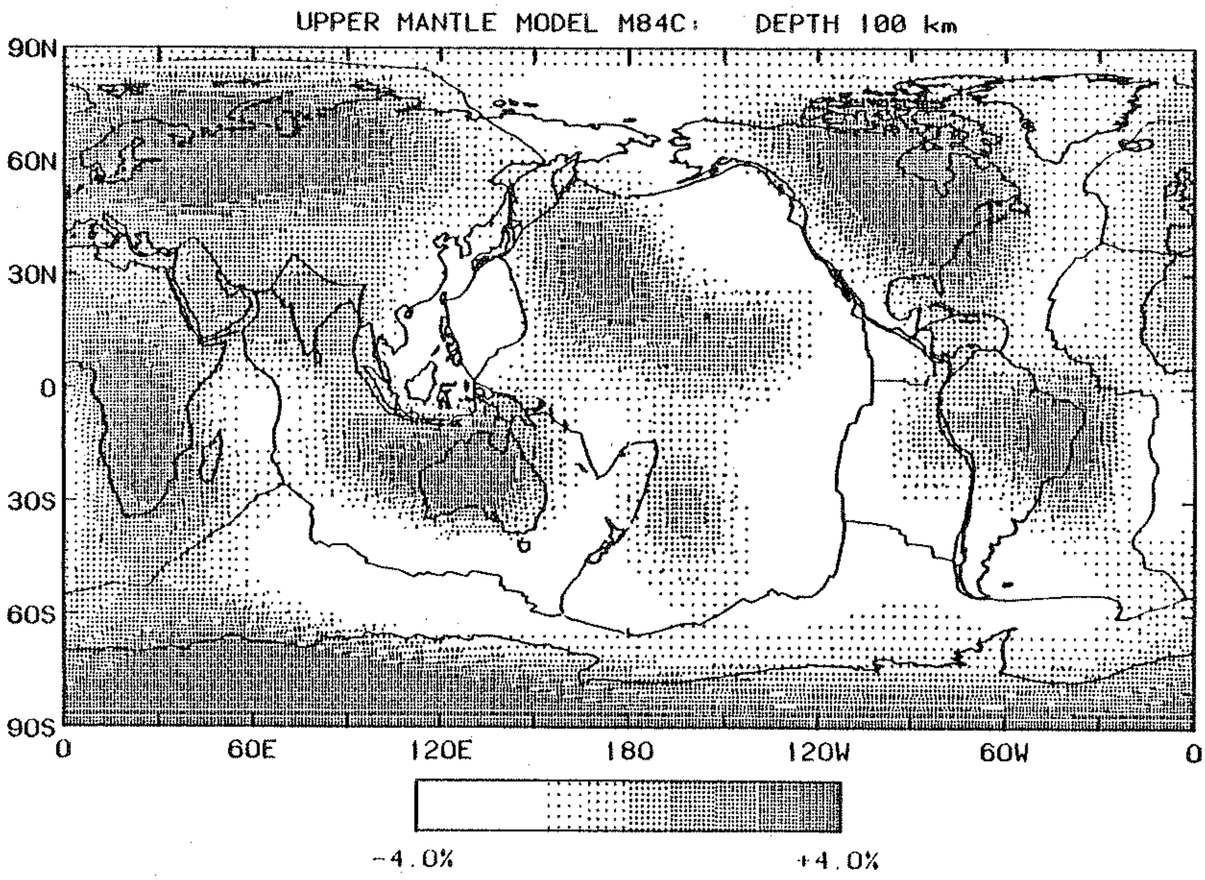


Figure 3.24. A map of heterogeneity in shear wave velocity at the depth 100 km from the model M84C. (Woodhouse and Dziewonski, *J. Geophys. Research*, 1984)

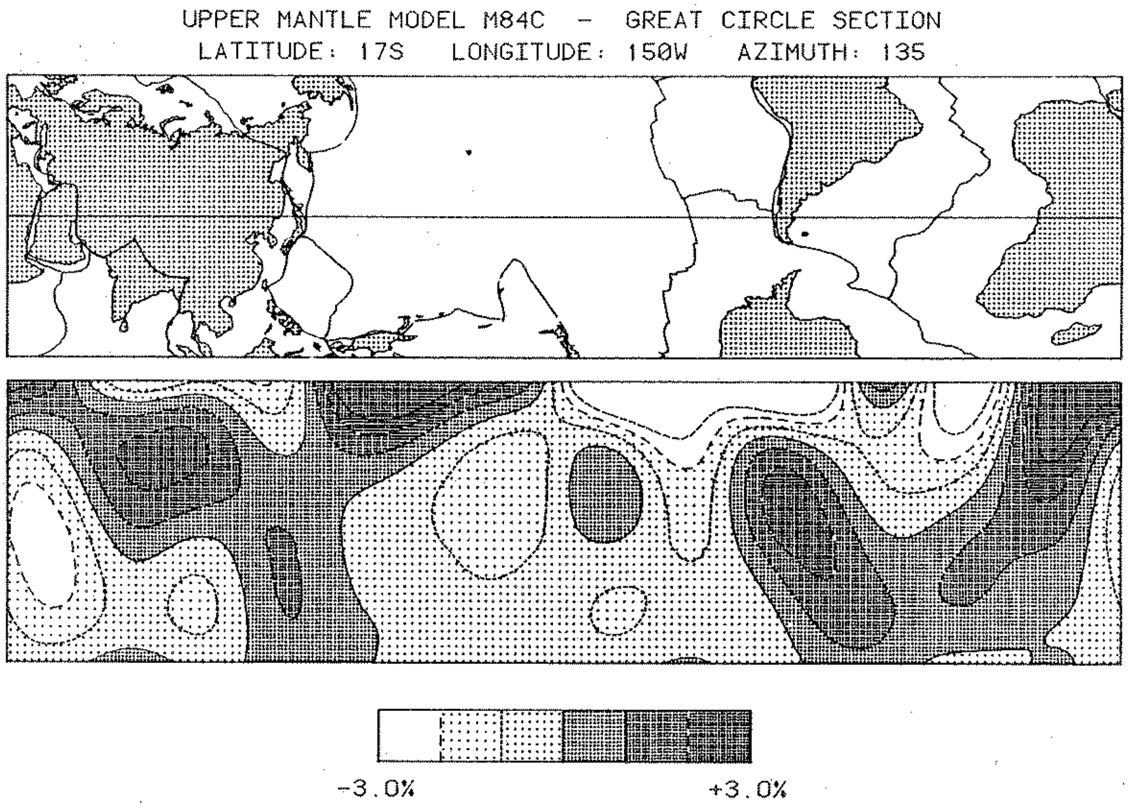


Figure 3.25. A great circle section through the upper mantle model M84C. The center line in the map is the great circle along which the section is taken. Perturbations in shear wave velocity in the depth range 25–670 km are represented. Vertical exaggeration 15:1. See caption to Figure 3.24. (Woodhouse and Dziewonski, *J. Geophys. Res.*, 1984)

South America, much of the south and central Atlantic and parts of West Africa, and the other extending from 50° N to 65° S in the western Pacific. The entire Pacific basin east of the 180° meridian, together with N. America is a region of low velocities, as is the Eurasian continent. The Red Sea remains a localized low velocity anomaly. At these depths there is a strong degree 2 component, in agreement with independent studies.

Figure 3.25 shows a vertical section through the upper mantle model (note the vertical exaggeration of 15:1). The center line in the accompanying map shows the complete great circle along which the section is taken. Features of interest here include the depth extent of the low velocity anomalies associated with the ridges of the southeast Pacific, and the strong velocity gradient near the surface on passing from young to old ocean floor across the Pacific basin. Subduction at the limb of the Asian continent is manifested in a deep high velocity feature. The Atlantic high velocity anomaly at the base of the model, mentioned above, is seen to arise from the union at depth of the anomalies associated with the South American and African continents.

Some improvement in the resolution of heterogeneous structure could be achieved using the available long-period body-wave data, and such work is currently underway, but major progress will require a substantial increase in the number of high quality digital stations. Body wave data will also be needed in studying heterogeneities in the lower mantle.

In recent studies models of lower mantle structure have been constructed using reported arrival times of P-waves. The problem of resolution is particularly acute, since large areas of the globe — particularly the Pacific — are largely devoid of seismic stations. It was found to be possible to obtain stable results in terms of a spherical harmonic expansions up to degree and order 6 and a 4th order polynomial in depth for the depth interval 670—2891 km.

Further progress will require the use of reflected and multiply reflected body wave phases, which will also help to constrain upper mantle structure. These later arrivals are, however, difficult to read on analog records and reliable measurements will require data in digital form. Arrival times may then be "read" by correlation with synthetic seismograms, or other techniques, or models may be constructed by direct modeling of waveforms. The volume of data needed to achieve good global coverage can only be processed digitally, and the success of such studies will depend upon a greatly extended digital network.

3.3.2.4. New Opportunities For Regional Surface Wave Studies

A substantially improved digital network of truly global coverage would open up numerous opportunities for regional surface wave studies. Application of surface-wave dispersion and attenuation theories to regions of dimensions on the order of hundreds to thousands km allows the extraction of both velocity and Q structures down to asthenospheric depth. The detailed characterization of the lithosphere and the asthenosphere is undoubtedly a prime target of seismological research for the future decade, for these two portions of the earth control the most fundamental dynamic process of our planet. On a continental scale, a high-performance broadband digital network with adequate coverage should yield sufficient surface-wave data in a few years for a detailed inversion for both velocity and Q structures. Since surface-wave paths are reasonably well-constrained, the surface-wave dispersion and attenuation data lend themselves conveniently to a tomographic type analysis by which lateral variations of heterogeneity, anisotropy, and Q distribution can be mapped. A detailed 3-dimensional distribution of velocities and Q down to the asthenospheric depth would permit us to delineate the plate configurations, and the details of the low velocity layer. Combined with the anisotropy information, the mapping of convection flows could eventually become a reality.

A sample of this type of regional surface-wave analysis is shown in Figure 3.26 where only six SRO stations in Eurasia are used in conjunction with 43 events. Mainly based on fundamental mode Rayleigh wave dispersion data over the period range from 15s to 250s, it is possible to map the 3-dimensional shear velocity distribution down to a depth of 300 km for the Eurasian continent. Five crustal and upper mantle E-W cross-sections are shown in Figure 3.27 which gives an approximate delineation of the low velocity layer and the distribution of the

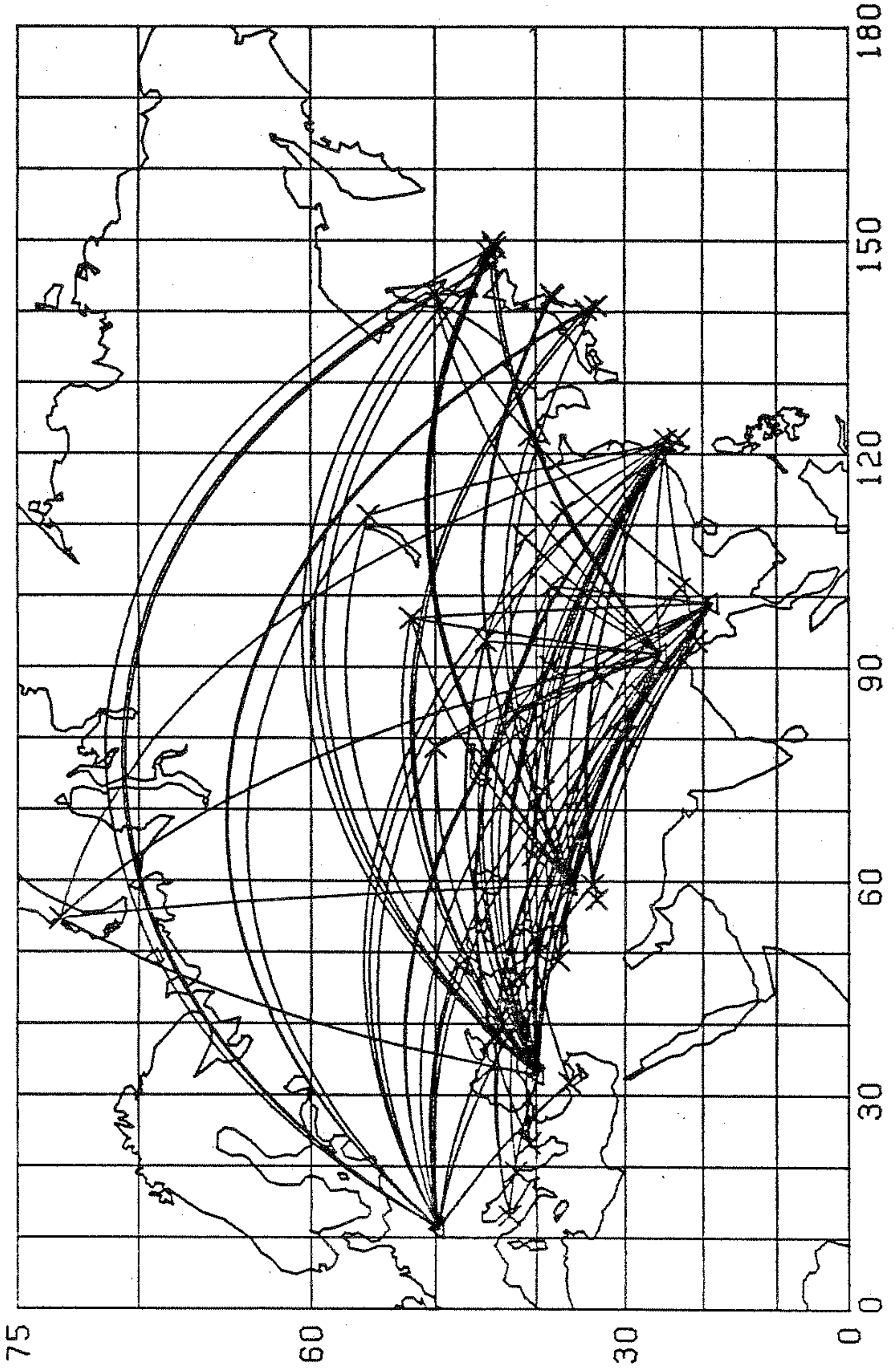


Figure 3.26. Surface-wave paths for 43 events recorded by six SRO stations in Eurasia. Due to the lack of station coverage in northern Eurasia, much of the northern part is under-sampled. (Teng, with permission)

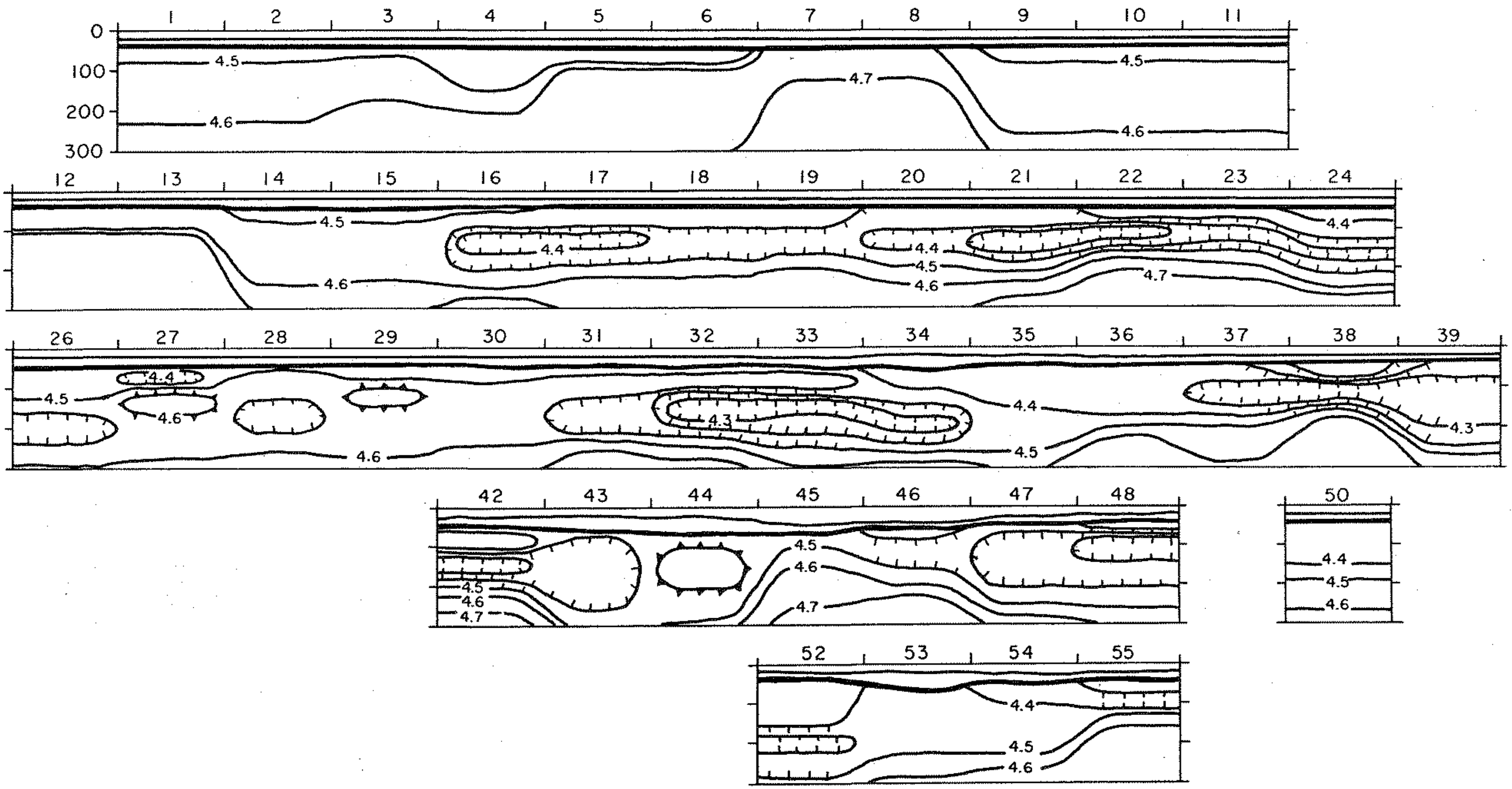


Figure 3.27. Five crustal and upper mantle cross-sections of the Eurasia continent. Vertical scale is in km, horizontal scale is 10° per grid, with the extreme left grid boundary being 10°E longitude. From bottom to top, cross-sections are drawn from 25°N to 65°N latitude at 10° intervals. Low velocity layer is defined by 4.4 km/sec contours, and shield regions by 4.7 km/sec contours. (Teng, with permission)

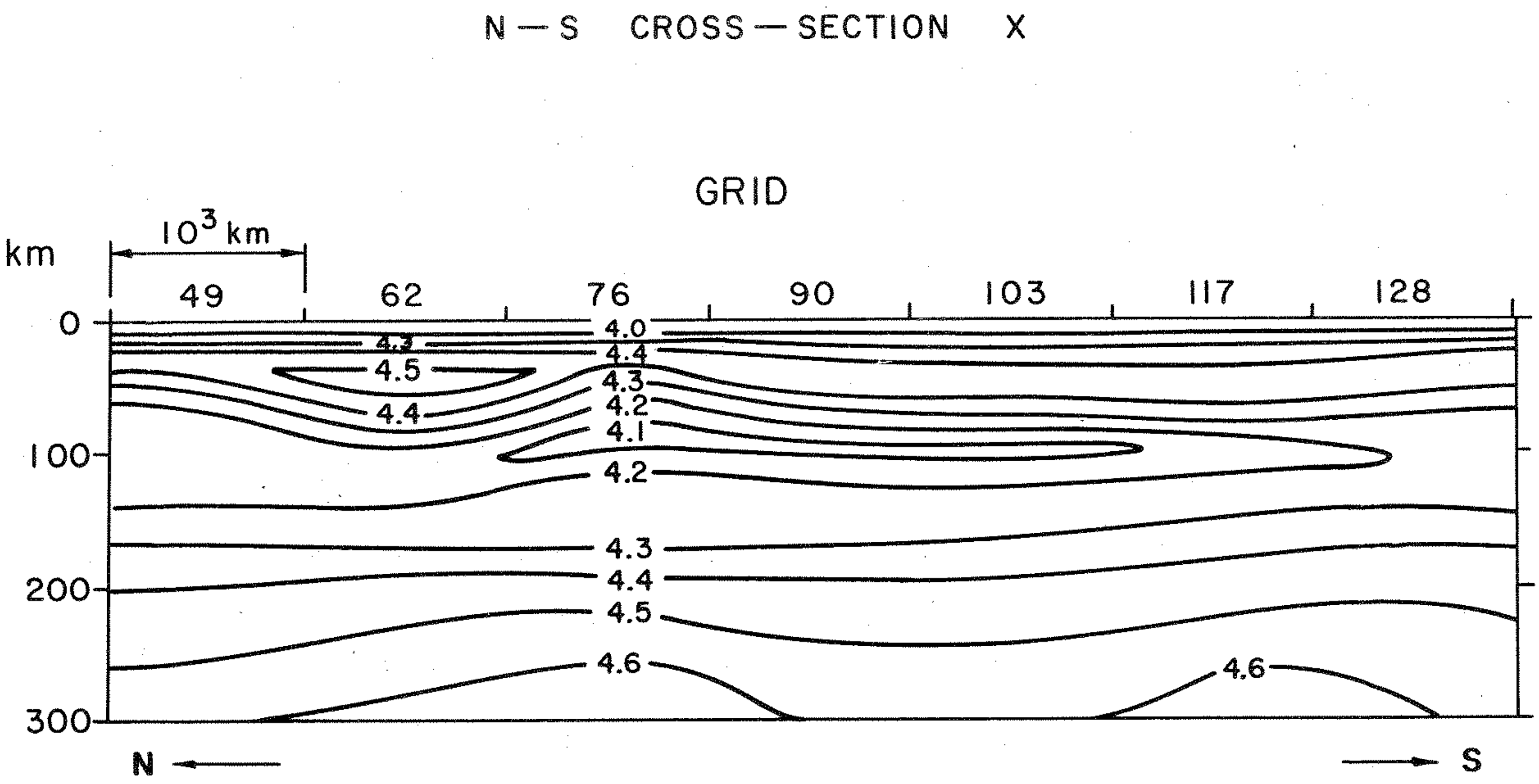


Figure 3.28. A N-S cross-section of the Pacific basin along the longitude 100°W from 20°N to 50°S in latitude. Scales are the same as Figure 3.27. Note the variations in the low velocity layer and the high velocity (4.5 km/sec) layer approximately underlying the Cocos plate. (Teng, with permission)

shield-like upper mantle. A similar approach applied to the Pacific basin not only yields the age correlation with velocity and lithospheric thickness, but also reveals the low velocity nature at the ridge system. Figure 3.28 shows one of the N-S cross-sections from a surface-wave in which only a small number of SRO stations with limited bandwidth and dynamic range were used. It takes little imagination to realize that for a substantially improved station coverage, instrument bandwidth and dynamic range, one would be dealing with a data set of unprecedented quantity and quality: a data set that is capable of yielding information for multi-mode phase and group velocity dispersion, attenuation, and anisotropy, etc. with a precision never before achievable. This precision will certainly translate into a three-dimensional picture of crust and upper mantle.

The same approach of surface-wave mapping can be applied to regions of dimensions much smaller than a continent by simply working on shorter period end of the surface wave spectrum. For close-in mapping, the aftershock sequence of both local or distant main shocks can be used as the source. Figure 3.29 shows schematics of possible field experiments. For efficient execution of these experiments, rapid and accurate determination of aftershock sequence is a necessity. Thus, the proposed real time or near real-time mode of operation of the global digital network will be most useful for rapid instrument deployment in strategic sites for optimal data collection. This short-period surface wave mapping experiment is an example of the combination of real-time capability of the global network with the portability of the instruments for the Lithospheric Seismology Project.

3.3.3. Attenuation Problems

All types of seismic waves lose energy as they propagate through the earth. Those losses may occur because of absorption of energy owing to intrinsic anelasticity of the rock material traversed by seismic waves, by scattering produced by lateral complexities in earth structure, or by some combination of the two.

The attenuation of seismic waves is expressed by most investigators as the specific quality factor for shear waves (Q_μ) or compressional waves (Q_α). Approximate average values throughout much of the earth have been known for several years. It is also known, however, that Q values vary laterally through the crust and upper mantle. This lateral variation is apparent for the mantle from studies of body phases such ScS, from long-period surface waves, and from free oscillation studies. Q variation in the crust is apparent from surface wave studies at short periods and from studies of regional phases, such as *Lg* and S_n. Furthermore, Q varies with frequency in both the upper mantle and the crust, at least in the frequency range above about 0.2 Hz. In addition, the degree of frequency dependence of Q may itself vary from region to region.

The regional variation and frequency dependence of seismic attenuation are consistent with a regional variation in the thermal structure of the upper 200 to 400 km of the mantle. The relaxation spectrum of the earth throughout the entire frequency band of elastic deformations can be explained by the effect of the geotherm on the activation of mechanisms of intrinsic anelasticity (Figure 3.30). Body wave observations indicate that attenuation in the mantle decreases in the vicinity of 1 Hz. (Figure 3.31). The peaked responses of traditional analog short period instruments make the observation of this frequency dependence difficult. The record must be digitized, the instrument deconvolved, and the effects of noise treated. Each of these procedures introduces errors. In the case of WWSSN short periods, useful spectral information can rarely be extracted above 2 Hz. A digital instrument capable of resolving 3 to 5 Hz will be necessary to conclusively resolve the nature of the frequency dependence of attenuation in the mantle. Global deployment of such instruments will also strongly amplify and help delineate regional differences in attenuation and the variations in the thermal state of the upper mantle.

Although much has been learned regarding Q in the earth, its regional variation, and frequency dependence, much more needs to be done. It is possible that the regional variation of Q is related to the tectonic evolution of the crust and mantle. To determine whether there is

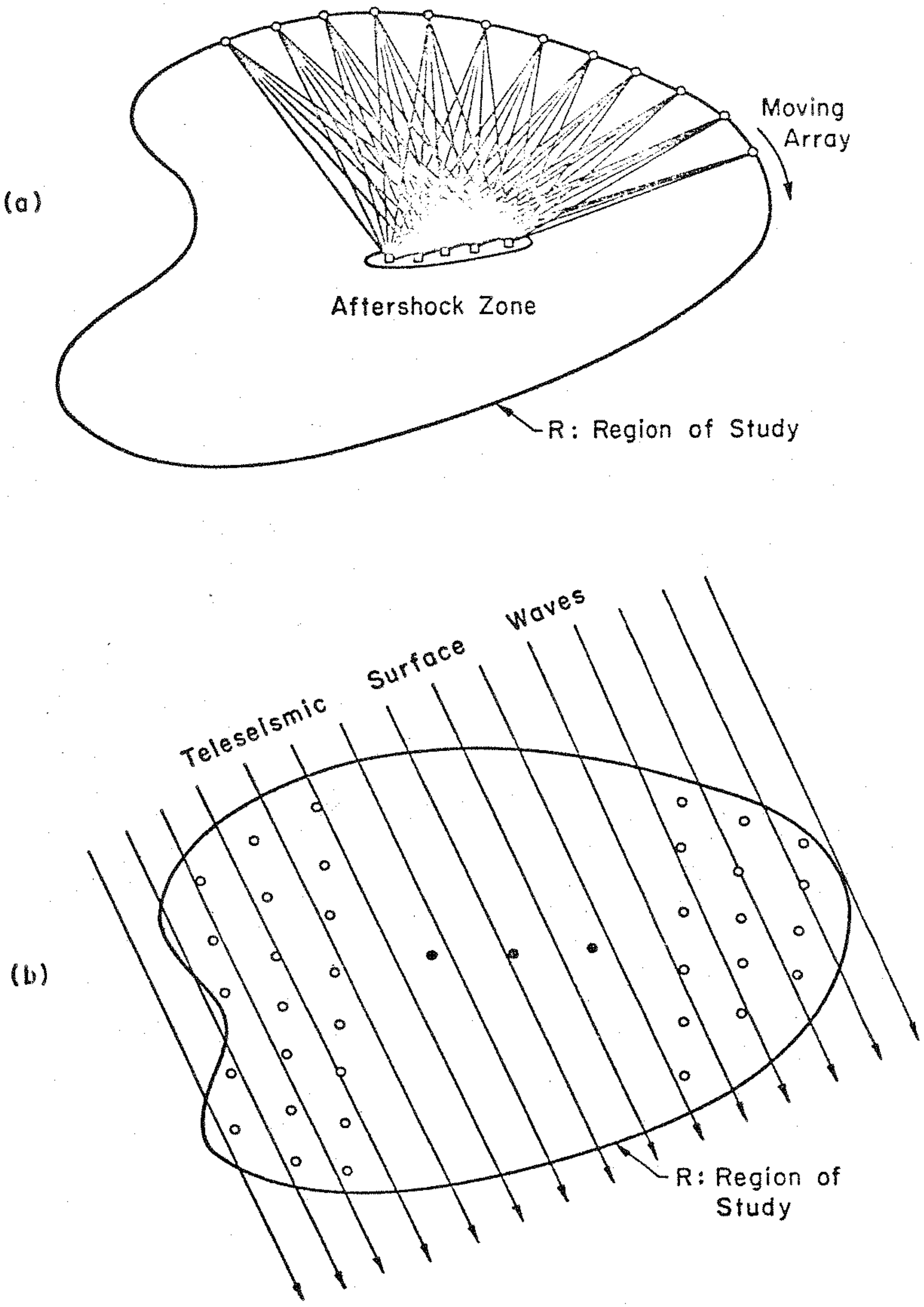


Figure 3.29. Schematics of possible field experiments for short-period surface wave mapping. a) Local aftershocks as sources, b) Teleseismic aftershocks as sources. (Teng, with permission)

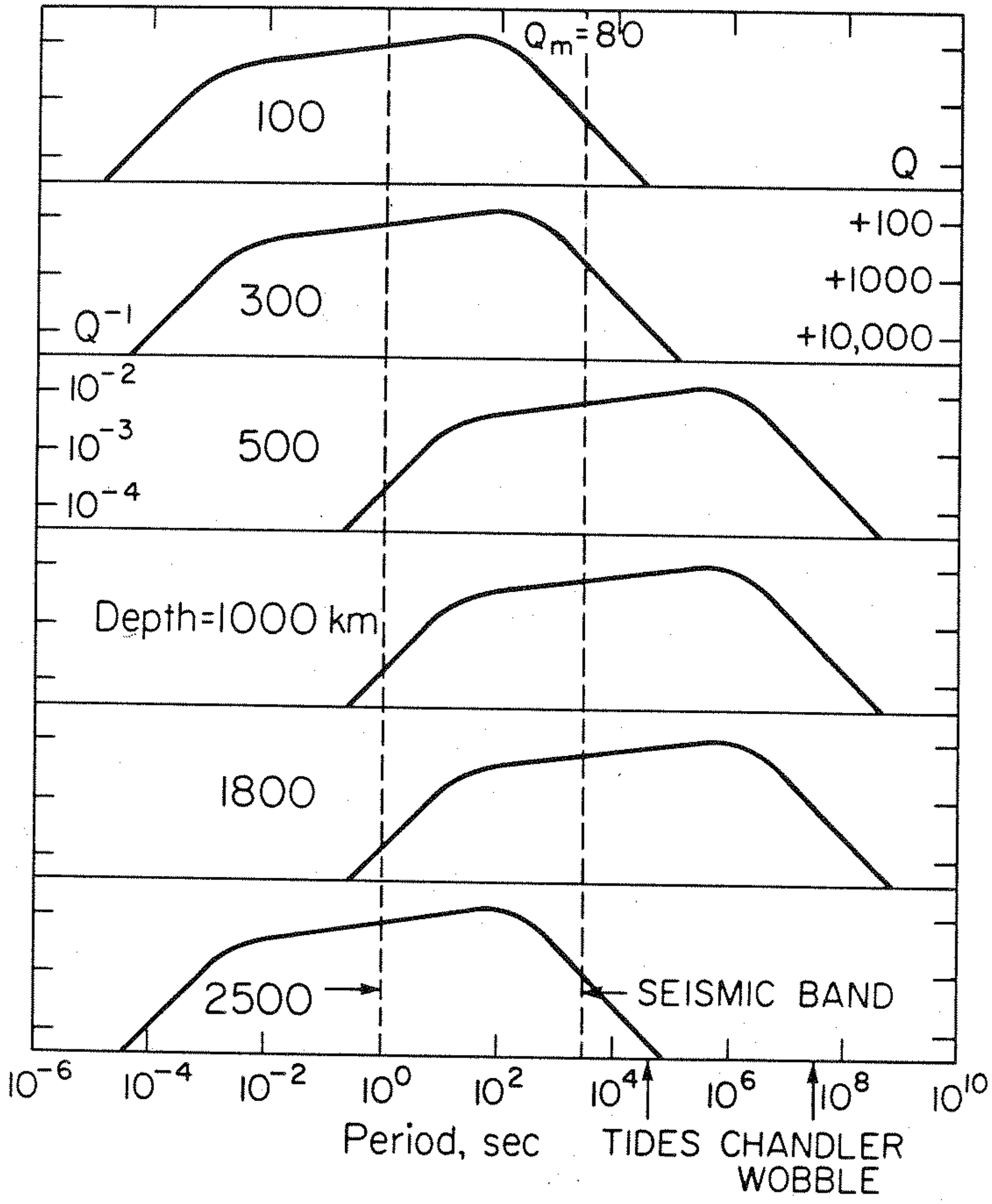


Figure 3.30. The behavior of the seismic relaxation spectrum with frequency and depth proposed by Anderson and Given (*J. Geophys. Research*, 1982).

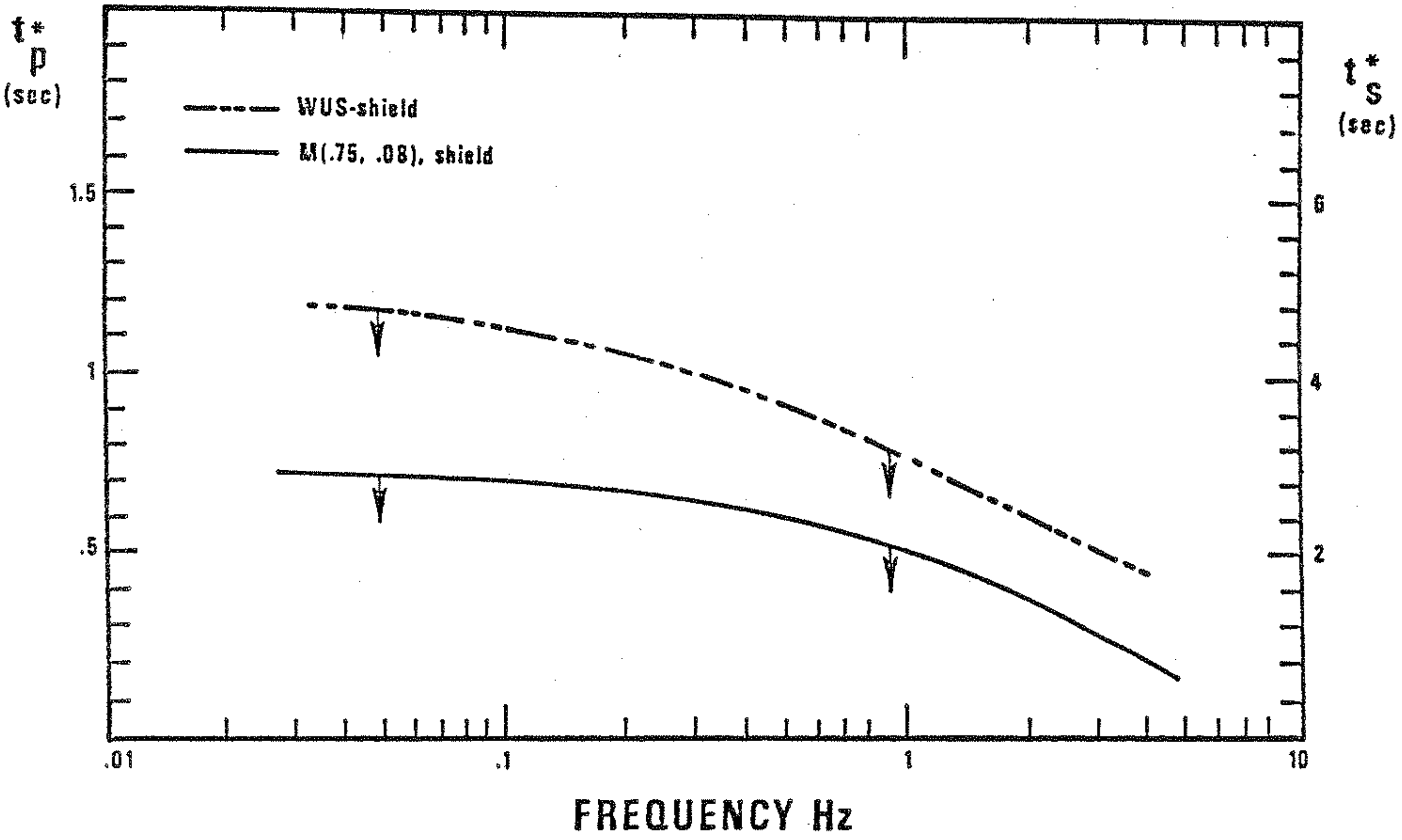


Figure 3.31. The frequency dependence of t_p^* and t_s^* (the path integrated effects of intrinsic attenuation on P and S waves) proposed by Der *et al.* (*Geophys. J. R. Astr. Soc.*, 1982).

such a relationship and to deduce what it is will require an understanding of the attenuating mechanism. If attenuation is due to intrinsic losses, what are the loss mechanisms? If it is due to scattering what are the nature and distribution of scatters? The extent to which intrinsic losses and scattering contribute to seismic wave attenuation probably vary with frequency, with depth, and with geographical location in the earth.

One of the major challenges of seismology over the next several years will be the attempt to sort out the mechanisms which contribute to the attenuation of seismic waves in various regions of the earth. To do so, however, will require broad-band data from instruments with high dynamic range, distributed throughout several diverse tectonic regions of the earth. Thus, research on regional variations of Q and its frequency dependence will be one of the important areas which will benefit from the proposed expanded global digital network.

3.3.4. Studies of Anisotropy

The earth's mantle is composed of anisotropic crystals. Rocks from the mantle show a strong preferred orientation of the constituent minerals, a result of flow and recrystallization. The presence of laminations, sills, dikes and various other fabrics of all scales gives an apparent anisotropy when traversed by seismic waves. Thus, even the crust, composed of relatively isotropic crystals having little preferred orientation, may appear anisotropic to long-period seismic waves because of small scale layering. Seismic anisotropy therefore is expected at all depths and is a powerful constraint on small scale fabric and flow.

It is difficult to separate anisotropy and heterogeneity. The well known discrepancy between Love and Rayleigh waves can be explained by SH-SV or polarization anisotropy. This type of anisotropy can be mapped on a global basis from studies of the velocity of Love and Rayleigh waves. Figure 3.32 shows a map of $(SH^2-SV^2)/SH^2$ at 250 km depth from a recent study. This parameter should be positive in regions of horizontal flow and negative in regions of vertical flow.

The azimuthal variation of Rayleigh wave velocity gives an indication of flow directions. Figure 3.33 shows the fast direction for Rayleigh waves at 200 seconds period. Studies of this type can eventually constrain convection models of the earth's mantle. To be even more useful these studies require a global network of 3-component digital seismometers.

Other manifestations of anisotropy such as SH-SV travel time anomalies, polarization studies and body wave azimuthal dependence require large numbers of well calibrated instruments and detailed modelling of heterogeneity and converted phases.

3.3.5. Relationship to Local and Regional Studies

The integration of the proposed global network with closely-spaced stations for regional and local studies will provide the basic data necessary for seismic imaging of the "whole earth structure." Large-scale resolution, down to 1000 km or so, necessary to examine the lateral heterogeneities by the proposed global network will complement the fine resolution of the crust and upper mantle structure planned for the lithospheric seismology program at scales from a few kilometers (the same scale as heterogeneities mapped on the surface) to several hundred kilometers. Structures with lengths of tens or hundreds of kilometers, anticipated in the deeper lithosphere and upper asthenosphere, are in the transition range between global and regional scale studies and will require co-recording to be resolved—an aspect of considerable importance for the global network and lithospheric arrays that will have a major complementary overlap.

Broadband recording of earthquakes, over 5 to 6 ranges in magnitude, can provide important new data on the space/time variations of source properties on mainshock-aftershock sequences. This will be particularly important to assess source variations as indicators of spatial and temporal variations in the local and regional stress fields. These data can be complemented by precise hypocenter determination and evaluation time relationship between earthquake sources and local heterogeneities (pre-existing faults, anomalous velocity layers, etc.): geophysical parameters critical to earthquake prediction. Further refinement in source-rupture histories

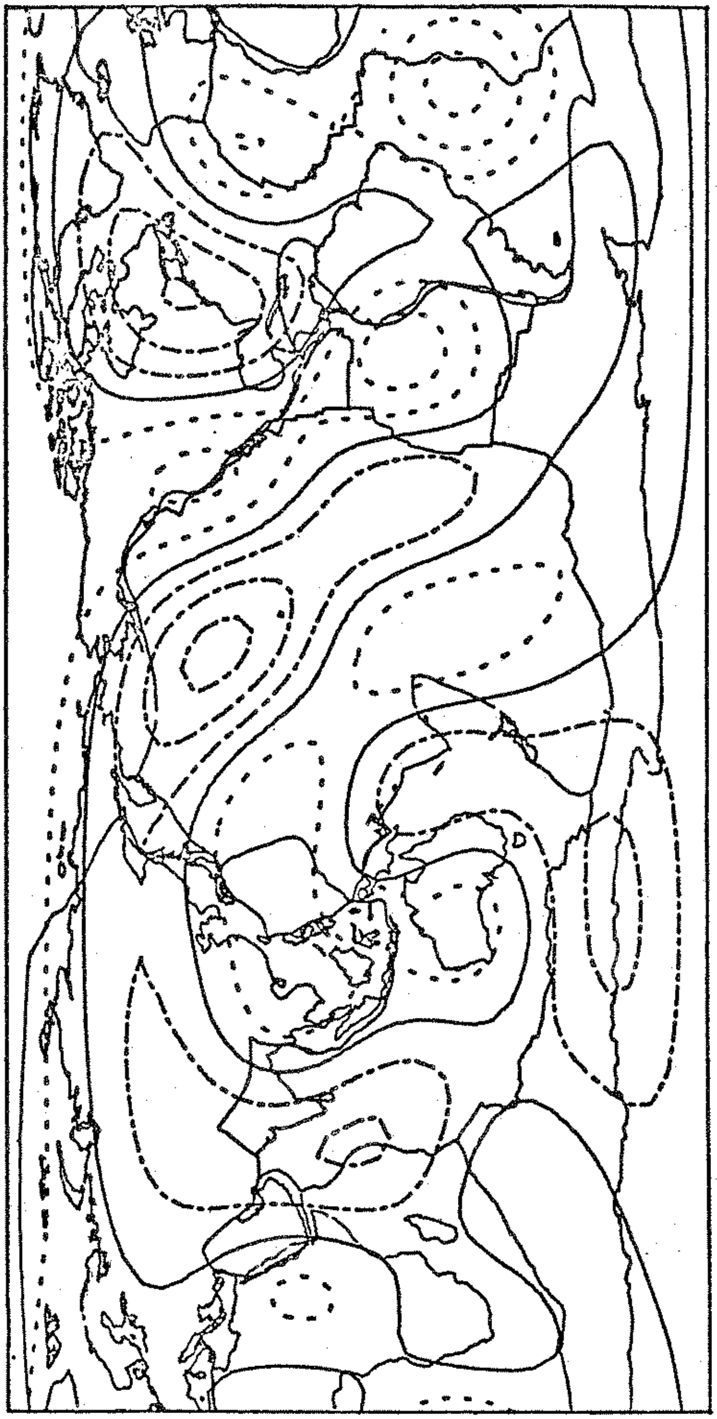


Figure 3.32. Shear wave anisotropy, $(SH^2\text{-}SV^2)/SH^2$, at 200 km depth. Spherical harmonic representation up to $l=m=6$. (Nataf, Nakanishi, and Anderson, *Geophys. Res. Lett.*, 1984)

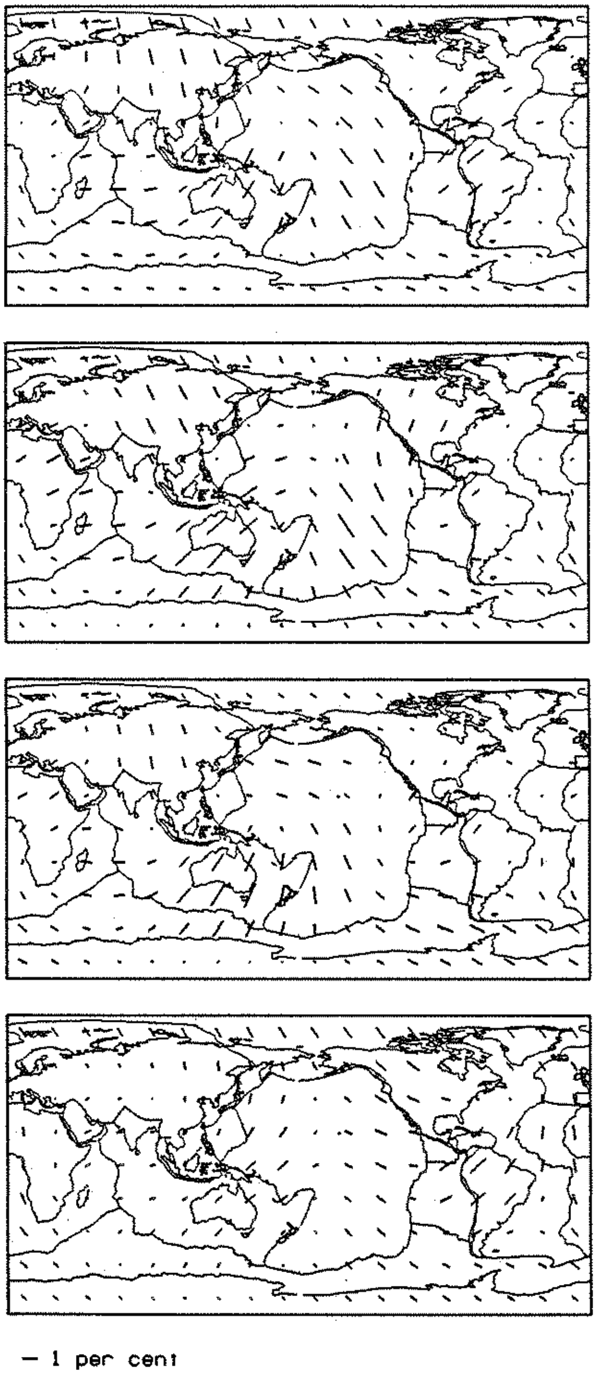


Figure 3.33. Azimuthal anisotropy of Raleigh waves at 100 sec (top), 150 sec, 200 sec and 250 sec. Spherical harmonic representation up to $l_{max} = 3$. The lines are aligned in the fast direction. (Tanimoto and Anderson, 1984)

and time-variations in velocity structure, determined from accurate source modeling, will be important to regional studies of seismicity. Space-time evaluations of earthquake patterns appears to be a critical feature of prediction analysis. With the integration of global data and detailed lithospheric data, accurate and long term seismicity trends can be evaluated.

The broad coverage at global scales heretofore unobtainable with the expected higher resolution of the global digital network can delineate asthenosphere and lithosphere structure anomalies and unusual earthquake sequences. These anomalous features can then be targeted for detailed studies using the lithospheric-scale arrays of portable digital instruments.

All the above ideas embody the concept of scale-variable seismological studies of the entire earth where widely spaced global stations provide gross structure on a global basis and source properties of large earthquakes and the closely-spaced stations targeted at regional and local lithospheric problems can provide the necessary coverage for detailed earthquake analyses, evaluation of lithospheric structure, and resolution of shallow structure.

3.4. Special Problems in High-Frequency Seismology

It was pointed out in Section 3.1 that seismology entails the study both of earthquake sources, and of the characteristics of seismic wave propagation in the earth. Because the presence in a seismogram of a signal of a certain size is a product both of source and propagation effects, explanation of that signal is liable to be nonunique. Uncertainty is reduced by studying many sources at many distances, and across a range of frequencies. But substantial uncertainties remain, particularly in the explanation of signals at frequencies above 1 Hz.

3.4.1. Fine Structure of the Upper Mantle

Studies of the waveforms of body waves indicate that rapid velocity increases occur at 400 and 650 to 700 km depth. These velocity increases generate a double triplication in the travel time curve of P and S waves in the 10° to 30° range (Figure 3.34). The triplications are best observed over the range in which the reflection from the transition zones is total (Figure 3.35). In this range, the time separation of the different branches is less than 10 seconds. To resolve the branches, observations must be made at frequencies higher than 0.2 Hz. This problem in resolution makes it difficult using long period data to rule out the existence smaller scale (less than 2%) velocity increases between 400 and 700 km depth. Models based on long period data may simply map these fine scale features into a steeper smooth gradient between 400 and 700 km depth. Short period data can be used to resolve the upper mantle triplications. Digitally recorded data can be used to extend these studies into as high frequency band as it is still possible to model deterministically properties of the source and propagation medium.

3.4.2. The Sharpness of Transition Zones

Small features of radially symmetric velocity models have profound consequences for the dynamics of the mantle, limiting the possible modes of mantle convection and constraining models of the early chemical differentiation of the whole earth. An example of such a feature, is the sharpness of the velocity transitions at 400 and 700 km depth. Do these increases take place over 50 km depth, 5 km depth, or discontinuously? If the transitions occur discontinuously, or over a zone less than 5 km thick, then it is difficult to explain the velocity profile without having a compositional change as well as phase change at 700 km depth (Figure 3.36). A compositional change would be evidence in support of a system of convection in the upper mantle separate from that of the lower mantle. Long period studies can only conclude that the velocity increases must occur over depth ranges less than the shortest wavelengths of long period body waves (50 km). Several independent types of body wave experiments may be necessary to infer the sharpness of the velocity transitions. Precursors to the P'P' phase observed on short period instruments have been interpreted to be narrow-angle reflections from the underside of the 670 km transition. These are still the primary evidence cited for the 670 km transition being less than 10 km thick, but not all of precursors can be unambiguously interpreted as underside reflections. The reflectivity of transition zones can be calculated as a

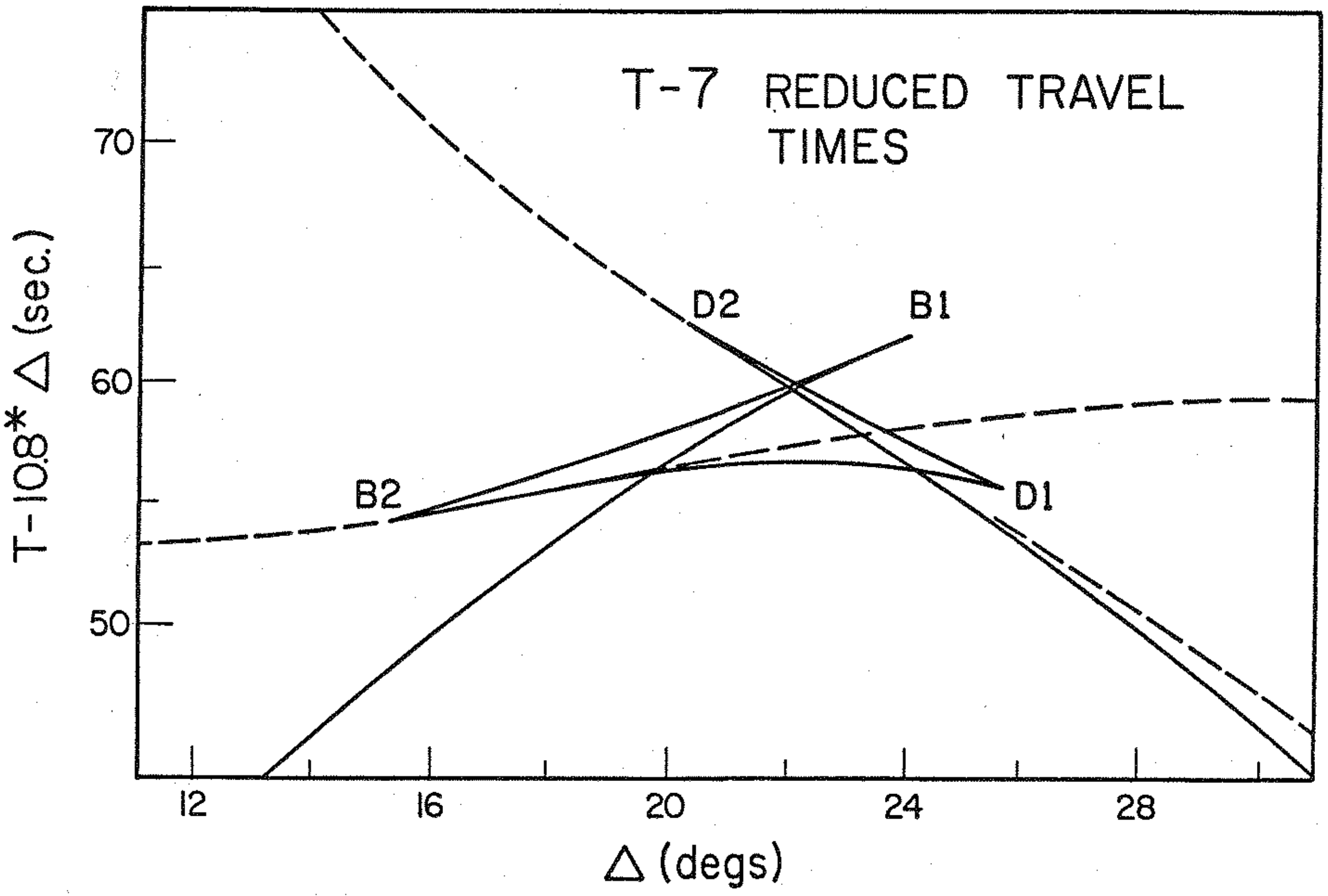


Figure 3.34. Reduced travel-time curve for model T-7 of the upper mantle. Weaker amplitude partial reflections and interference head waves are dashed. (Cormier and Choy, *J. Geophys. Res.*, 1981)

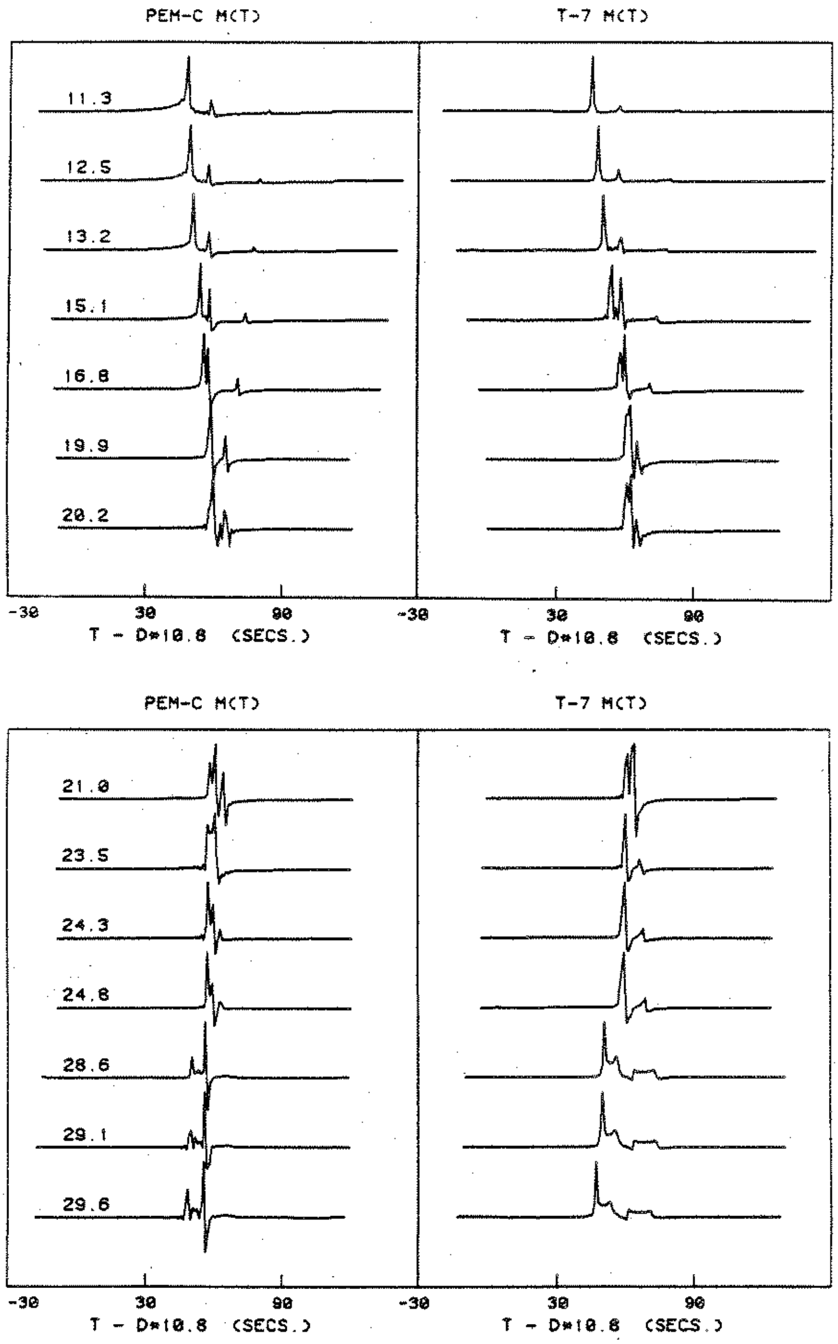


Figure 3.35. P waveforms (top) and displacement responses (bottom) predicted for a surface focus source having a delta time function. Synthetics predicted by models T-7 and PEM-C of the upper mantle are compared. Numbers to the left of traces give the distance in degrees. Note that in the presence of noise, the triplicated arrivals would be most observable in the 14 to 28 degree range if the instrument response could resolve arrivals spaced 10 seconds or less in time. In the bottom panel, the distances correspond to the data records of the Oroville earthquake shown by Burdick and Helmberger (1978). Peak amplitudes are normalized to the same height in each trace. The relative peak amplitudes normalized to the peak displacement at 20.2° are 0.60, 0.71, 0.76, 0.86, 0.94, 1.04, and 1.00 for PEM-C and 2.51, 1.86, 1.59, 1.08, 1.23, 0.94, and 1.00 for T-7. (Cormier and Choy, *J. Geophys. Research,* 1981)

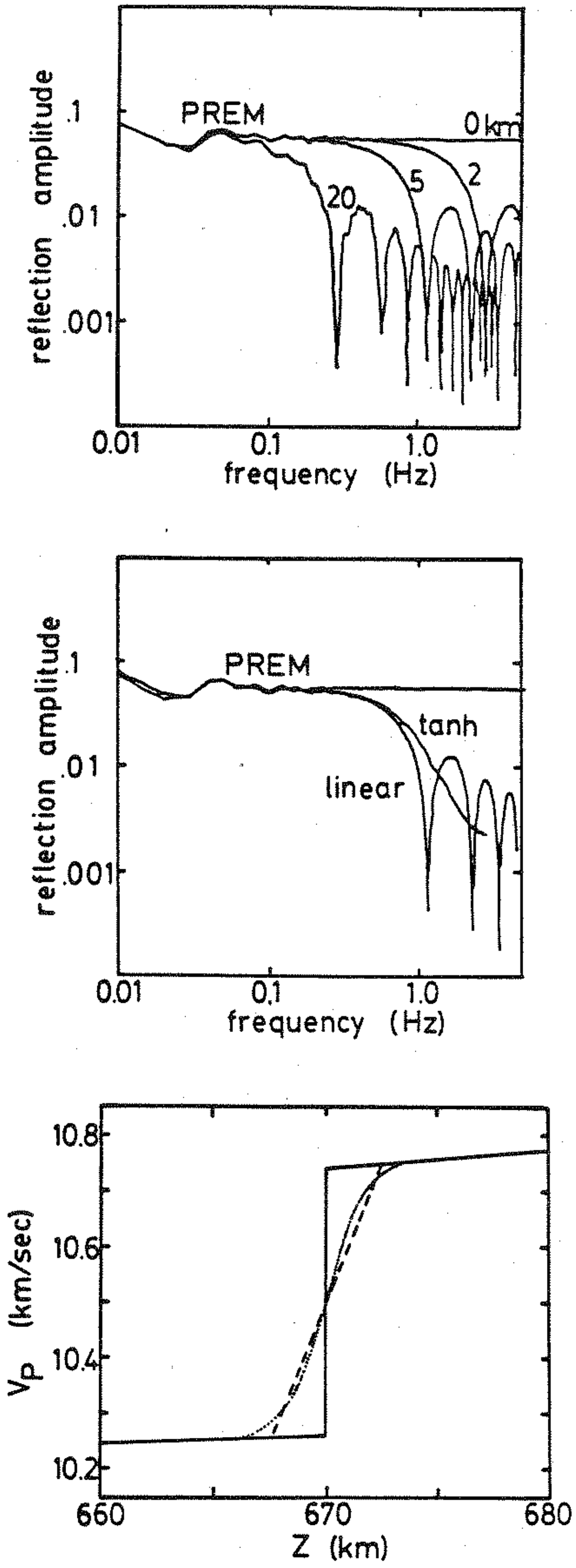


Figure 3.36. 1 Hz reflection coefficient computed for a P′P′ wave incident on the underside of a transition zone at 670 km depth in the mantle. Coefficients are computed for 0, 2, 5, and 20 km widths of the transition. (Lees *et al.*, *J. Geophys. Res.*, 1983)

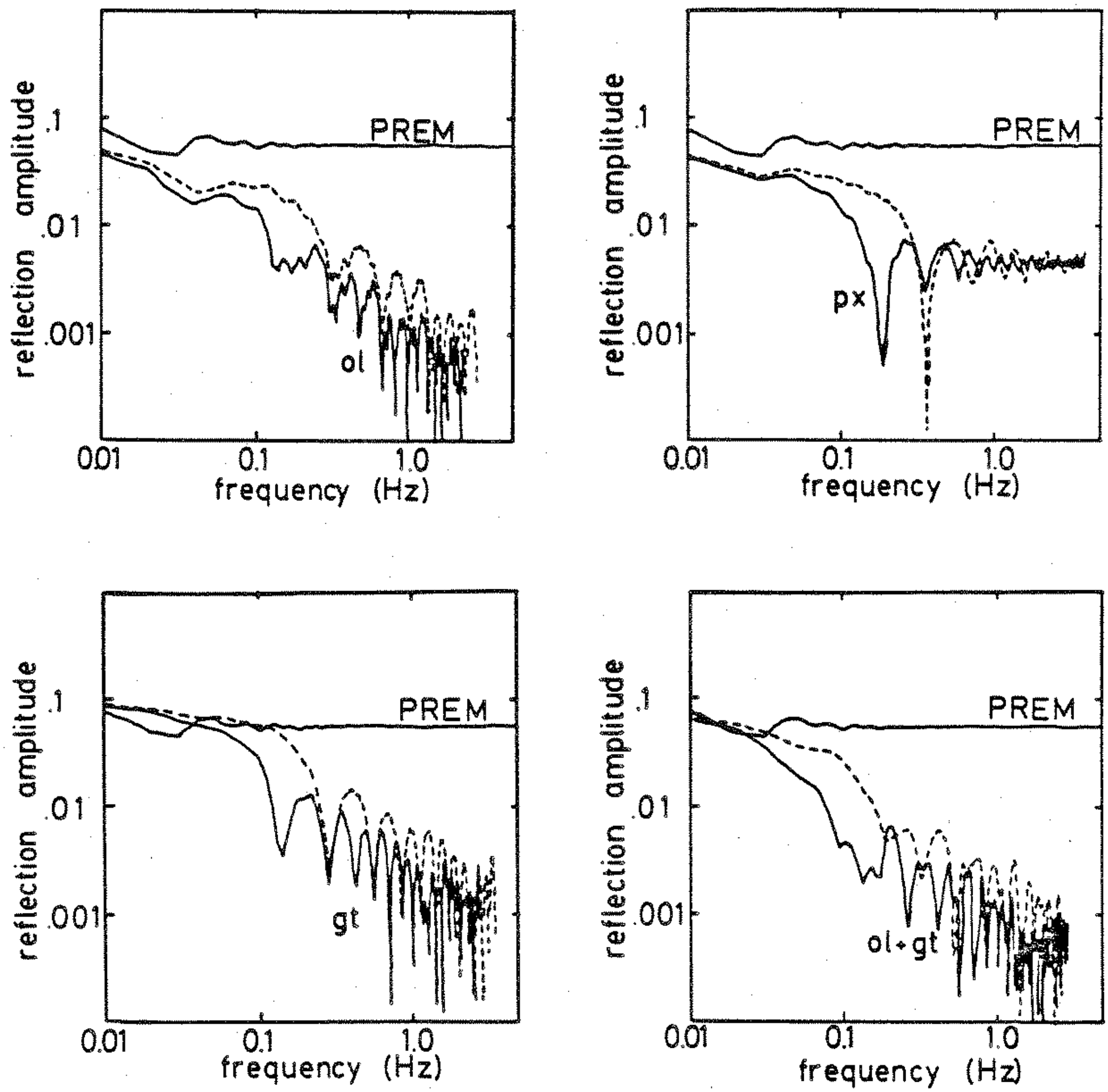


Figure 3.37. The frequency dependence of the P'P' reflection coefficient of the 670 km transition computed for olivine, pyroxene, garnet, and olivine + garnet models of mantle mineralogy. (Lees *et al., J. Geophys. Res.*, 1983)

function of frequency (Figure 3.37) by modeling the transition zone as a sequence of thin homogeneous layers. Such calculations demonstrate that new constraints on the thickness of the transition can be found using converted phases. By examining the frequency dependence of a variety of reflected and converted phases more precise estimates of the transition thicknesses can be made. This task can be enhanced and accelerated by the existence of three-component, digital instruments recording up to 5 Hz. The "thickness" of discontinuities provides a powerful constraint on petrological models.

3.4.3. Structure at the Base of the Mantle

Several independent sets of seismic data suggest that the lowermost 400 km or so of the mantle (region *D″*) is a zone of diminished velocity gradient, possibly higher intrinsic attenuation, and strong heterogeneity. Heterogeneities having scale lengths of 100 km or more may reflect the pattern of return flow in lower mantle or whole mantle convection. Body wave models of this region can be significantly improved by the existence of three-component digital data up to 5 Hz. Several experiments commonly used to constrain the structure in this region depend on the measurement of the frequency content of body waves. Two examples are the distance decay into the core shadow and the frequency content of diffracted P and S phases, and the frequency content of precursors to the PKP-DF branch. The frequency content, travel-time, and slowness variations of the precursors to PKP-DF can be explained by scattering of body waves into the core caustic by heterogeneities near the base of the mantle or bumps on the core-mantle boundary. A global study of PKP-DF precursors, including their frequency content and complexity in selected time windows, can be made possible by short period digital recordings. Regional variations in their behavior may aid in mapping the base of the mantle. An exciting result of the past few years has been the discovery of a discontinuity embedded in *D″*. This makes us rethink the thermal boundary layer explanation for this region.

3.4.4. The Outer Core, SKS, and S Waves

Most seismic data suggest that the outer core is a chemically well-mixed liquid, characterized by a smooth gradient in compressional velocity. The scatter of amplitude ratios of SKS and SKKS phases, which sample the upper part of the outer core, however, may indicate either some structural complexity in the outer core or the effects of lateral heterogeneity along their ray paths. SKS phases provide the most important constraints on the structure of the outer core and the base of the mantle, but detailed experiments using them have been few due to the extra work required to digitize and rotate three-component data. Digitally recorded three-component data will facilitate SKS studies as well as more general studies of S phases. Polarization anomalies and particle motion will be studied, on a global basis, for lateral heterogeneity as well as anisotropy.

3.4.5. The Inner Core

Body wave studies have concluded that the upper 200 km of the inner core is a zone of strong gradients in P velocity, S velocity, and attenuation. When a source having a sufficiently simple source-time function is selected for study, the separation of the DF and CD branches of PKP can be observed to within 10° or less of the D cusp (Figure 3.38). In this distance range, the waveform can be used to constrain the position of the D cusp to within 1°. Digital processing can be used to enhance the observability of the C cusp (Figure 3.39), which together with waveform data near the D cusp, can be used to constrain the velocity jump of the inner core boundary to within 0.05 km/sec. The resolution of these studies would not have been possible without digital data. A global network of short period digital stations can be used to confirm these observations for different regions of incidence on the inner core boundary. The progressive solidification of the inner core and gravitational differentiation of the outer core has been proposed to be an energy source for sustaining the earth's magnetic field. Synthetic experiments indicate that second order features of the PKP-DF + PKP-CD waveform are sensitive to the S velocity profile in the uppermost inner core. The S velocity distribution may reveal the zone over which complete solidification of the inner core occurs.

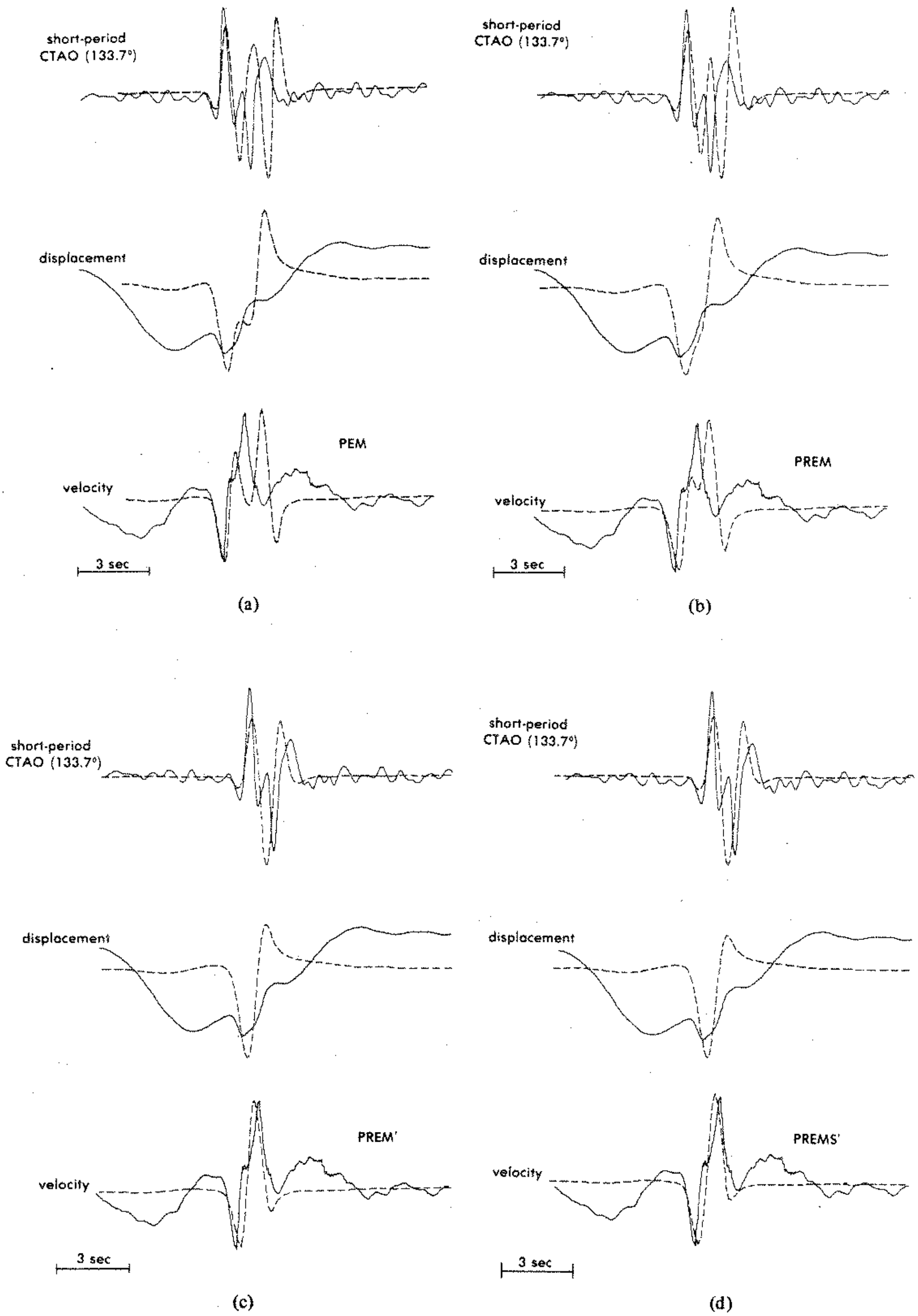


Figure 3.38. Data and synthetic comparisons of a PKP-DF and PKP-CD phase observed at 133.7° from a deep focus event. Note that double pulse is observed. Short period and broadband data are reconstructed from long and short period bands of the GDSN station at CTAO. (Choy and Cormier, *Geophys. J. R. Astr. Soc.*, 1983)

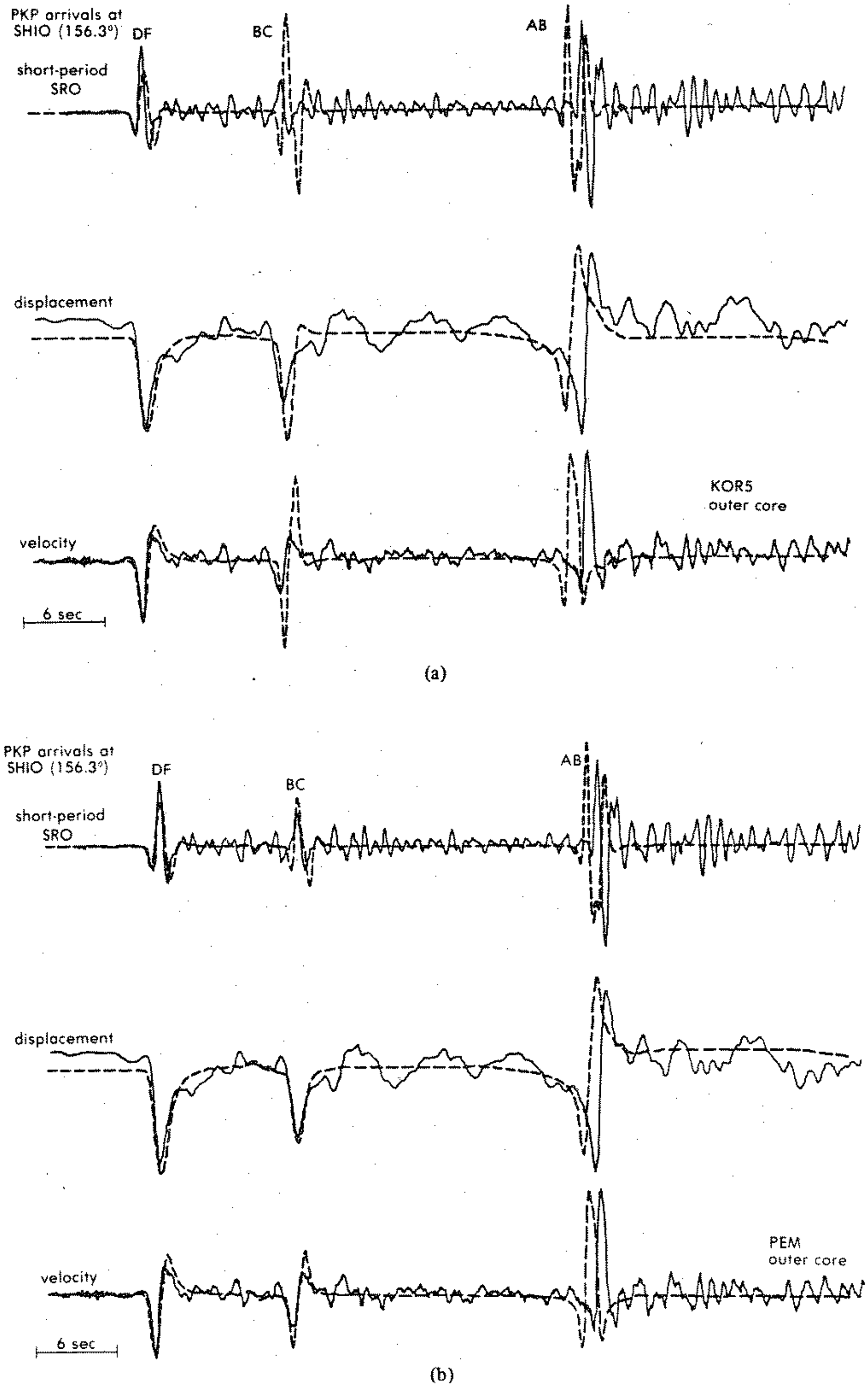


Figure 3.39. Data and synthetic comparisons of PKP branches observed at 156.3 degrees from a deep focus event. Note that BC branch near the C cusp is enhanced in the data by broadband deconvolution of short and long period GDSN seismograms. (Choy and Cormier, *Geophys. J. R. Astr. Soc.*, 1983)

3.4.6. Scattering and Multipathing

Many features of high frequency body waves cannot be explained by propagation in a radially symmetric earth composed of compositionally homogeneous layers. The high frequency energy in the coda of P and S phases is surely, in large part, a consequence of scattering by heterogeneities concentrated in the crust and uppermost mantle. It may only be possible to model the effects of these heterogeneities using a statistical description of scale lengths and velocity fluctuation. As a starting point of even statistical descriptions, however, quantitative measurements must be made on the coda of frequency content and complexity in different time windows using a digitized seismogram. A global digital network will allow the study of regional variations in P and S coda, defining variations in the scale lengths of heterogeneities and contributing to the testing of theories of scattering. In the 0.5 to 2 Hz band, the first several cycles of a body wave can, in many cases, be successfully predicted using deterministic models of earth structure. Multipathing has been observed in the short period waveforms of body waves refracted by continental margins and descending slabs. New methods of modeling the waveforms of body waves in three-dimensionally varying structures can now be applied to the interpretation of short period waveforms showing evidence of multipathing. The understanding of multipathing may be aided by examining the particle motion of body waves on three-components. Short period digital data will aid in the detection of smaller scale three-dimensional structures, such as the high velocity perturbation of a descending slab.

3.4.7. Attenuation Problems at High Frequencies

The high-frequency signal in a seismogram is an important characteristic of the spectrum radiated by the source. But, to study that characteristic is to come to grips with the attenuative qualities of high-frequency wave propagation, and to find how it varies in type (intrinsic dissipation or high-frequency scattering?) and with position in the earth (attenuation varies with depth, and also with the laterally-varying tectonic/geological character of the earth's upper layers). The scientific study of these questions has been advanced to a high level by the oil industry, using seismic waves that have penetrated just the upper few kilometers of the crust. Detailed studies of such data have led seismologists in that industry to methods of separating attenuation caused by dissipation (intrinsic friction) from attenuation caused by scattering, and then to make estimates of qualities of the earth's structure that have not previously been addressed. For example, the statistical properties of inhomogeneity in seismic velocities (the percentage change in such velocities, and the scale length or correlation distance for the inhomogeneities) can be translated into a seismologically-based estimate of lithology. Such work cannot be done for deep earth structure in the absence of a data base. However, certain stations now recording digitally do show good signals, even above 8-10 Hz, from teleseisms. The proposed new global network will, from its high sampling-rate channels, afford the opportunity to see which levels in the earth are effective in scattering, and which regions are dissipative.

The study of high-frequency attenuation is a project that has direct connection to work at lower frequencies. The connection arises because of causality relations such as the Kramers-Krönig equations (an integral constraint across all frequencies) and the need to allow for some physical dispersion in the frequency range below 1 Hz. This dispersion is needed to explain observed pulse shapes with frequency content in the range 0.01—1 Hz, and to reconcile earth structure inferred from normal mode data in the range 0.0003—0.03 Hz with structure inferred from travel times of frequency around 1 Hz.

At present, seismologists needing to invoke dispersion usually use a logarithmic formula that assumes (a) attenuation is caused by intrinsic friction and not by scattering, and (b) attenuation is proportional to frequency (constant Q). Though adequate for some purposes, assumptions (a) and (b) are each flawed, and a resolution of the issues will depend heavily on properties of observed high frequency seismic waves. Some of the underlying issues are contentious (for example, the debate on whether t^* should be assigned a value of around 1, as seems appropriate for a mid-range of frequencies; or whether it should be smaller, as indicated by the presence of high frequencies in teleseisms). Such vigorous debate can only be resolved with better data at high frequencies.

3.5. Free Oscillations of the Earth

It is little more than 20 years since the free oscillations of the earth were first unambiguously identified. The mean periods of free oscillation now constitute the dataset which provides the most important constraints on the spherically averaged structure of the earth. Indeed, it is the only dataset which provides any constraints on the radial distribution of density within the earth.

The present mode dataset is the product of the intensive study of a few very special events. The vast majority of observations that have been used in radial-earth modeling come from only two earthquakes; the huge 1964 Alaskan earthquake and an unusually large deep event in Colombia in 1970. These events provide only limited coverage of the earth and the potential for bias in the mean periods is high.

There are two reasons for this unsatisfactory state of affairs: 1) the lack of instruments with significant response at low frequencies prior to 1975 meant that only the largest events gave a usable signal, 2) the large amount of time required to digitize a sufficient number of long analog seismograms deterred all but the most tenacious investigators. The lack of easily accessible high quality data meant that only the crudest investigations of aspherical structure were possible and attention was firmly focused on determining the spherically averaged properties of the earth.

Towards the end of the seventies, sufficient digital data became available to investigate the effects of aspherical structure on long period spectra. The last few years have led to some spectacular discoveries and it is clear that the spectra are rich in anomalous signals right down to the lowest frequencies.

Aspherical structure causes splitting of spectral lines. The rotation and concomitant ellipticity of the earth leads to splitting which is theoretically well understood. All modes of the earth whose splitting has been fully resolved have found been found to be anomalously split - and not by a small amount. Figure 3.40 illustrates spectra from a number of IDA stations of the split mode ${}_{10}S_2$. It is clear from the latitude variation of the lines that the higher frequency line has the shape of the geographic spherical harmonic, Y_2^0 and the lower frequency line has the shape of $Y_2^{\pm 2}$. Stacking of these records to isolate individual singlets verifies the observation that the mode shapes are dominantly geographical spherical harmonics and, with our limited number of stations, isolation of individual singlets is quite good (Figure 3.41). The curious thing about this observation is that the lines are over three times farther apart than theoretically predicted for a rotating earth in hydrostatic equilibrium. [The anomalous distance between the lines led to the mis-identification of the higher frequency line ${}_{10}S_2^0$, as a different mode, ${}_{11}S_2$. The frequency of the lower line, ${}_{10}S_2^{\pm 2}$, was associated with the mean frequency for ${}_{10}S_2$ which is consequently a biased datum.] These observations are direct evidence of large amplitude large-scale structure within the earth. To interpret them fully requires a knowledge of the singlet shapes on the surface of the earth. The proposed global network of well calibrated broadband instruments is essential to retrieve such information as quickly as possible.

The vast majority of modes have too many singlets too closely spaced in frequency ever to be resolved. Splitting manifests itself by shifting of the apparent peak location of the mode (Figure 3.42). This phenomenon is understood and can be interpreted in terms of aspherical elastic structure. The apparent attenuation rate of the mode is also strongly perturbed in a way which is not understood and masks any signal due to aspherical anelastic structure. The peak shifts of large angular order, surface wave equivalent modes ($\ell >> n$) show a very simple dependence upon the orientation of the path between the source and the receiver (Figure 3.43). This kind of behavior is only to be expected for large scale aspherical structure. The patterns of peak shifts suggests that most of the power in the even orders of the expansion of aspherical structure lies in the degree 2 terms. There is growing evidence that the source of this inhomogeneity is relatively deep - in the transition zone of the earth. Our ability to infer aspherical structure from peak locations depends upon having very good coverage of the sphere. There is

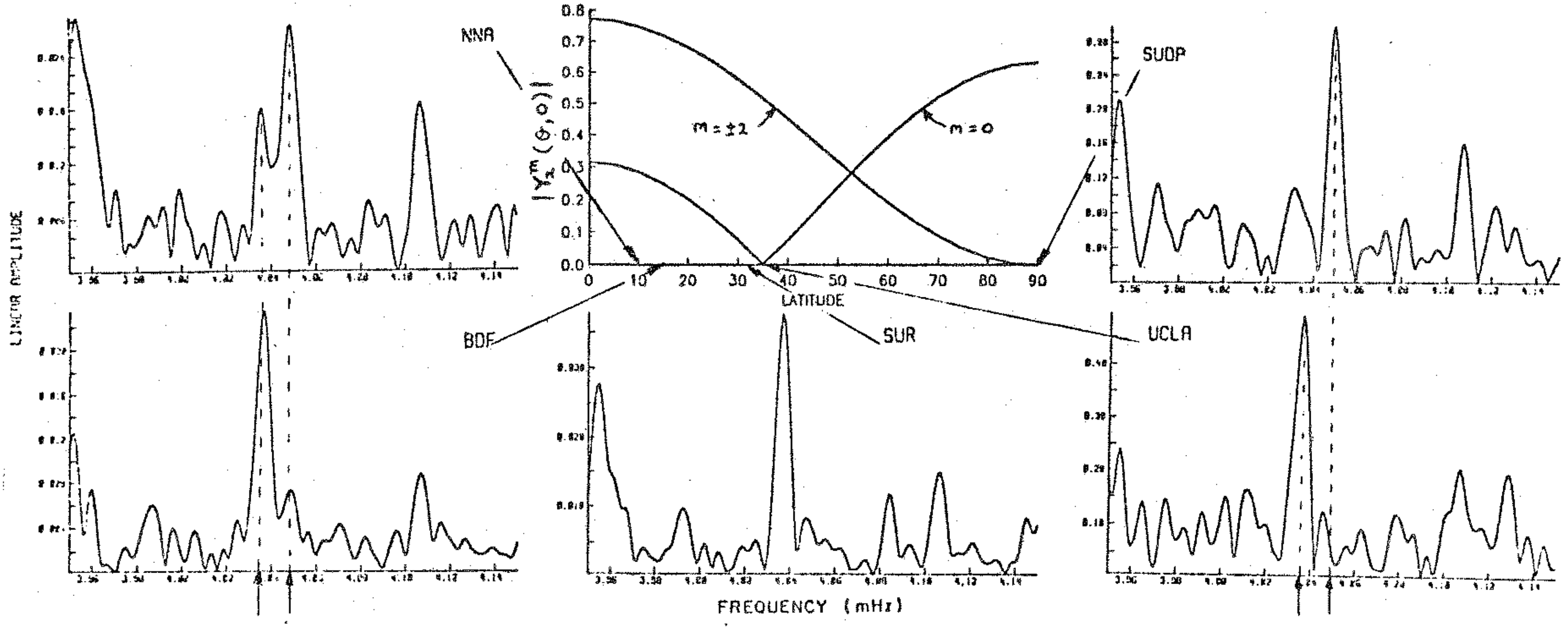


Figure 3.40. Spectra of 80 hr recordings from an event in Tonga showing the anomalously split multiplet ${}_{10}S_2$. Two lines are clearly visible, one at a frequency of 4.035 mHz and one at 4.049 mHz. The latitude variations of the amplitudes of the geographical spherical harmonics Y_2^0 and $Y_2^{\pm 2}$ are shown in the center panel (the longitude dependence has been ignored). Note that Y_2^0 is the only spherical harmonic with nonzero amplitude at the geographic poles. The latitudes of the various stations are indicated on the figure. Comparison with the spectra shows that the line at 4.049 mHz has the correct mode shape for ${}_{10}S_2^0$ and the line at 4.035 mHz is the doublet ${}_{10}S_2^{\pm 2}$. (G. Masters, with permission)

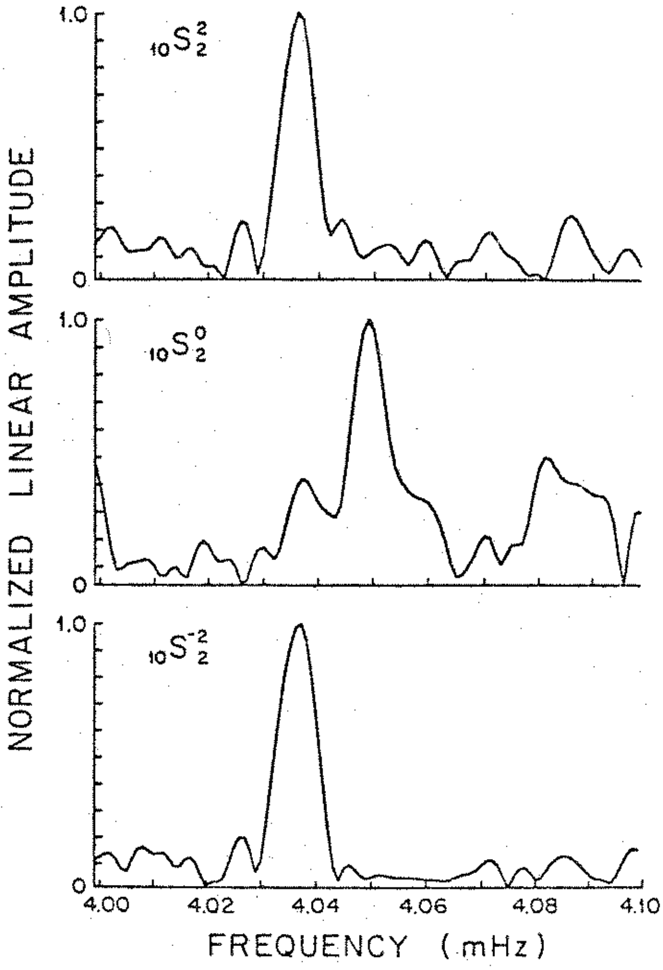


Figure 3.41. A spherical harmonic stack of five records from the Tonga event showing (from top to bottom $_{10}S_2^2$, $_{10}S_2^0$ and $_{10}S_2^{-2}$. The isolation of the individual lines is quite good but $_{10}S_2^0$ is displaced in frequency away from the other lines by approximately a factor of three more than theoretically predicted. Some, as yet unresolved, large scale aspherical structure is required to explain these observations. (Masters and Gilbert, *Geophys. Res. Lett.*, 1981)

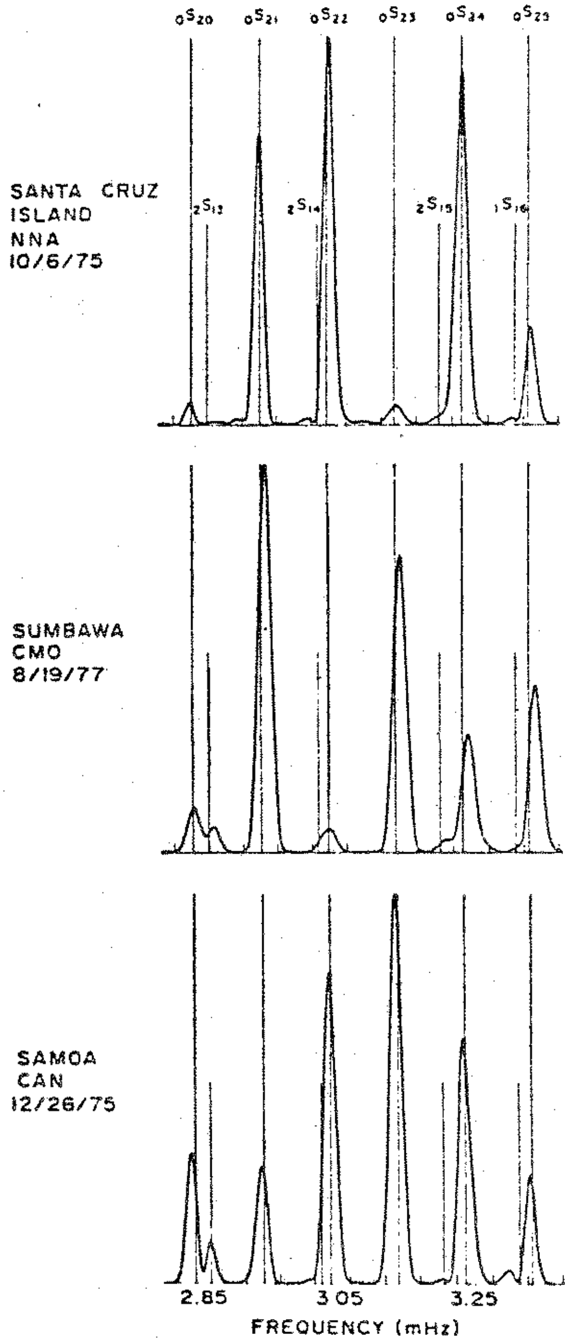


Figure 3.42. Power spectra of 20 hr recordings from the IDA array showing the fundamental modes $_0S_{20}-{_0S_{25}}$. The vertical lines show the degenerate frequencies calculated for the Earth model PEM-A. The peak shifts observed for different great circle paths are attributable primarily to lateral heterogeneity. (Silver and Jordan, *Geophys. J. R. Astron. Soc.*, 1981)

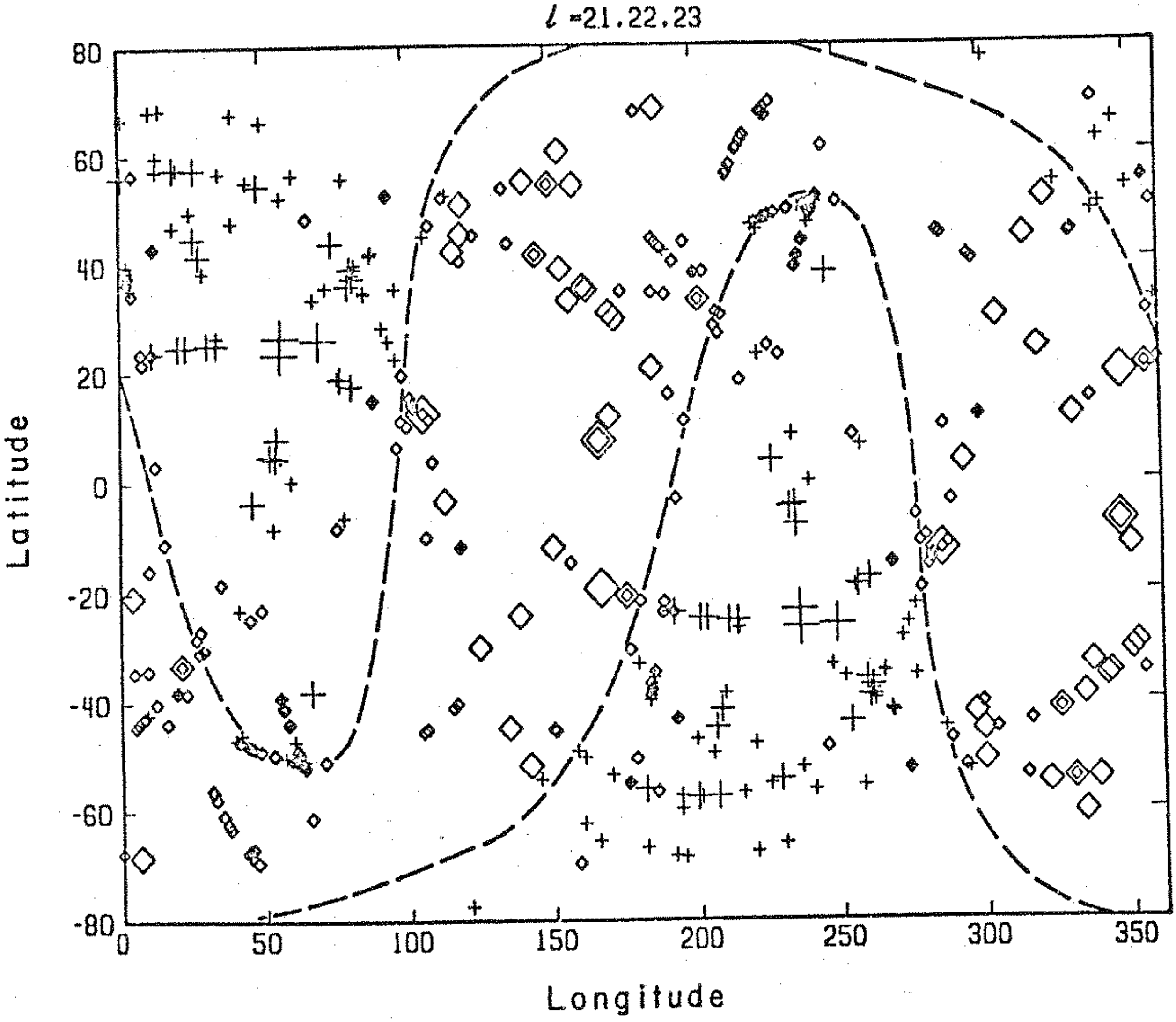


Figure 3.43. The effect of aspherical structure on the center frequency of multiplets can be seen by plotting the shift in frequency at the pole position of the great circle joining the source and receiver. Each symbol is plotted at a pole position: a plus sign corresponds to a positive frequency shift and a diamond corresponds to a negative frequency shift. The size of the symbol is indicative of the magnitude of the shift: the smallest symbols correspond to a 0–0.1% shift and the largest to a 0.3–0.4% shift. A degree-two spherical harmonic pattern accounts for most of the structure in the observations; the nodal lines of this pattern are shown by the dashed lines. This example is a combination of measurements for the modes ${}_0S_{21}-{}_0S_{23}$. (Masters *et al.*, *Nature,* 1982)

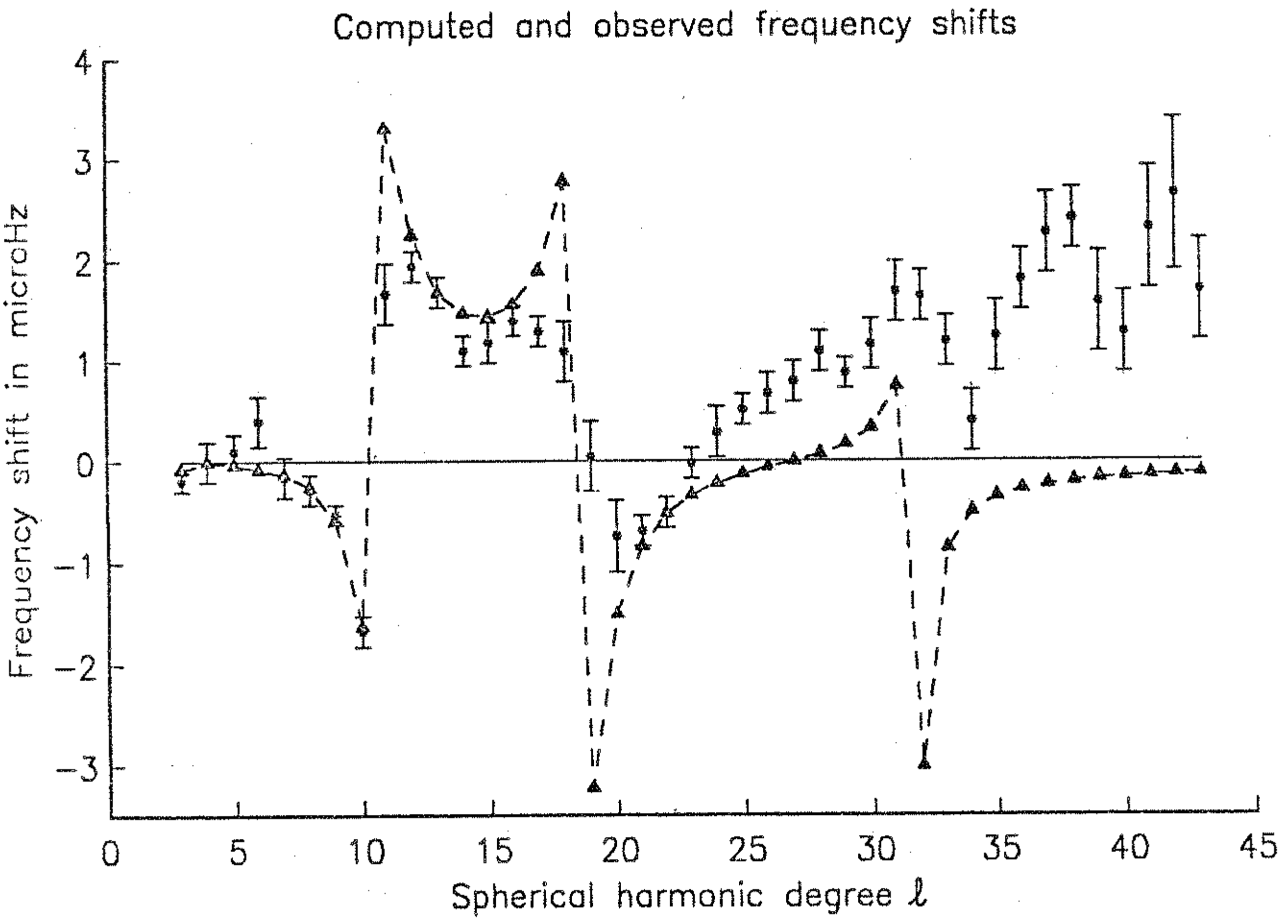


Figure 3.44. Observed mean frequencies (dots with error bars) and calculated mean frequencies (triangles) of the dominantly spheroidal part of coupled spheroidal-toroidal multiplets relative to the unperturbed ${}_0S_\ell$ multiplets of model 1066A. The calculations were performed including the effects of attenuation, ellipticity and the Coriolis force. It is the latter which dominantly causes the coupling. The shifts in the mean frequencies are generally well-modeled though the 1066A systematically under-predicts the frequencies of the modes above angular order 25. No existing Earth model provides an adequate fit to these new, high precision, data. (Masters *et al., J. Geophys. Res.*, 1983)

also a contribution to the peak shift due to the source mechanism of the event, so a well distributed array of instruments is crucial. The present networks have a strong bias of stations towards temperate latitudes and the resulting lack of equatorial and polar paths can induce indeterminacy in a study of this kind. Such paths are also extremely important in studying the effects of rotation on low frequency spectra.

Using peak shifts and other types of data some authors have proposed models of aspherical structure up to degree 8 (see section 3.3.2.3). However, these models do not fully explain the strong interference effects which give rise to the anomalous attenuation rates and complex amplitudes of these modes. Focusing and defocusing by lateral heterogeneity can probably explain these observations; modeling of multipathing effects are currently underway. However, we are still a long way from being able to model satisfactorily complete seismograms.

The splitting induced by aspherical structure considerably complicates low frequency spectra. However, there is another phenomenon caused by asphericity: mode coupling. This phenomenon is common in low frequency spectra, the main coupling agency being the Coriolis force. When modes couple a hybrid "super mode" is formed. Usually the coupled modes can still be separately observed though their mean complex frequencies are perturbed from the uncoupled state. Examples of shifts in the mean complex frequencies are illustrated in Figure 3.44. These shifts are clearly several standard deviations of the measurements and must be accounted for in any interpretation of the data. With large datasets such sources of bias are quite easily identified and it will be possible to obtain extremely accurate mean periods, thereby constraining the spherically averaged structure with high resolution. Such resolution is needed if many questions regarding the nature of convection in the deep earth are ever to be answered.

What does the future hold? Low frequency seismology can be a very precise science given a good global distribution of well calibrated easily accessible data. We are learning a lot with the instrumentation available, although a lot of time is spent coping with problems of data format, calibration inaccuracy, and inadequate instrument response and dynamic range. Our recent successes are probably due to the size of the anomalous signals in the data. These largest signals will probably be explained in the next few years but the full richness of the free oscillation spectrum will only be explained with improved instrumentation and better global coverage.

3.6. Relation to Other Areas of Earth Sciences

The importance of studies of the true structure of the Earth described in previous sections extends into many areas of Earth Sciences. The following subsections provide examples of application of seismological results to problems of geodynamics and their relation to the fields of petrology and geochemistry. There is little question that, for example, studies of the core structure are of great importance to solving the question of the geodynamo. The role of the new array in studies of the lithosphere is discussed in a separate section.

3.6.1. Geodynamics, Convection and the Geoid

Understanding convection in the mantle is one of the more important goals of geophysics. Heat transport via mantle convection is the ultimate driving mechanism for the plate tectonic engine. Global digital data will allow us to obtain the information that, in conjunction with observations of the geoid, will provide fundamental constraints on geodynamics, mantle convection, and the driving mechanism for plate motions.

Flow in the mantle results from lateral variations in density caused primarily by lateral variations in temperature. This flow in turn leads to further lateral variations in the temperature field, maintaining the convective motion. The proposed global network will provide much improved resolution of lateral variations in seismic velocities in the lower mantle (using body waves) and of seismic velocities and density in the upper mantle (using surface waves). The isotropic components of these lateral heterogeneities can be related in a straightforward way to lateral variations in density: high temperatures lead to low seismic velocities and low densities, while low temperatures do just the opposite. Thus the new data will make possible mapping of

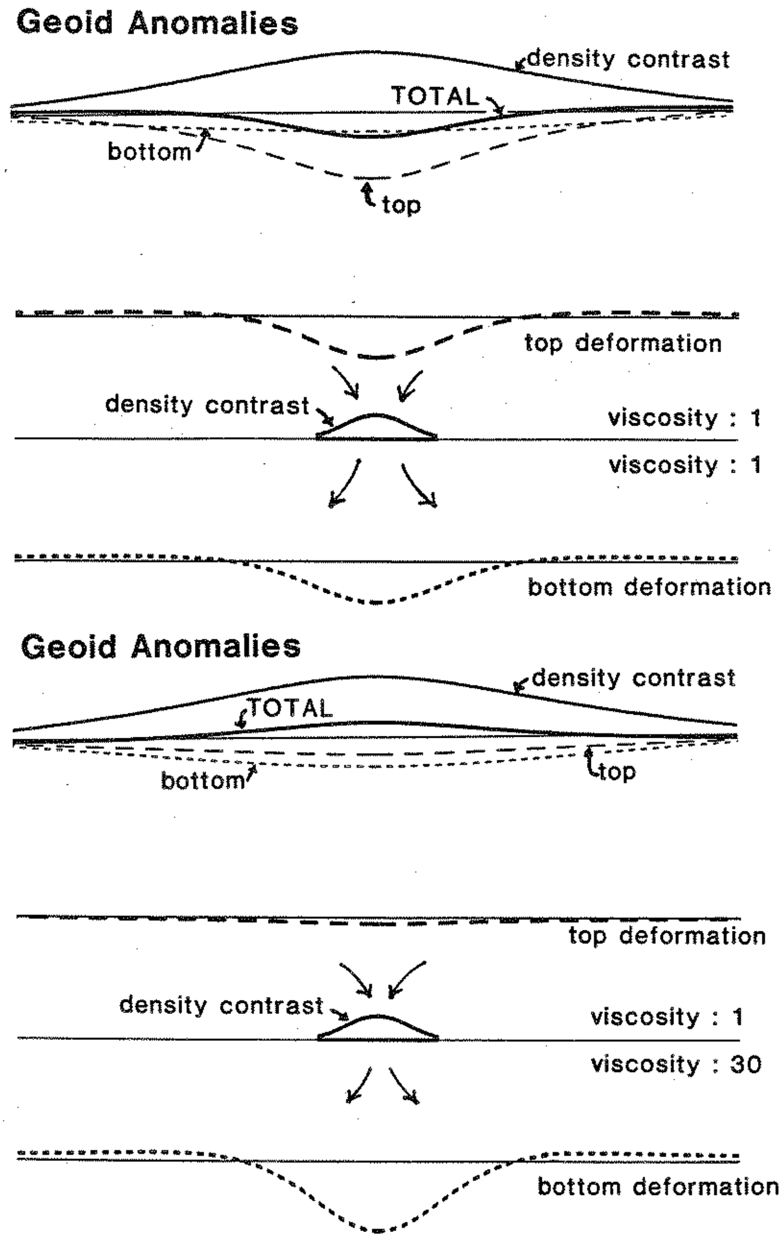


Figure 3.45. An illustration of the generation of dynamic geoid anomalies. A dense sinker is placed at mid depth in a fluid layer. The flow caused by the sinker causes a dimple at the upper surface and a downwarping of the lower surface. These contribute in a negative sense to the total geoid anomaly. For a uniform viscosity fluid (top), the total geoid anomaly is negative. For a fluid in which the viscosity increases with depth by a factor of 30 (bottom), there is less deformation of the upper surface and the net geoid anomaly is positive. It remains smaller in amplitude than that due to the dense sinker alone. If the pattern of density contrasts in the mantle can be determined using seismic methods, the observed gravity field can be used to constrain the variation of viscosity with depth. (Hager and Richards, with permission)

the density contrasts responsible for driving mantle convection and plate motions. Such constraints are sorely needed for understanding of the thermal and chemical evolution of the earth, as well as for understanding of the driving mechanism for plate motions.

Observations of seismic anisotropy will also place fundamental constraints on mantle convection. This is because flow results in preferred orientation of the (anisotropic) crystals comprising mantle rock. For example, olivine becomes oriented such that its a axis is parallel to the flow direction; the a axis also is the direction of maximum P-wave velocity. Detection of the fast direction for P-wave propagation in the olivine-rich upper mantle allows the determination of the direction of mantle flow. Similar results also hold for S-wave anisotropy, although the relation between flow direction and direction of maximum shear velocity is more complicated.

Although seismic observations alone provide powerful constraints, it is probably by combining observations of lateral variations in seismic properties with high-quality observations of the Earth's gravity field (such as those obtained by NASA) that we will achieve the next level of understanding of mantle dynamics. To show why, it is necessary to discuss the straightforward, although somewhat subtle and perhaps unfamiliar, physics of gravity anomalies in a dynamic earth.

Hot mantle rock behaves elastically on seismic timescales, but on much longer timescales it behaves in a viscous manner, responding to applied stresses by slow, creeping flow. Horizontal density contrasts within the mantle excite flow, which in turn results in deformation of the earth's surface, the core-mantle boundary, and any internal density contrasts that result from compositional changes. It is necessary to consider these surface deformations in computation of gravity or geoid anomalies.

The basic physics of the dynamics of geoid anomalies is illustrated in Figure 3.45. In Figure 3.45a, a dense sinker is placed at mid-depth in a fluid (representing the mantle) with uniform viscosity. The resulting flow causes deformation of both the upper surface and of the core-mantle boundary. This boundary deformation occurs on the same timescale as postglacial rebound, short compared to the time it takes for the position of the sinker to change appreciably. Thus, boundary deformation can be taken to occur instantaneously from the standpoint of mantle convection.

The total geoid anomaly is the sum of the positive effect of the dense sinker and the negative effects caused by boundary deformations. For this layer of uniform viscosity, the net dynamic geoid anomaly caused by a dense sinker is negative; the effects from the deformed boundaries overwhelm the effect from the sinker itself.

The effect of an increase in viscosity with depth is shown in Figure 3.45b, where the lower half of the fluid has a viscosity a factor of 30 higher than the top half. Now the deformation of the upper boundary is less than that in Figure 3.45a and the net geoid anomaly is positive.

For a given density contrast, the magnitude and sign of the resulting geoid anomaly in a dynamic Earth depends on the viscosity structure. Observation of the gravitational field of the Earth thus provides the most sensitive of all experiments, the null experiment, where the net result is a small number determined by the difference of large effects. The sign of the result depends on which of the effects is dominant. The anomaly also depends on the depth of the convecting system, with deep systems leading to larger geoid anomalies for a given density anomaly. Observations of the geoid in conjunction with observations of seismic velocity heterogeneities place constraints upon the variation of mantle viscosity and the depth of mantle convection.

We can illustrate the approach of combining observations of seismic velocity heterogeneity and observations of geoid variations by using recent models of lower mantle seismic heterogeneity derived from ISC P-wave travel time residuals. We assume that velocity and density perturbations are linearly related, with a proportionality constant of $5(\mathrm{km/sec})/(\mathrm{g/c^3})$. Dynamically consistent geoid anomalies, including the effects of surface deformation and self-

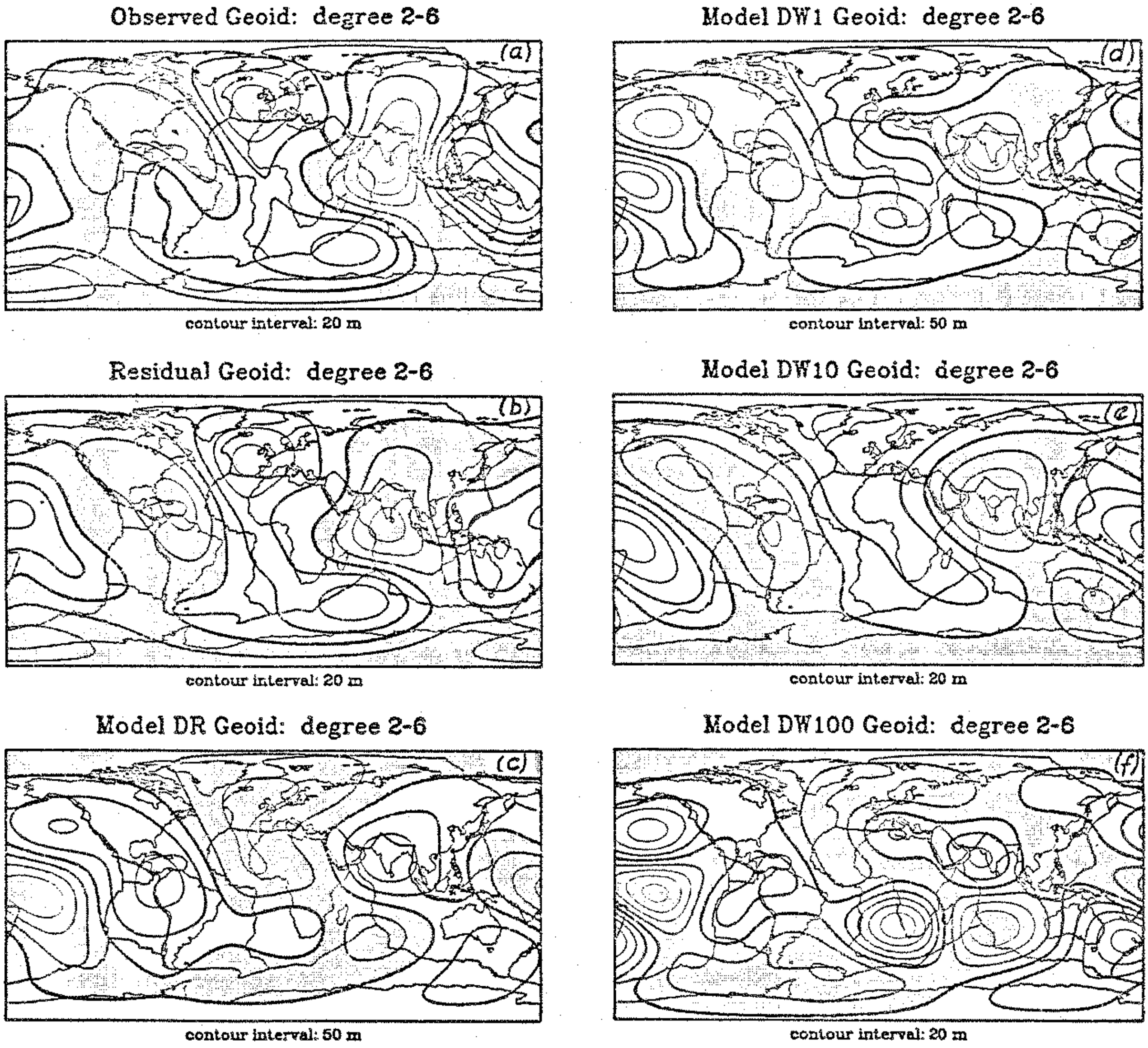


Figure 3.46. Contour maps of long-wavelength geoid anomalies referred to the best-fitting ellipsoid. Negative areas are shaded. (a) Observed geoid (GEM-L2); (b) Residual geoid, with a dynamically consistent model of the effects of subducted slabs removed; (c) Model geoid calculated using Dziewonski's lower mantle seismic model and ignoring the effects of surface deformation (equivalent to assuming a rigid earth); (d) Model geoid using the seismic model and including the effects of surface deformation calculated for mantle with a uniform viscosity; (e) a mantle with a factor of 10 increase in the viscosity of the lower mantle relative to the upper mantle; (f) Overlaying (b) and (e) shows the excellent agreement for this viscosity structure. (Hager, with permission)

gravitation, are calculated for a series of viscosity models. These can then be compared to either the observed geoid or a residual geoid with the effects of subducted slabs removed.

Figure 3.46 shows the observed geoid, a residual geoid, and four model geoids calculated from a lower mantle body wave model (Dziewonski, 1982) through degree and order 6. Model DR assumes the "dynamic" response functions for a Rigid earth, i.e, surface deformation is ignored. Model DW1 assumes Whole-mantle flow with uniform viscosity. Model DW10 assumes whole-mantle flow with the lower mantle viscosity a factor of 10 greater than that of the upper mantle, while in model DW100, this viscosity ratio is 100.

If surface deformation is ignored (DR), the geoid anomaly is usually of opposite sign from the observed or residual geoids. For uniform mantle viscosity (DW1), the long-wavelength components have the proper sign, but there is too much high frequency noise. Model DW10 provides an excellent match spatially to the residual geoid, while the fit is once again poor for DW100. Thus by combining the seismic results and dynamic earth models with the geoid, we can constrain the viscosity variation with depth in the mantle, as well as provide the first satisfactory explanation for the long wavelength variations in the gravity field.

While these results are extremely exciting, they are preliminary and indicative of the potential of the network, rather than being the final word. To a large extent, this is due to our still rather crude resolution of lower mantle seismic structure. The correlation between the dynamic geoids calculated for two lower mantle seismic models (Clayton and Comer, 1983 and Dziewonski, 1982) is high for degrees 2 and 3 and comparable to the correlation between either geoid model and the residual geoid. However, for higher degrees, there is no significant correlation between the dynamic geoids calculated using the two seismic studies, nor is there a correlation between either dynamic geoid and the residual geoid. This appears to be the result of the different methods used to assign velocity (and density) anomalies to areas of the mantle where body wave coverage is poor. Improved seismic arrays would provide body wave data to increase the resolution of these studies.

Density heterogeneities in the upper mantle also contribute to geoid anomalies. Figure 3.47a shows the residual geoid for degrees 4-6 after slab effects are removed, while Figure 3.47b shows the 200 sec Love wave phase velocity anomalies from a recent study. It is apparent that there is a correlation between slow regions and geoid highs not associated with subduction zones (e.g. Basin and Range, Kerguellen, Red Sea, Iceland). These models are at present fairly crude however, and better data is obviously needed.

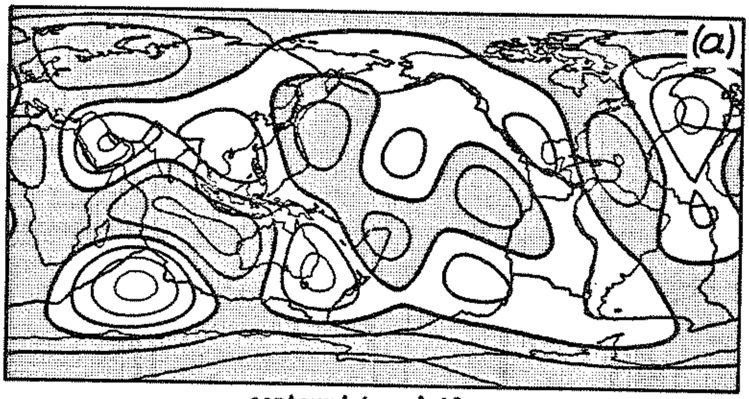
In summary, the high quality data which would be collected by the proposed digital array will provide fundamental constraints on mantle dynamics. It will allow construction of maps of the density inhomogeneities driving mantle convection and plate motion and maps of the directions of mantle flow. In addition, when combined with the high quality geoid data available from NASA, it will place powerful constraints on the distribution of viscosity and the depth of mantle circulation. It will allow us to understand for the first time the source of long and intermediate wavelength variations in the Earth's gravity field.

3.6.2. Petrology and Geochemistry

Seismology provides information about both the structure and physical state of the earth's interior. Mapping of discontinuities and lateral variations is a structural problem. The thickness of the crust and lithosphere, the depths of continental roots and the depths of oceanic ridge and hotspot anomalies are structural seismological questions which have impact on models of plate tectonics and magma genesis. It has recently been found that oceanic ridges can be traced to depths in excess of 400 km. This means that the mid-ocean ridge basalt reservoir is in the transition region rather than the low-velocity zone as generally assumed. More detailed mapping should, in the future, make it possible to map the depth extent of hotspots and answer questions about the locations of geochemical reservoirs.

Three-dimensional maps of the upper mantle show that the low velocities associated with ridges and the high velocities associated with shields are displaced at depth from their surface

Residual Geoid: degree 4-6



contour interval: 10 m

PHASE VELOCITY LOVE 200 SEC L = 4-6

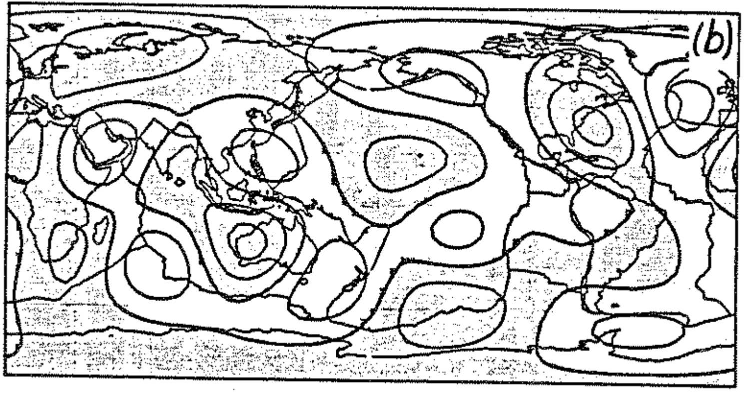


Figure 3.47. A comparison of (a) the geoid (with the effects of subducted slabs removed) for spherical harmonic degrees 4-6, with lows shaded, and (b) 200 second Love wave phase velocities, (Tanimoto and Anderson, 1983) with fast regions shaded. Highs (lows) in the geoid are usually associated with regions of slow (fast) phase velocity. (Hager, with permission)

expressions. Some ridges are fast at depth. Most subduction zones are slow in the upper 200 km but fast at greater depth. Most hotspots are located on the edges of slow regions of the upper mantle. These observations all provide new constraints on the depths of generation of various magma types.

The current situation is that the mantle appears to be heterogeneous at all scales and at all depths and that the largest lateral variations occur in the upper 250 km.

The question of whole mantle vs. layered mantle convection is also a structural seismological problem with important implications for the geodynamics, geochemistry and earth evolution. Global maps of seismic heterogeneity and anisotropy will contribute to the solution of this problem. The detailed mapping of the depth variability of the 400 and 650 km discontinuities will also constrain the nature of convection in the mantle and the sharpness of the discontinuities should help resolve whether these are chemical or phase boundaries.

Seismology is also a petrological and chemical probe. Seismic wave velocities depend on crystal structure, composition temperature and pressure. By comparing seismic velocities with laboratory data on various minerals, extrapolated by use of theoretical equations of state, it is possible to discuss the composition of various regions of the mantle. It has recently been proposed that the upper mantle transition region, 400—670 km, is eclogite rather than pyrolite or peridotite, and that the lower mantle is mainly perovskite. This violates the classical assumption that the whole mantle is olivine-rich peridotite. Figure 3.48 shows the variation of compressional velocity, shear velocity and density with depth for the mantle and for various minerals and mineral aggregates. The high gradient between 400 and 670 km can be explained by a solid state reaction between clinopyroxene and garnet, i.e., this is a mixed phase region. It appears now that only the shallow mantle is olivine-rich.

3.7. Lithosphere Problems

Most studies of crustal and lithospheric structure in the past have used high frequency local arrays or exploration techniques. These methods have high resolution but limited depth of penetration and poor global coverage. Methods of body wave and surface wave tomography have recently been developed to the point where maps and cross-sections can be prepared showing variations in the thickness and properties of the seismic lithosphere and asthenosphere on a global basis. Short-period surface waves are sensitive to velocity and thickness of the outer layers of the earth. Horizontal resolution is a function of number of stations, the vertical resolution is a function of the period of the surface wave. Current global maps of velocity variations in the lithosphere-asthenosphere system are limited to long wavelength, ~2500 km, features. A broadband global digital network, with about 100 stations, will permit the crust, lithosphere and asthenosphere to be mapped on a local and regional scale but with global coverage. The techniques making this possible also provide information on the anisotropy, which is related to crystal orientation and flow direction.

Body wave tomography, using local or transportable arrays and teleseismic events, can be used to image lithospheric and asthenospheric anomalies at all scales. Portable and semi-permanent arrays complement the global digital array in the study of the lithosphere. One provides global coverage, the other provides high resolution at a few sites.

3.8. Need for Large Scale Computing Facility

In section 3.1 the structure of research problems in seismology was discussed. Problems were put into two categories; forward problems and inverse problems. In the former, one is interested in computing functionals of a model, so-called gross earth functionals. Examples of gross earth functionals are travel times, dispersion curves for phase and group velocity, complex frequencies of free oscillation, pulse shapes, intricate waveforms, entire seismograms, functional derivatives of model distribution, and Green's functions for several source and receiver specifications.

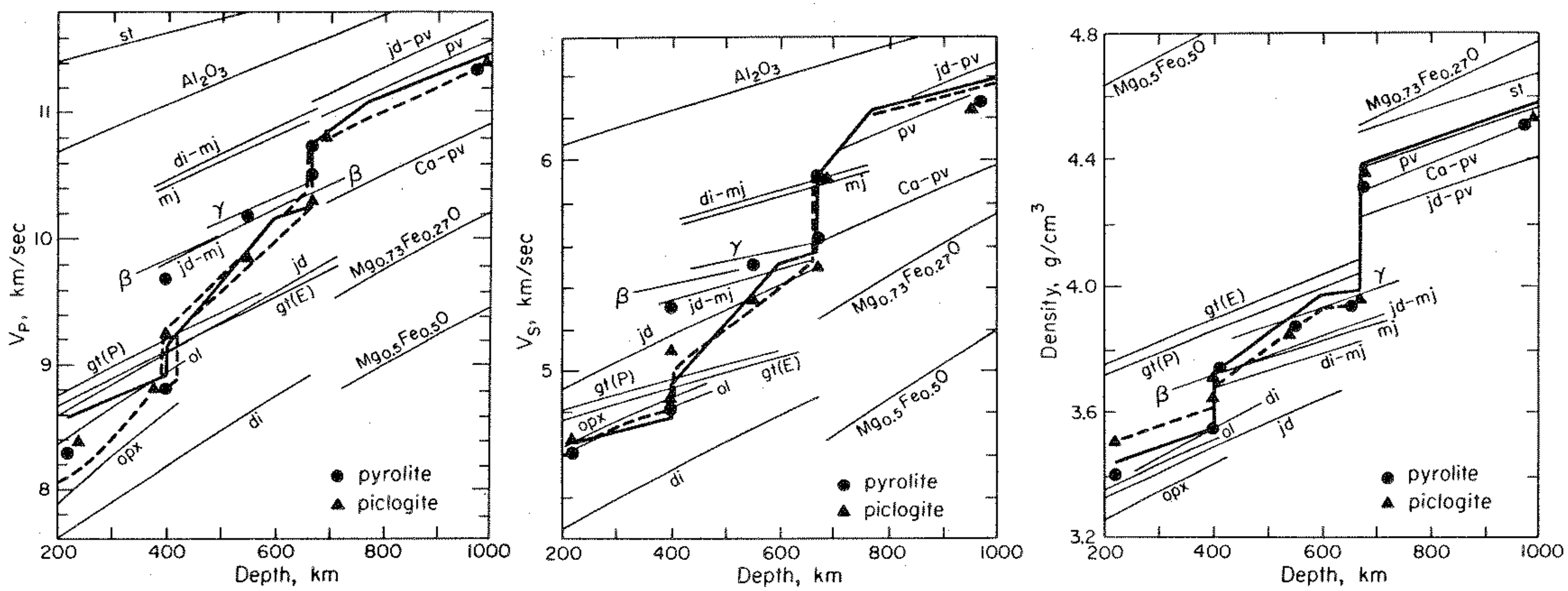


Figure 3.48. Variation of compressional velocity, shear velocity and density for various earth models (heavy solid and dashed lines) and various minerals and mineral assemblages. (Bass and Anderson, *Geophys. Res. Lett.*, 1984)

For inverse problems one attempts to adjust the parameter distributions in a model so that certain of its gross earth functionals are in better agreement with the observed, equivalent gross earth data. The adjustment is usually iterative in nature, each iteration requiring the solution of large ($\sim 10^3$) to huge ($> 10^6$) systems of linear equations.

Many of the computational tasks are very simple, such as the summation of modes of free oscillation, each one a decaying sinusoid, to synthesize Green's functions or seismograms. Others, like ray tracing in three dimensions, are more intricate. A few, solving systems of coupled ODE in a heterogeneous medium for example, are both numerically very intensive and recursive.

Those tasks that fall within the realm of numerical linear algebra are often vectorizable and the use of a supercomputer (e.g. Cray 1-S or X-MP, CDC Cyber 205) can result in a hundred-fold increase in performance over a fast mini computer (e.g. VAX 11-780, PRIME 850). Even the use of a long-word array processor (e.g. FPS-164, CSPI MAP-6420) can result in a tenfold increase over a fast mini. A few of the tasks in numerical linear algebra that involve matrix-vector operations are "matrizible" and can be coded on a supercomputer for a thousand-fold increase over a fast mini. Rather than reduce the computer time needed by the research seismologist, these improvements in performance allow larger scale problems to be treated. A 100 CPU-hour job on a mini translates into a 1 CPU-hour on, say, a Cray. The seismologist's learning curve soon compels him to run 100 CPU-hour jobs on the Cray, resulting in research projects inconceivable for a mini.

For recursive, intensive problems vector or super-vector machines have little to offer beyond the very fast CPU. What is needed here is a very fast multiple processor machine (e.g. Deneleor HEP series, Cray 2-x) with each processor able to operate independently and read the same memory.

In the case of huge ($10^6 \times 10^5$), sparse (99.99% empty) systems very rapid and efficient indexing becomes just as important as the vector or matrix-vector nature of the calculation. Special purpose computers for these systems, which arise from tomographic problems, are not available. In fact, seismologists today have only the most limited access to adequate supercomputer facilities, while the need exists now and is growing rapidly to justify a complete supercomputer facility for seismology.

To fix ideas about computer speeds in numerical linear algebra a VAX 11-780 executes at the rate of 0.14 MFLOPS (million floating operations per second), a FPS-164 is 1.3 MFLOPS and a Cray X-MP is 33 MFLOPS. If one forces matrix-vector operation by vector unrolling in FORTRAN the FPS-164 is 4.0 MFLOPS and the Cray X-MP is 134 MFLOPS. For the Cray X-MP only one processor is used.

Computing with a very large dataset is very input-output (IO) intensive rather than CPU intensive. The data flow from the 100 station global network that is the subject of this research plan is about 2 gigabytes (Gb) a day if the sampling rate is 20 times a second. For processing purposes we can think of an array $S(J,K)$ where J is the time index and K is the station-component index for each event (earthquake, explosion, impact). Often for signal analysis we want the transposed array $S^T(K,J)$. Transposing a 2Gb array is a very large computational task, even if one uses a very efficient prime number sorter on the columns of the array. Whopping IO tasks of this kind, (time, space) or (wavenumber, frequency) to (frequency, wavenumber) transposition, plus other stacking, phase equalization, and signal/noise enhancement procedures will increase by a factor of at least 100—200 over the next 3—5 years. The lack of adequate computational facilities for the users of the data from the global network is a critical matter and underscores once more the urgent need that seismologists have.

While a supercomputer facility is not included in the budget in this plan it is clear that access to a modern facility is necessary now, and a complete supercomputer facility for seismology is indicated in the not too distant future. For the short term one of the new NSF sponsored regional facilities (e.g. Berkeley, San Diego, Urbana/Champaign) may suffice. For a typical supercomputer facility the budget in Table 3.1 is reasonable.

Table 3.1 Seismological Supercomputer Facility

		Capital Cost
1	Cray X-MP 2 Processor 4 M words	$11,000,000
2	Disk controller	120,000
8	600 Mb disk	600,000
1	Mass store and Mainframe computer	1,000,000
4	Hyperchannel	160,000
1	Cray buffer memory	200,000
2	Mini computer comm. processors	700,000
2	256 Mb solid state disk	200,000
4	STC optical disk	600,000
	Misc. tape drives, controllers, printers	100,000
	TOTAL	$15,580,000

Monthly maintenance costs of about $100,000 are in line with the capital cost of the facility. An operating budget of about $800,000/mo. is indicated by the size of the facility.

At this stage it is premature to discuss whether the facility would stand alone or be part of one of the NSF proposed regional facilities. However, it is unmistakably clear that the seismological community will soon need thousands of CPU hours per year of supercomputer time.

4. TECHNICAL PLAN

4.1. Introduction

Stated in its simplest terms, the goal of a new generation global seismograph network is to produce broadband, wide dynamic-range digital data from a global network of at least 100 stations and provide for the timely collection and distribution of these data to a wide variety of users. In order to achieve that goal, technical specifications must be developed which respond directly to current and anticipated future scientific needs discussed in the previous section and which take full advantage of current technology while providing the flexibility to incorporate future developments. It is not our purpose herein to present the details of the the network design, but rather, to present the general design philosophy, indicating those areas that will require special attention during the initial stages of development.

As described in the NAS report on "Effective Use of Earthquake Data" there are few technological limitations to gathering seismic data over the complete frequency and amplitude range of ground motions produced by earthquakes. Beyond the specific requirements of the seismograph sensor itself, almost all of the hardware components required for a digital network can rely on technologies developed outside of seismology. This is in sharp contrast to the WWSSN development, where virtually every component in the seismograph station and much of the equipment for data recording were specifically developed for the seismological application. Inherent in the improved data quality from a digital network is a corresponding increase in data quantity and a much greater flexibility in data processing. Some important problems related to a digital network lie in developing an effective mangement for the collection, storage and distribution of these data, discussed further in section 4.5.

Advances in electronic and telecommunication technology, as well as developments in seismic sensors now offer the opportunity to give earth scientists reliable and continuous global coverage of the earth's seismicity in nearly real time. Most of the existing seismological stations are limited by the technology, now obsolete, which required compromises in the frequency band and the sizes of events recorded. The key technical requirements of the new network dictated by the scientific goals are:

- digital data acquisition with real-time or near real-time data telemetry;
- bandwidth from hours to approximately 10 Hz;
- dynamic range sufficient to resolve ground noise and to record large teleseismic signals;
- low noise instrumentation and environment;
- linearity.

From a practical viewpoint, for modular standardization is highly desirable. Past experience with operating seismic networks, regional or global, has graphically demonstrated the disadvantages of constructing a network from a diversity of individual stations with differing characteristics. It is cumbersome and costly from a viewpoint of network operations, and increases dramatically the complication of data collection and analysis, often diminishing the reliability of the final scientific results. Of course the network must maintain the flexibility to encourage participation with stations of differing characteristics as long as they meet certain standards.

The WWSSN is a completely standardized analog network. Station components remained virtually unchanged over its 20 year history and differences between stations were limited to absolute magnification. Within that standardization lay both the greatest strength and the greatest weakness of the network. Because of the analog nature of photographic recording, the system, once established, was inherently incapable of modification. A modern system, in contrast, with discrete and relatively independent components (i.e., modularity) is easily modified and hence can be updated as new technology is developed and still maintain the necessary degree of standardization. Thus, the proposed network, if carefully configured should provide the science with its observational tools for at least twenty five years after deployment. The

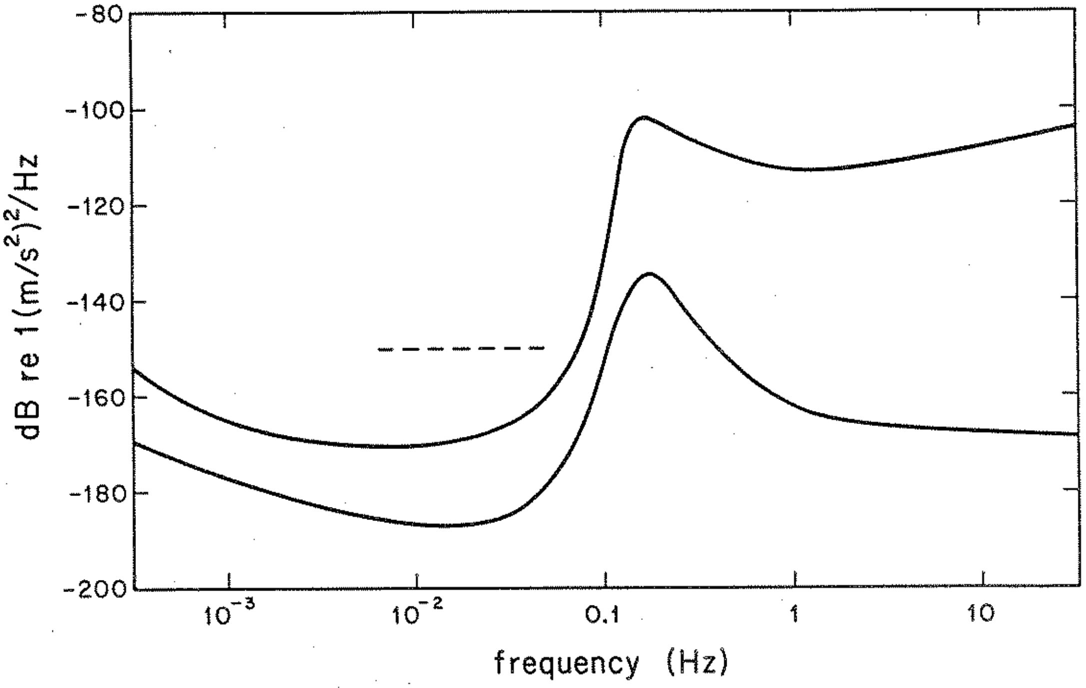


Figure 4.1. Ground noise reported at seismic stations. The dashed line indicates the ground noise to be expected on horizontal instruments at the surface or in shallow installations during windy periods. Few sites achieve the lowest noise levels, particularly at the higher frequencies. (Agnew, with permission)

decisions on the type and characteristics of the instruments, the mode of recording, transmission and collection of the data, the procedures of archiving and dissemination will be preceded by experiments and design studies. These studies, some of which are already underway, will represent some of the most important activities during the first two years of this plan.

The technical plan described in this section pertains to state-of-the-art stations that could be installed within this project. Clearly, the network envisioned here would be complemented in the most important way by networks or individual stations, either presently existing or to be installed by other countries. It is clear from examination of Figure 2.1 that cooperation of many countries that did not participate in the WWSSN project will be needed to make the global coverage more even. The issue of international cooperation is addressed in Section 5. What needs to be stressed here is that addition of digital stations in unique locations would be of great value to science even if they were not to cover the full frequency band or the real-time telemetry were not feasible. A truly global network of standardized broadband instruments, like the real-time data broadcast by satellites throughout the world, represents an evolutionary goal. In these terms, this project should be thought of as an evolutionary one; the plan points out that the necessary technology exists today.

4.2. Data Requirements

4.2.1. Introduction

In designing the seismograph system for the new network, the foremost issue is the definition of the data requirements in terms of resolution, bandwith, and dynamic range. Both the amplitude and frequency range of interest in seismology cover many orders of magnitude (thousands of seconds to tens of Hertz; nanometers to centimeters). In the past it has not been technically possible to cover this entire spectrum of signals with a single system. The application of modern techniques in electronics and control theory offers major improvements in seismometer design not utilized in existing networks. Indeed, the broadband records produced by such instruments, merely by providing a more accurate representation of earth motion, offer new possibilities in interpreting seismic data that are now hidden by the usual narrow band recordings. The eight years of experience of the Graefenberg (Germany) array provides a convincing example of the advantages of broad-band recording.

4.2.2. Bandwidth

Over what frequency band do we need to detect signals down to the level of ground noise? At low frequencies, the response can easily be extended to zero frequency. Indeed most high-quality seismometers are electronically fed back and usually have a flat response from zero frequency to some high frequency cut-off. However, as a practical matter, it is often desirable to provide a low frequency cut-off to the response. The earth tides can be recorded on a separate channel with a low sample rate and this provides a very useful calibration signal and helps to monitor the drift of the instrument. The response at long periods must allow us to record the gravest modes of free oscillations of the Earth for sufficiently large events.

A high frequency limit cannot so easily be set. This limit determines the sampling rate of the network and so controls the data volume which must be handled. The observations summarized in the previous sections suggest that a sampling rate of of about 20 samples/second would be adequate for an initial network configuration. As we gain experience with this data rate, it should be possible to increase the high frequency limit in the future if science warrants this.

4.2.3. Ground Noise and Dynamic Range

Figure 4.1 illustrates the range of ground noise reported at seismic installations. Few sites achieve the lowest levels.

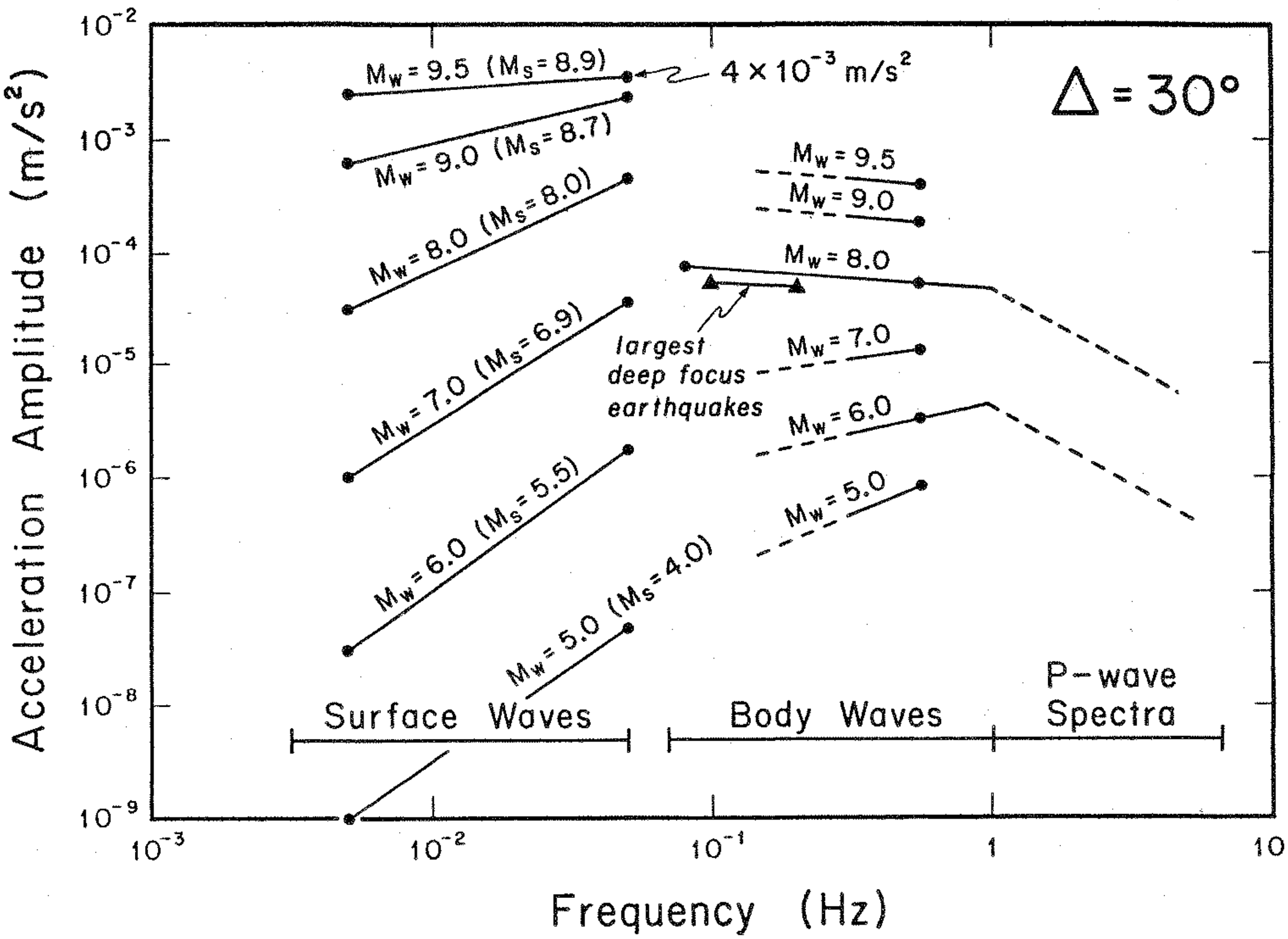


Figure 4.2. Acceleration of ground motion at Δ = 30° expected for earthquakes with $M_w = 5$ to 9.5. For the frequency range from 0.005Hz (200 sec) to 0.05 Hz (20 sec), estimated time-domain amplitudes of surface waves are shown. For the frequency range of 0.05 Hz (20 sec) to 1 Hz (1 sec), estimated time-domain amplitudes of P and S waves are shown. For the frequency range of 1 Hz (1 sec) to 5 Hz (0.2 sec), time-domain amplitudes estimated from spectral amplitudes of P waves are shown. At frequencies higher than 1 Hz, the estimates are subject to large uncertainties due to regional variations of Q and velocity structures. Triangles indicate the data for the largest deep focus earthquake. (Kanamori, with permission)

At long periods ($f < .1$ Hz) most noisy locations are those near coasts. This is only a problem when geographical distribution requirements dictate the use of a small island site. Ground tilt from wind turbulence is a major source of noise on horizontal component instruments in this band (see dashed line Figure 4.1) and may be expected at most surface sites. Some locations may be equipped with borehole seismometers.

Keeping noise levels low is an important factor in site location but the real interest in seismology is in recording transients and so we must primarily be concerned about recording large signals. There are two aspects to consider:

a) linearity of the seismometer; the voltage produced should be a linear time-invariant function of the ground motion so that the relationship between them can be described using linear filter theory

b) dynamic range of the system; neither the full scale clipping nor the noise produced by quantization should obscure any signal we wish to study.

It is unlikely that a single seismograph will record the full range of ground motion experienced in the near field of an earthquake, so a decision must be made as to what should be recorded on scale with high fidelity. As the station separation for a 100 station network is approximately 20°, it is reasonable to use this distance as the limit beyond which all stations should remain on scale. For near field on-scale recordings, stations could be equipped with separate, relatively inexpensive strong motion accelerographs.

An earthquake with a moment exceeding 10^{28} dyne-cm occurs every one or two years; earthquakes approaching 10^{30} dyne-cm occur every few decades. It would therefore be desirable to require the system to be capable of producing low distortion, on scale records of an earthquake of moment $\sim 10^{30}$ dyne-cm ($M_w \approx 9.3$) at a distance of 20°. Figure 4.2 shows the peak acceleration expected at regional distances from a range of magnitude earthquakes and over the range of frequencies. Over most of the seismic frequency band, acceleration will rarely exceed 10^{-3} ms^{-2}. Only for very large events which occur about once a decade will the accelerations reach 4×10^{-3} ms^{-2}.

The system should be designed to record these levels of acceleration while resolving ground noise at quiet sites. Consideration of Figures 4.1 and 4.2 lead to a specification of greater than 120 dB dynamic range, or the ratio of full scale to resolution. This specification, in turn, leads to the specification of the number of bits in the analog-to-digital converter. Modern force-balance seismometers typically have an analog dynamic range (self noise to clipping) of 120 dB at midband. The resolution (or accuracy) of analog-to-digital converters has been less until recently, ranging from 72 dB (peak to peak) for a 12-bit encoder to 96 dB for a 16-bit encoder. In order to take advantage of the dynamic range of the seismometers, the operating range of encoders has been increased by a gain-ranging technique in which the analog signal is attenuated in a series of steps as the encoder output approaches full scale. The technique permits large signals to be recorded, but the resolution of the encoder, referred to input voltage or equivalent earth motion, decreases in proportion to the attenuation. In recent years, 24-bit encoders have been commercially developed. The increased resolution of these encoders is achieved by bit enhancement (a process involving oversampling and averaging) and the actual resolution is frequency-dependent. However, they are expected to have a resolution of at least 120 dB at 0.1 seconds and higher resolution at longer periods.

It could be argued that seismometer nonlinearities obviate the need for higher resolution encoders because distortion products create a noise floor 80-90 dB below the full-scale signal. However, the nonlinearities in seismometers have not been thoroughly studied, and the use of 24-bit encoders should avoid the distortion that can occur in the gain-ranging process. At the same time, until the 24-bit digitizers pass the field tests, considerations should be given to the development of gain-ranged digitizers with 16-bit (96 db) resolution, as they are readily available, involve lower-level technology, and are likely to be less expensive.

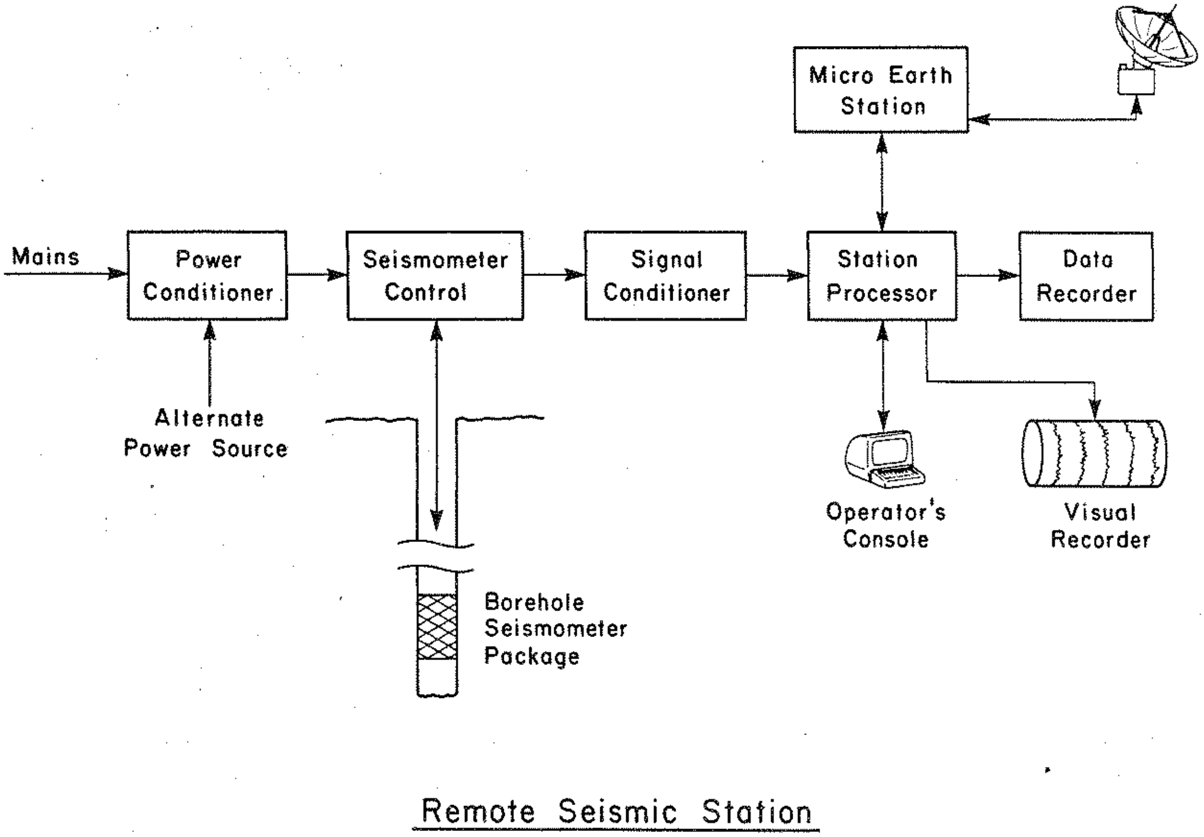


Figure 4.3. Block diagram of the remote seismic stations. Seismometers may be installed on the surface or in boreholes. Data will be recorded locally and telemetered where possible via satellite to central recording facilities. (Berger, with permission)

4.2.4. Continuous versus Triggered Recording

Some seismographic instruments operate only in the "triggered" mode; strong motion instruments, for example. Other instruments record ground motion continuously; for instance, stations of the IDA or, at a data rate 400 times higher, the RSTN networks. The GDSN stations provide continuous recording of long-period channels and triggered recordings of mid period and short-period data.

The use of triggered recording has been required in the past due to the limitations in the capacity of the recording medium, transmission rates in the case of telemetry, and the ability of the data collection and archival centers to process, store, and distribute a particular volume of data at an economically justifiable cost. But it is clear that triggered recording has serious disadvantages.

Signals below the trigger level will not be detected or recorded at an individual station, but if the data from all the stations were combined, the use of array processing techniques might lead to a sufficient improvement in the S/N ratio to detect such signals. The experience of the LASA and NORSAR arrays provides many examples of this kind. Studies of radiation patterns, seismic sources, the effect of lateral heterogeneities on amplitudes of body waves and attenuation could lead to biased results if the low-amplitude signals were artificially eliminated. An objection to the reliance on triggering algorithms can be made on more general grounds. These algorithms are designed to respond to the expected characteristics of the signal, but, in case of unusual sources or seismic phases of an atypical frequency content, they may not trigger. A network with recording based on a triggering mechanism would, at best, record the expected signals, but would also make new discoveries by future researchers much less likely.

Ninety days of continuous recording were used in derivation of one estimate of the attenuation of the mode ${}_0S_0$; the amplitude of the mode was below the least count. It is clear that the GSN must provide continuous recording of data; the only question is what should be the maximum sampling rate of the continuously recording channels. It appears that 20 samples per second should be entirely feasible in view of the developments in the digital storage technology during the last decade. A sampling rate of this order adequately covers the range of frequencies in which deterministic modelling is now feasible.

Inevitably, the design of the system will need to be a compromise between scientific objectives and technical and economic limitations. These issues will be discussed in later sections; however, the overall design should be configured to allow both continuous- and triggered-mode recording.

4.3. Seismic Stations

4.3.1. Introduction

The design and development of the seismic station system is one of the most important tasks in the program. The 100 sets of station instrumentation are also the most costly item in the budget. Development risks do not appear to be significant; nevertheless, decisions must be weighed carefully and, wherever possible, candidate instruments and techniques should be tested before selection is made.

Figure 4.3 illustrates in block diagram the key elements of the proposed seismic station system. Some of the stations systems (preferrably all) will be equipped with transceivers for data telemetry and message communication via satellite circuits. Some stations may have to function without the telemetry link, and design will permit this. There could be telemetered data systems installed at remote locations that are unattended for long intervals (months). At some sites, it may be desirable to install the seismometers at a distance from the existing station facilities to avoid cultural noise.

Key elements in the seismic station system design goals are:

- Performance; approximately 10 Hz bandwidth; better than 120 dB dynamic range; high linearity; accurate calibration.
- Modularity; flexibility in operational configuration, eases maintenance, and allows for gradual upgrading.
- Standardization; implemented in a way that permits a variety of hardware configurations to meet differing station situations.
- Reliability and Maintainability.

4.3.2. Station Density and Distribution

There are many reasons why a global network should be as widely distributed as possible. The present lack of instrumentation in the Pacific and Indian Oceans has lead to an underestimate of seismicity in these regions. With a good distribution of stations source mechanism can be determined for an event above certain fixed magnitude threshold anywhere in the world. Clearly the larger the number of stations, the smaller the events that can be detected and analyzed. It is our experience that a reliable source mechanism is obtained if an event is recorded by about 10 stations well distributed in azimuth about the source.

The construction of models of spherically averaged Earth also requires a uniform distribution of stations to minimize the bias of the gross Earth dataset by the effects of aspherical structure. Similarly, the study of large scale aspherical structure requires an even sampling of the surface of the Earth.

The global coverage will remain uneven without deployment of instruments on the ocean floor. While the necessary technology exists for continuous operation of land-based stations, many developments are still necessary for the ocean bottom stations. Because the availability of these data is of critical importance to the truly global sampling of the earth, we have included in Section 4.3.4 a brief discussion of the issues relevant to the seafloor seismic recording. All efforts that would make it practical in the near future should be strongly encouraged.

No specific station distribution is proposed here. Such decisions must be preceded by discussions with representatives of other countries and design studies which will determine the optimal network given realistic constraints on possible station sites and the uneven global seismicity.

4.3.3. Station Siting

The dynamic range and bandwidth that are scientific requirements of the system are predicated not only upon the instrumentation but also upon the noise environment of the station. Clearly, the siting of the seismic stations is as critical a design parameter as is the instrumentation itself. While much use can be made of existing seismic vaults, inevitably some new sites will be needed. The chief technical criteria for a good site is low seismic noise. This is usually determined by measurements made at a prospective site with portable equipment. In some cases the low noise criteria must be relaxed in order to assure adequate global coverage.

At a particular site, the noise environment can usually be improved significantly if the seismometers are emplaced in a borehole, some hundred meters below the surface. This technique has been demonstrated to reduce greatly the seismic noise generated mostly by the wind at the surface. It also reduces the effects of surface tilts that plague long-period horizontal seismometers. Unfortunately, borehole emplacement adds significantly to the installation costs but at many sites it may be highly advantageous.

Other important factors in site selection are:

- accessibility
- power availability
- local support,

the last being the most important non-technical specification. It has been demonstrated, many times over, that the best of stations are those with a dedicated local staff and that while all other criteria for a good station may be met, the lack of local support almost always spells disaster. In this respect, the proposed network will benefit greatly from the experiences gathered by the existing network operators over the past two decades and the goodwill they have succeeded in establishing and maintaining in foreign countries.

4.3.4. Seafloor Seismic Recording

As two-thirds of the earth's surface is covered by oceans, stations on islands cannot adequately provide the required spatial distributions. In particular, islands in the Pacific, south Atlantic, and Indian oceans are unevenly distributed. Furthermore, at higher frequencies the wavelength of the seismic waves approach the dimensions of the islands and the area of the lithosphere flexure associated with these islands. Regional studies requiring relatively short period data to study the structure of the oceanic lithosphere, asthenosphere and uppermost mantle may be precluded by the global station distribution confined to land areas. In addition, seismic noise at microseismic frequencies (0.1–0.3 Hz) is a great deal higher on islands than on the seafloor largely due to the effects of wave action.

Noise levels on the seafloor, once felt to be prohibitively high, have recently been found to be comparable to many continental sites at microseismic frequencies (0.1–0.3 Hz) and as low as some of the best continental sites at frequencies in excess of 1 Hz. Figure 4.4 illustrates a number of noise displacement power spectra at frequencies of 0.1–10 Hz which are of interest. The curve labeled MSS (Marine Seismic System) was computed by stacking a series of spectra from the recent DARPA-sponsored NGENDEI experiment in the southwest Pacific. The instrument was a nominal 1 Hz vertical geophone in a 140 meter deep borehole in 5600 meters of water between the Tonga-Kermadec Trench and Tahiti. The noise levels, even within the microseismic peak at 0.2 Hz, are lower than the classical Brune-Oliver upper bound on noise at continental sites.

At high frequencies the power levels are only on the order of a decade higher than those of the quietest site yet documented on any land mass. Ocean bottom seismographs (OBS'), under the same conditions are significantly noisier as can be seen by the comparisons to OBS Suzy. The spectral lines at 10 and 20 Hz in the MSS and OBS spectra are due to local drilling ship noise. Some sites on the seafloor, where mild weather conditions and basaltic outcrops occur, are as quiet as the seafloor borehole sites. This is illustrated in Figure 4.5 where the dashed lines represent upper and lower limits on seafloor noise as observed by over a decade of OBS deployments by the Scripps Institution of Oceanography. These are compared to the OBS and borehole (MSS) levels from the previous figure. The lower dashed line corresponds to a deployment on the basalt of the East Pacific Rise at 21°N while the upper dashed line was observed at a northern Pacific site between Hawaii and the continental U.S.

The noise level on the seafloor at lower frequencies behave in a fashion similar to observations on continents. Figure 4.6 is an acoustic pressure (roughly proportional to velocity) noise power spectrum obtained by an acoustic sensor operated by the Scripps Institution of Oceanography. Below the microseismic peaks the noise level drops precipitously to very low levels and begins to climb rapidly at frequencies on the order of 10 mHz. The increase in levels is caused by temperature fluctuations in the seawater and provides only an upper bound on actual ground noise levels.

Noise levels on the seafloor thus pose no impediment to placing broadband instruments in the world's oceans. Problems with power supply, corrosion and data storage as well as the difficulty of operating a long period sensor in a small, isolated package must be dealt with in a seafloor seismograph although the technology exists to make steady and rapid progress with these difficulties. Satellite telemetry systems operating from moored buoys are in an advanced state of development at the Woods Hole Oceanographic Institution. A buoy capable of transmitting digital data at 4800 baud between latitudes of 60°N and 60°S will be operational in 1985 and is anticipated to have a lifetime of five years. The $50,000 cost of the buoy is

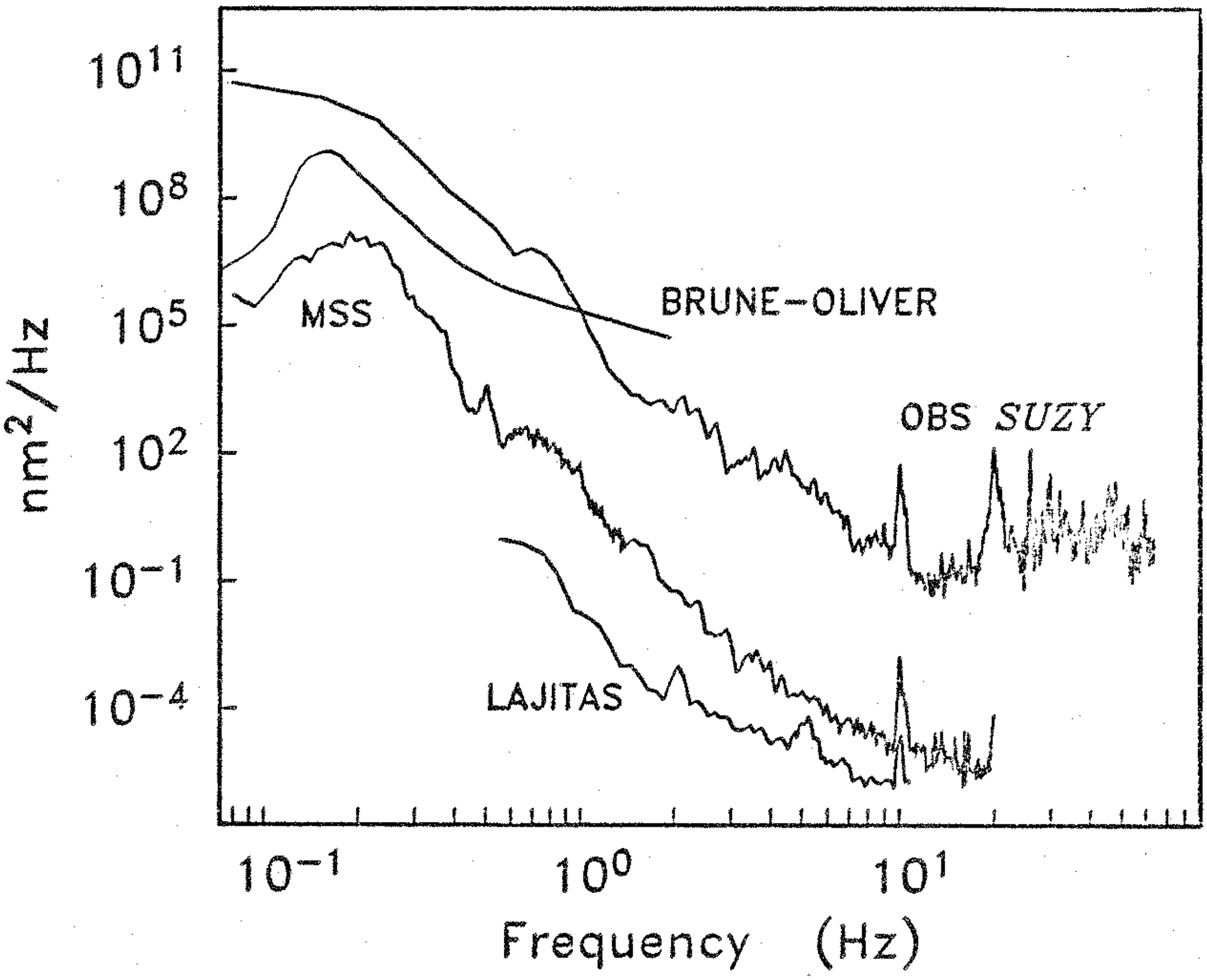


Figure 4.4. Seafloor and sub-seafloor displacement power spectra for seismic noise compared to the Brune-Oliver upper bond for continental noise and the extremely quiet Lajitas site in the Great Bend area of Texas. (Orcutt, with permission)

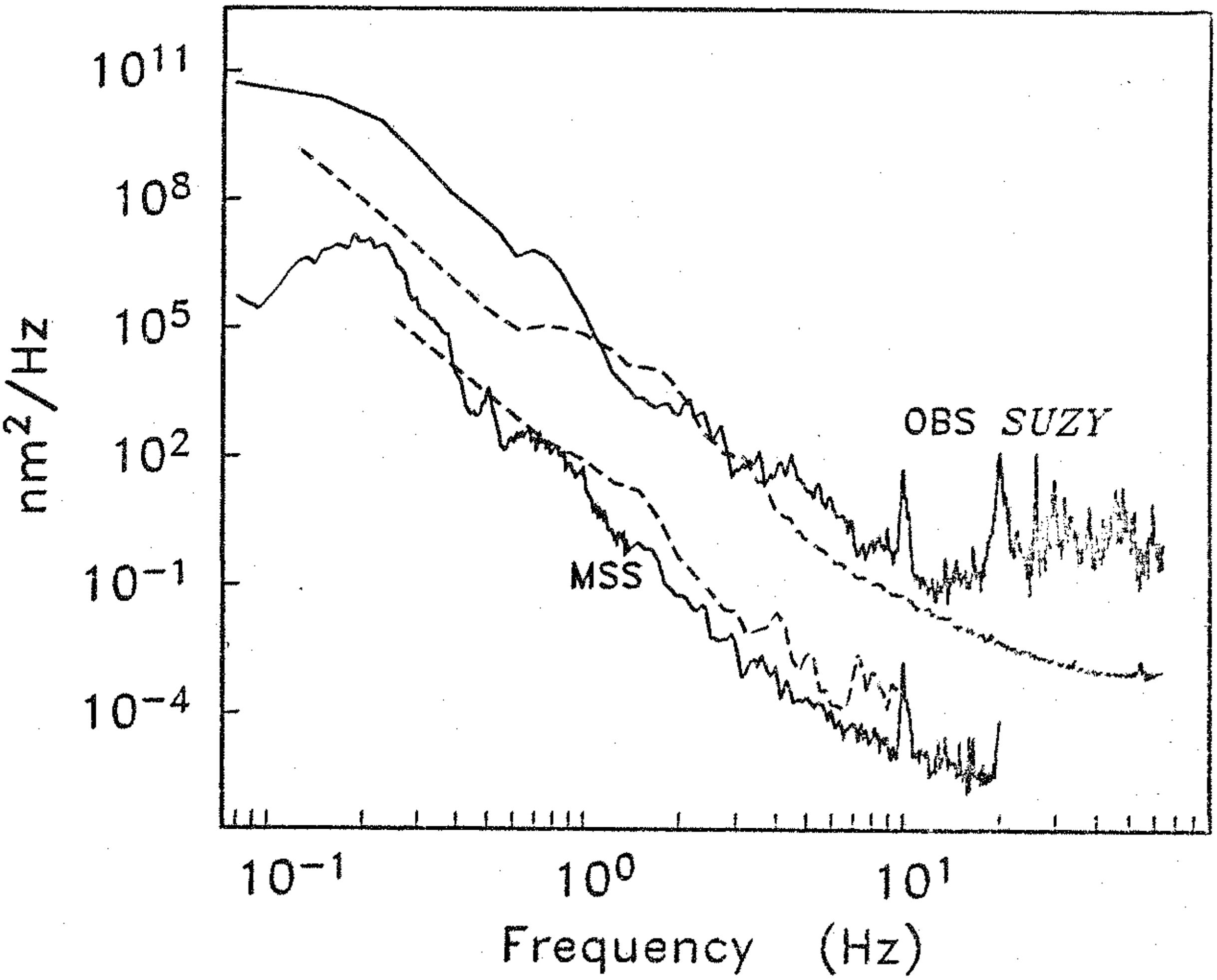


Figure 4.5. Comparison of noise levels at and below the seafloor in the South Pacific with previously estimated upper and lower bounds on displacement power spectra at the seafloor. (Orcutt, with permission)

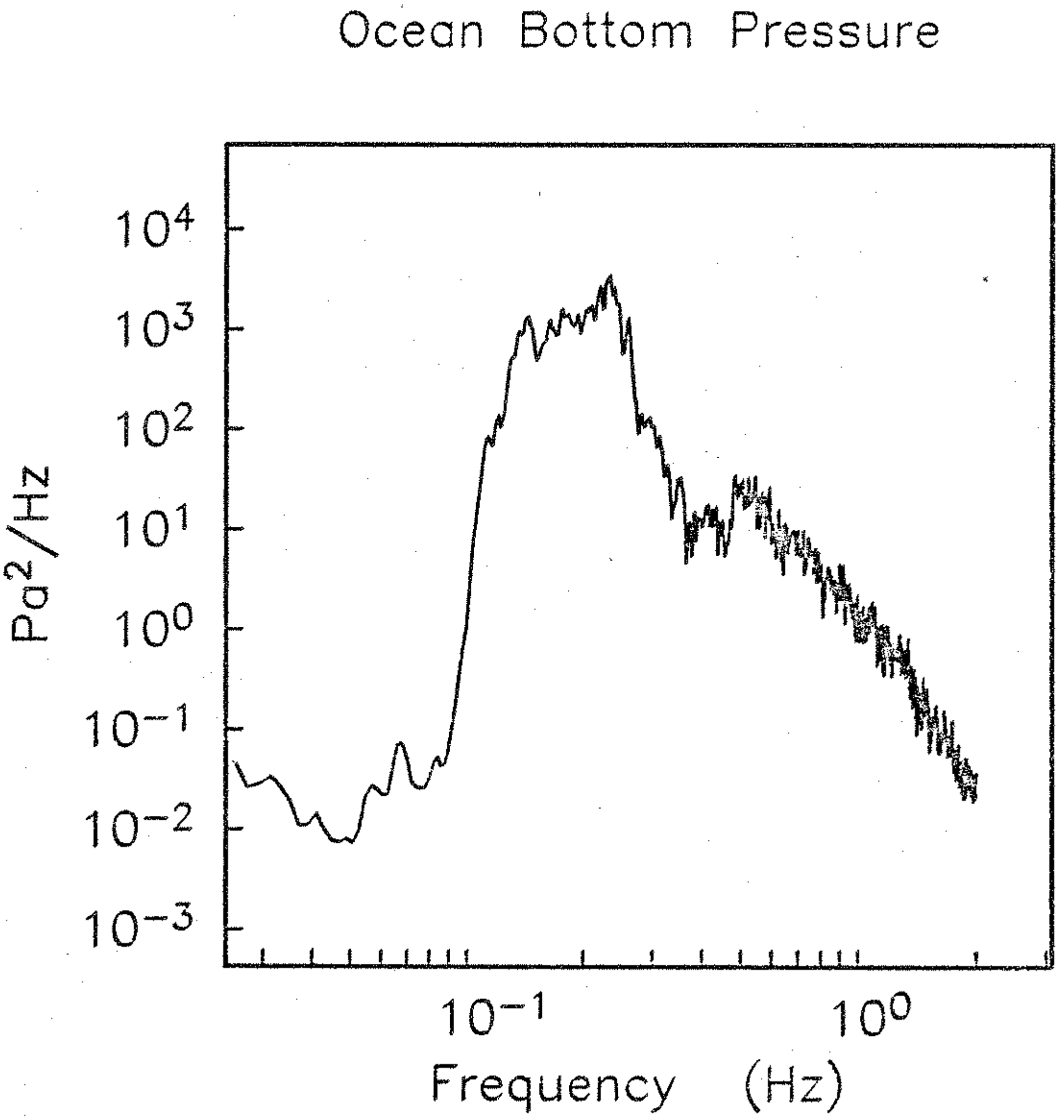


Figure 4.6. Behavior of seafloor noise as measured by a pressure sensor at frequencies lower than those in Figures 4.3 and 4.4. The decrease in noise levels below 0.1 Hz is identical to that observed on continents. (Orcutt, with permission)

reasonably low and can be linked to either seafloor or borehole instruments. The installation of a test system by 1986 is anticipated and an expanding role for seafloor seismic stations is expected as the global network grows.

4.4. Real-Time Data Telemetry

The goal of real-time telemetry from the GSN stations to several data centers around the world is clearly an exciting aspect of this proposal. In section 3.2.5, scientific rationale for such real-time telemetry is discussed. The most important aspect, however, of such telemetry is its cost-effectiveness. With the GSN configured with real-time telemetry, it will be significantly cheaper to operate and distribute the data than otherwise. Further, in the design of the GSN, we are trying to configure a network that will become fully operational in the 1990's and serve as a principal data source well into the next century. Thus, we must be looking forward, and it is clear from current trends in telecommunications that the next decades will see widespread use of satellite data communications and significant reductions in costs. Satellite telemetry of seismic data has been demonstrated in North America using conventional telecommunications technology. The Regional Seismic Test Network operated by Sandia National Labs and funded by DOE consists of 5 stations located in the US and Canada transmitting data in real-time to receiving stations at Livermore, CA., Albuquerque, NM., and Alexandria, VA. The technology utilized is frequency division multiplexing. In the past, however, the remote stations and the receiving stations were large and expensive and the satellite channel rentals high. With this level of costs, and the complexity of the equipment it would clearly be beyond the budgetary scope of this project to consider real-time telemetry of the entire network's data stream. But, the technology and the cost associated with satellite telemetry of information is rapidly decreasing. Figure 4.7 gives some idea of the dramatic decrease in costs over the past decade and all indications are that this trend will continue.

For the GSN, a somewhat different technology is being considered. The principal features of this system are:

- small, low-cost earth stations,
- low satellite channel costs.

A candidate system being presently investigated utilizes what is called spread-spectrum technology, recently introduced into the commercial markets. Refined over the past 30 years in military radar and radio astronomy applications, the technology has resulted in very small earth stations with low power requirements. The technique minimizes interference from other satellite or terrestrial sources by utilizing more frequency bandwidth than conventional signals transmitted at comparable data rates. Earth stations with antennas as small as 1.2 m in diameter have been successfully produced in quantity and are now in routine operation in the United States. Some 6000 low-cost ($2.5K) one-way stations currently are receiving broadcast data with such services at UPI, Dow-Jones, Commodity Prices, etc.

Two-way spread spectrum ground stations (costing $6500) have been operating in the U.S. for about one year. These stations use the spread spectrum coding to multiplex signals coming from different stations through the satellite. The signals are received by a large central ground station where they are decoded and either routed locally to their final destination or rerouted out through the satellite link back to the small ground stations.

It must be emphasized, however, that at the present time obtaining real-time telemetry from all 100 stations will present difficulties. Telecommunications is, in general, a highly regulated field and each country has different regulations governing satellite communication. Our design studies presently underway are based on the use of the INTELSAT network for stations not within the range of U.S. domestic satellite. However, it is not unlikely that there will be station sites from which real-time telemetry will not be feasible at least at present from either political or economic reasons. Thus, in the GSN design, other modes of data collection are planned.

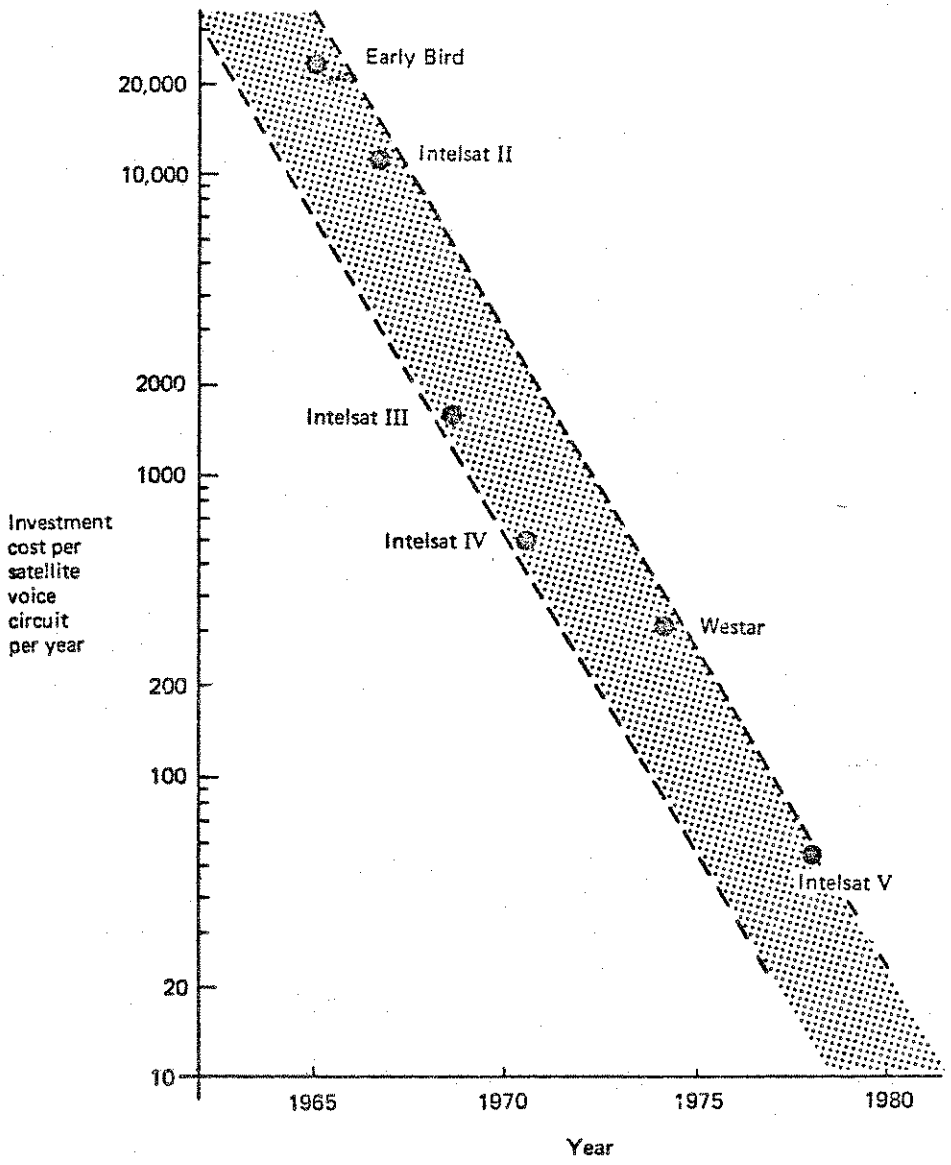


Figure 4.7. The falling cost of satellite circuits. (Martin, *Communications Satellite Systems*, Prentice-Hall, Inc., 1978)

At stations where for one reason or another real time telemetry is not feasible, the data from all channels will be recorded on site. This requires sufficient on site storage to minimize operator handling, yet not so much that timeliness of transmission to the data center is impacted. Experience indicates that about two weeks of recording time is reasonable. Further considerations include the robustness of the recording unit under field conditions and the ability of the media to survive the international mails.

4.5. Data Flow

4.5.1. Data Rates and Volumes

One of the key specifications in the system is the network sampling rate as this controls both the bandwidth and the volume of data produced. The sampling rate of the seismic signals is determined by the highest frequency of interest. While networks designed to study local and regional seismicity often cover frequencies up to 30 Hz and beyond, it is generally agreed that for global seismic studies 10 Hz is adequate. Thus, the typical seismic station will sample each of its three orthogonal components 20 times per second with perhaps three additional channels sampled at once per second. Allowing four 8-bit bytes (4B) per sample to accommodate todays 24-bit digitizers and leave room for future expansion, we arrive at the following data rates:

Each station:

3 channels at 20 samples/sec at 4B/sample
\+ 3 channels at 1 sample/sec at 4B/sample
= 252 B/sec

100 Station Network:

Aggregate data rate	= 25KB/sec	(kilobyte)
	= 2.2 GB/day	(Gigabyte)
	= 795 GB/yr	

Figure 4.8 compares the data flow from several seismic networks operated in the past, and now operational with the proposed network. LASA (Large Aperture Seismic Array) was a DOD funded array operated in the late 1960s and early 1970s. This input came from some 525 separate channels at its peak operation and collected data at the prodigious rate of about 200 tapes/day. Needless to say, data did not accumulate at this rate for very long. Event triggering was used to record the entire array data only for "signals" from distant seismic sources. The same technique is applied today to the GDSN data, by event detecting at the remote seismic stations rather than at a central location as did LASA. Thus the output or archived rate is only 12.5% of the input rate. The RSTN network includes only five stations in North America but the data is satellite telemetered and represents a modern system in prototype. SCARLET is the USGS/CIT network operating in southern California and is representative of such regional systems designed specifically to monitor local seismicity. Its output rate is only a little over 1% of its input rate.

The IDA network represents the other extreme of the seismic network spectrum. Every recorded bit is archived but the data rate is very low reflecting the specific research goals to which it was designed. Finally, the proposed global network's data rate is shown with its full output rate. Clearly, collecting, organizing, and disseminating this volume of data is a major task, one that is at the root of the overall system design. In later sections these problems will be discussed in some detail.

4.6. Data Management

In this section, the data flow and distribution from the proposed global network is discussed. The tasks of gathering, cataloging and disseminating data from the multitude of diverse

SEISMIC NETWORK DATA FLOW

	INPUT	OUTPUT		
NETWORK	KB/SEC	KB/SEC	GB/YEAR	MEDIA
LASA	20	VARIABLE		200 TAPES/DAY
GDSN	2.4	.3	10	1 TAPE/DAY
RSTN	2.7	2.7	86	4 TAPES/DAY
SCARLET	30	.4	12	1 TAPE/DAY
IDA	.008	.008	.25	6 TAPES/YEAR
GSN	25	25	795	OPTIONAL

Figure 4.8.

sources now in existence are not considered. There is now, and will likely be for the immediate future a need for a facility to perform these tasks. Indeed, the recent NAS Report "Effective Use of Earthquake Data" (1983) outlined the minimum requirements of a "National Center for Seismological Studies." This report was directed towards the overall problem of effective use of seismic data from a multitude of sources and it stressed:

> "Digital data are opening exciting new areas of research and applications that until now have not been possible even with the best analog data. To realize these potential scientific breakthroughs in seismology fully, these data must be effectively disseminated to a wide user community concerned with both basic research and applications of seismic data..."

It is clear that there is a present urgent need for such functions to be performed and in the NAS report the minimum requirements of such a center are enumerated.

The requirements of the network's data management system can be summarized by the following list:

- *Data Collection*
    1. Telecommunications to handle the data flow in real time, or nearly real time.
    2. Real time monitoring of the functional operation of the network in order to identify quickly and correct any interruption of normal data flow.
    3. Evaluation of data quality from stations sending data by mail, merging of these data with those recorded in real time.
    4. Ability to upgrade easily the data acquisition characteristics (especially sample rates of short period) to accommodate improved technology of data storage and acquisition, or special (design) experiments.
    5. Ability to control, from a central location, the network characteristics of operation (i.e., reconfiguration of sample rates, filter characteristics, etc.)
- *Data Archival*
    1. Large on-line data storage capability.
    2. Rapid de-archival of off-line data.
    3. Comprehensive indexing of entire dataset to provide rapid and easy recovery of specific data sets.
    4. Database management system to provide users with ability to retrieve both indices and waveform data via "seismological queries."
- *Data Dissemination*
    1. Remote access to the data by a "seismic workstation" allowing remote users the capability of quickly accessing the windows of interest.
    2. Extensive graphics capabilities for analog representation of the data on screen, film, or paper.
    3. Ability to distribute waveforms for selected time windows or events in digital form on easily usable mediums (i.e., magnetic tape, floppy disks, etc.).
    4. Computational ability to produce desired instrument response or true ground motion by processing with appropriate filters.
    5. Provide facilities and assistance for visiting scientists.
    6. Provide "quick look" capabilities of data available for particular time windows through a comprehensive indexing scheme.

These tasks need not be done at a single facility. Indeed, there are many arguments for distributing the overall processing load. If the network is telemetered in a broadcast mode, then the entire real-time data stream can be received by anyone with even modest means. Network Operations, Earthquake Information Services, Data Archival, etc. could all be performed at separate facilities (See Figure 4.9). If, however, a significant proportion of the data flow is recorded locally at the remote seismic stations and subsequently sent to a central location, then it follows that the final compilation of the full dataset will of necessity have to occur at a single facility. This does not mean that the real-time data stream cannot be used to perform rapid

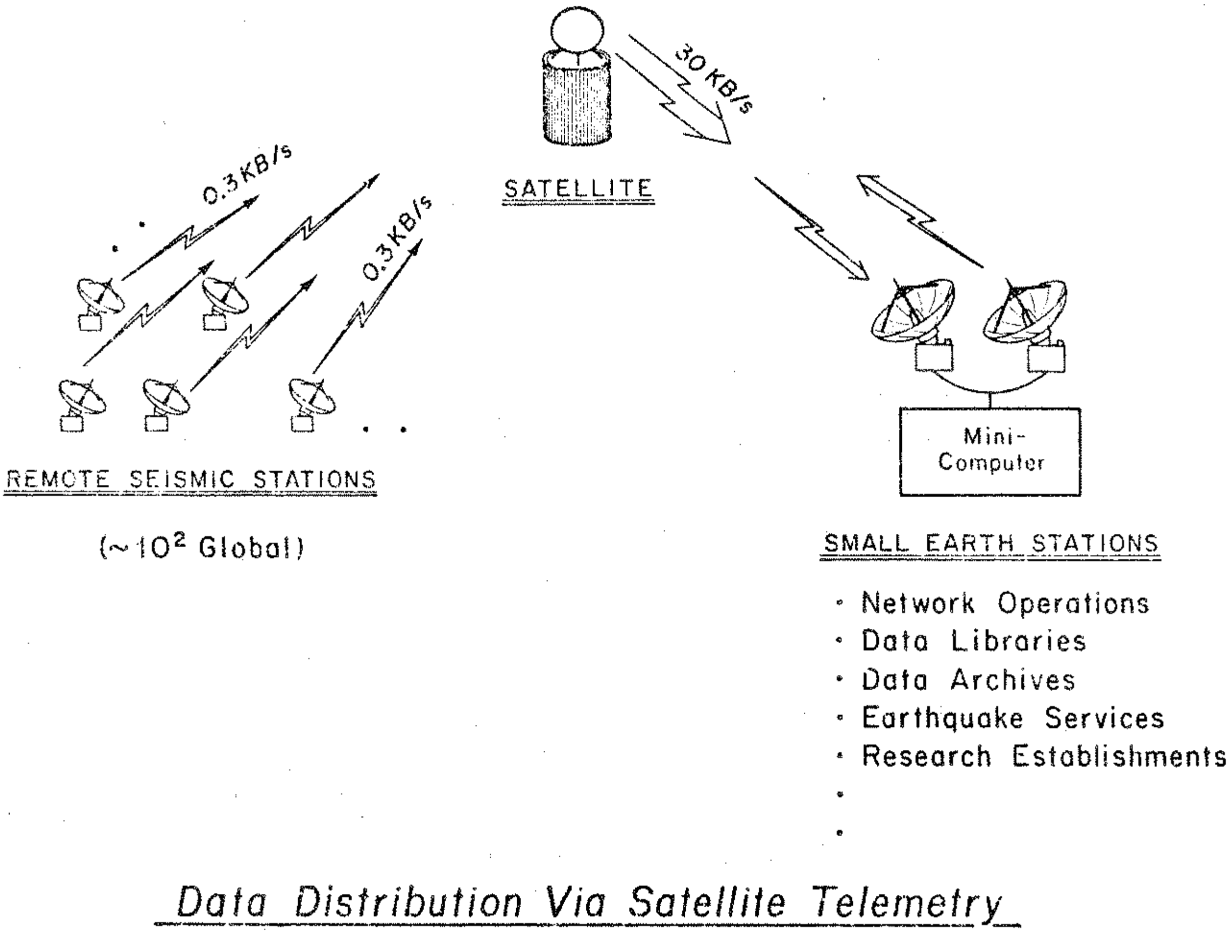


Figure 4.9. Data Distribution via Satellite Telemetry. Remote seismic stations transmit their data in a broadcast mode that can be received on a small earth station. The various data recording, monitoring and real-time analysis functions can thus be distributed.

analysis of source parameters, but in analysis of the operations of this network it is clear that real-time telemetry has overwhelming advantages and not in the data handling alone. In the planning, however, it is assumed that both types of data must be accommodated.

There may be several of these data centers nationally and worldwide, connected together as a computer network. They would provide focal points for seismic network operations and for data services activities. They might also provide facilities for visiting scientist to perform data intensive research. Remote computer and data access would be provided and supported via small, relatively cheap seismic work stations available to data users.

4.6.1. Data Collection

In this section, it is assumed that the network data are in a common format and arrive at a central location either in nearly real-time, or appropriately delayed, via mail.

It should be pointed out that even with 100 operational stations , the aggregate data rate of 25 KB/sec is not high in terms of the throughput of either modern telecommunications networks or small computers. Tasks such as monitoring the network state-of-health, event selection, or simply recording the entire data flow are relatively simple tasks, easily performed by small minicomputers. The big jobs — big in the sense of computational effort and equipment needed — are the organization, archival and dissemination of the data.

The first row of table 4.1 shows the data volumes generated per station-day, network-day, and network-year. Table 4.2 shows the capacity/volume of various storage media. The first five use magnetic tape and are available now. The last two use optical disks and are now appearing on the market. The scale of the problem may be gauged by noting that the aggregate data rate amounts to 18 reels/day of 6250 bpi tape.

Table 4.1

Storage strategy	Station-day Mb	Network-day Gb	Network-year Gb
all data	21.77	2.177	795.1
compressed	5.44	5.44	198.7
triggered	2.58	.258	95.2
both	.65	.065	23.7

Table 4.2

Device	Capacity/Volume Gb
1600 bpi tape	.03
6250 bpi tape	.12
cartridge streamer	.07
IBM 3850	.05
Nippon M860	.18
Shugart optical disk	1.00
STC optical disk	4.00

There are two well known means of reducing the volume of digital seismological time series data. The first depends on the correlation of band limited data. Because most of the data is Earth noise which uses only a small portion of the available dynamic range, a straightforward algorithm can probably yield a compression of a factor of four overall (including status bits) with no loss of information.

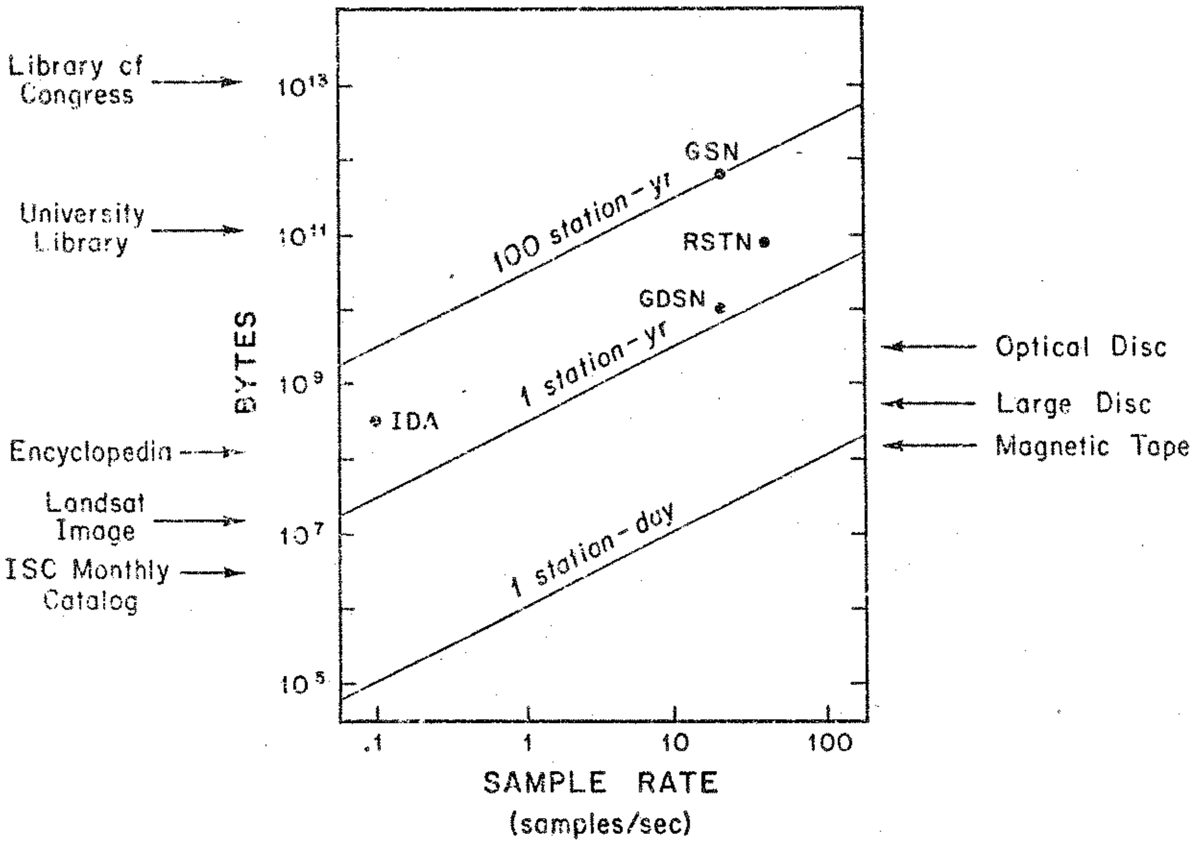


Figure 4.10. Volume of data accumulated at various sampling rates and network densities, after the *Effective Use of Earthquake Data*, NAS press, 1983.

The second technique is "triggering" which was discussed at some length in section 4.2.4. Here we discuss "post-facto triggering" which might overcome some of the objections stated there. Personnel at the National Earthquake Information Service (NEIS) estimate that the current global threshold for a complete catalogue (from a location point of view) is about magnitude 5.5. For aftershock studies it seems reasonable to include events somewhat smaller than this threshold. If, on average, 20 minutes of the high rate data for all events of magnitude 5.0 and above are saved, then about 100 min of high-rate data per day are saved. This will result in an overall data compression of nearly a factor of eight. The data volumes resulting from compression, triggering, and both together are shown in table 4.1.

Note, however, that to implement such an algorithm will require a significant departure from current practice. Currently, short period channels are triggered in the field. This results in many more triggers for small nearby events than for large teleseismic events. Consequently, the recording time/trigger is generally very short to reduce data volume. To implement triggering in a more rational way will inevitably require that all data be transmitted to a data center and that triggering be done at a later date after the location and magnitude of all candidate events is determined. Nevertheless, the objection remains that destroying available data might prevent future discoveries. Arbitrary magnitude thresholds and time windows would represent, at best, our current state of knowledge.

4.6.2. Data Archiving

As we have shown, the network will be capable of generating in excess of 795 GB/yr (6×10^{12} bits/yr). Figure 4.10 illustrates the data volume and how it compares with other large data bases and the storage media capabilities of today. In response to the demands of customers who generate up to 10^{15} data bits/year, new storage devices are under development which will help matters in the future.

One of the most promising developments is the optical disc which, using laser technology, permits storing on one platter, about one foot in diameter, up to several gigabytes of data. Several such devices have either entered or are about to enter the market. In addition to the compactness of storage, the direct access to any record on disc can be accomplished in a few tens of milliseconds. This is particularly attractive in those seismological applications in which only a small fragment of a long time series is of interest; a wave-form containing only the P-wave, for example. However, caution is warranted in planning on a specific device or even a particular technology. Historically, many promising products have never reached the marketplace and some of those that were eventually delivered to test sites never became fully operational. In addition, the amount of software development potentially required to interface a particular mass storage device to a given computer system can be formidable.

Archiving is particularly important for seismology as any very large event is unique in its tectonic setting and geophysical significance. Such events are often studied over a period of years or even decades by numerous investigators as the methods of analysis and interpretation improve. This indicates that long term stability of the archival media is important and that the media should not wear out significantly with use (otherwise only data no one wanted could be saved reliably). Both factors argue in favor of the anticipated characteristics of optical digital disks as opposed to the known disadvantages of magnetic tape.

Table 4.3 shows the number of volumes per year that must be archived given various storage strategies and media capacities. As discussed above, the recommended storage strategies are either compressed (row 2) or compressed and triggered (row 4). Column 1 corresponds to 6250 bpi magnetic tape, columns 2 and 3 correspond to he Shugart and Storage Technology Corp. (STC) optical disks, and column 4 to the capacity anticipated for both optical disks and cartridge tapes in the next few years. Using 4 Gb optical disks and compressed, but not triggered data storage, less than 5 cubic feet of conditioned storage space per network-year of data would be required. In contrast, more than 140 cubic feet of space per network-year would be required for 6250 bpi tape under the same conditions.

Table 4.3

Storage Strategy	Volumes/year volume capacity			
	.12 Gb	1 GB	4 GB	6 GB
all data	6626	796	199	133
compressed	1656	199	50	34
triggered	785	95	24	16
both	198	24	6	4

4.7. Summary

While the detailed specifications of the proposed global system needs further study to delineate, certain overall characteristics can be stated; for the remote seismic stations:

- Standardized modular equipment for most stations
- Well distributed stations (~100 globally)
- Broadband frequency response (20 samples per second)
- High dynamic range (low noise, 140db at .04Hz to 100db at 5Hz)
- Accurate calibration (linear, (0.1%)
- Real-time digital data telemetry whenever possible
- Ancillary field recording

for the data centers:

- Telecommunications to handle the entire data stream
- Computational ability to detect and locate events
- Large scratch storage
- Mass storage if available
- Data distribution capabilities
- Data archival capabilities

> "The data problems in seismology are of such key importance for achieving potential scientific advances and so changeable with time that continued vigilance will be needed to ensure that new developments in technology are implemented in a timely manner, enabling United States scientists and engineers to stay at the forefront of modern seismology."

(From *Effective Use of Earthquake Data*, NAS, 1983.)

5. INTERNATIONAL ASPECTS OF PLANNING AND IMPLEMENTATION

5.1. Introduction

The purpose of the global digital seismographic network is to provide data on a global scale of seismic events that are likely to be of scientific or practical significance to a wide variety of researchers and other users. It is evident that a minimum requirement for the installation and operation of this network is access to suitable sites all over the world at which the stations will be placed. This calls for cooperative agreements between the sponsors of the project and the countries having sovereignty over the sites involved.

Fortunately, seismology has established a solid tradition of cooperation among countries in permitting access to sites for observatories and in sharing seismograms and related data. This cooperation is motivated mostly by the national interests of the cooperating nations, since many of the most important problems to which seismology contributes simply cannot be approached if the investigators are limited to data taken only within their national boundaries. There are good reasons, therefore, for confidence that the cooperation essential for establishing the network will be available and that support of the effort by a number of countries is a reasonable prospect.

The success of the WWSSN for the past 23 years is clear evidence that a good distribution of sites can be achieved. Many countries have welcomed the selection of a site within their territory as a boost to their indigenous efforts in seismology and as a guarantee of access to data for their researchers. This view will certainly hold for the installation of the most modern instrumentation available, as planned here. We envision a harmonious and productive collaboration with the U.S. Geological Survey in establishing the proposed network.

The way in which funding for the proposed network must be obtained in the United States involves a certain amount of iterative effort, without prior guarantee of success. At this time, there is no assurance that this plan will be funded. A fairly detailed, realistic proposal must be submitted *before* financial support is even considered. Such a plan must be later revised to reflect the level of support actually granted and to consider interests of other U.S. agencies. In this way, many important decisions are made before formal negotiations with foreign institutions are feasible. In an attempt to involve our foreign colleagues in this early planning, IRIS has issued, so far, invitations to participate in meetings of its various committees to two foreign organizations which seriously consider efforts that are parallel or complementary to ours.

The selection of the sites for new stations is an important matter, both for IRIS and for the local scientists in those countries. It is, therefore, essential that all of the participants in the enterprise be brought into the planning activity at the earliest stage. In support of this requirement the Senate of IRIS did on 21 October, 1983, in La Jolla, California, unanimously approve the following resolution:

> "The Senate, recognizing that international cooperation is essential to the establishment of a global network, instructs the Board of Trustees to establish international liaison as soon as possible, and in particular, to initiate a study of the optimal network configuration in consultation with interested bodies elsewhere in the world and in coordination with other global networks now deployed or being deployed."

5.2. International Telemetry

While the telemetry systems described in section 4.4 have been operating routinely for several years in the U.S., the technology has not yet spread to the Intelsat network of international communications. The one-way technology was introduced to the International Intelsat system in July, 1983, by the Inter-governmental Bureau of Informatics (IBI). This is an organization of some 36 member-states that operates under United Nations auspicies, headquartered in Rome, Italy. Among other activities, this organization is promoting the use of this low-cost technology for international communications. The one-way spread spectrum technique was demonstrated by transmitting data from Fuicino, Italy, ground station through the Intelsat satellite and received on the small stations in IBI's offices in Rome. In September 1983 the small ground stations were moved to Geneva for demonstration at the Geneva Telecom'83 Conference. Based on these successes, IBI with support from Intelsat is forming an international operation entity, called IBI Net, to operate a regular data service.

The IBI Net is being formed around the one-way stations. They provide information services such as news, weather, commodity prices, etc., to the IBI Net users. IBI's plans possibly will include expansion to two-way services with the beginning of demonstrations in late 1984-early 1985. If these plans materialize, the proposed Seismic Network could make use of the IBI Net. If IBI Net is not appropriate for the Seismic Network, then the network management can work directly with Intelsat for separate services.

5.3. Interaction with Present International Seismic Centers

Existing analysis centers, such as the ISC in England, the NEIS in Golden, Colorado, and the European-Mediterranean Center in Strassbourg, play a key role in current seismological practice. They provide either fast determinations of hypocenter locations and other source properties, or the definitive results that become the global data base of seismicity. As with all data operations in all parts of science, these centers are impacted by evolving instrumentation, computing equipment, and communications systems. The roles and modes of operation of these centers will change with time, and the implementation of the Global Network may impact them significantly.

For the present, it is important that the leadership of these centers be kept fully informed of emerging plans for the new Global Network and that their experience and knowledge in collecting, processing and disseminating seismic data and results be exploited in planning the new network. In addition, the years of experience of the USGS personnel in running a global network is invaluable in guiding its development and implementation.

We anticipate that data collected by the new global network will be used extensively by scientists of all nations. Likewise, high-quality digital data collected by other countries will be used by U.S. scientists. Therefore, effective means of exchanging data must be developed. The data centers discussed above will provide the key focal point for data exchange. The important questions of data exchange formats, media for data exchange, and mechanisms for individual scientists to obtain data must be addressed. Various international organizations will play an important role in establishing mechanisms for effective data dissemination to the entire seismological community.

5.4. Cooperation with International Scientific Organizations

The support of international scientific organizations can be very helpful in the effort to establish and operate a global digital seismographic network. The endorsement of the relevant scientific organizations is often a prerequisite for the cooperation of agencies within various countries. In addition, the forums provided by the international organizations offer the best mechanism for establishing data-exchange policies and procedures that will meet the needs of the users. Finally, an excellent way to insure the involvement of the scientific leaders in the geophysical communities in many countries is to approach them through the existing international organizations, in particular, the International Association of Seismology and Physics of the Earth's Interior (IASPEI), one of the associations comprising the International Union of Geodesy and Geophysics (IUGG). The IUGG Bureau will be asked to seek endorsement of the proposed global network from its Executive Committee. The Inter-Union Commission on the Lithosphere (ICL) will also be approached for its endorsement; this is important because ICL represents many of the users of the data to be gathered by the new global digital network. Recently, Working Group 5 (Structure of the Lithosphere and Asthenosphere) of the ICL included Global Networks among its key projects.

IRIS includes in its structure a committee charged with developing and maintaining good working relations with international organizations, as well as attending to broader aspects of international participation.

6. ORGANIZATION AND MANAGEMENT

6.1. Organizational Structure

The organization plan for IRIS was derived from a detailed study of the structure of three, somewhat similar, scientific federations; namely JOI, Inc. (Joint Oceanographic Institutions, Incorporated), UCAR (Universities Corporation for Atmospheric Research) and USRA (University Space Research Association). In addition, the opinions of the full membership of the original Senate of IRIS were sought at meetings on 20—21 October, 1983, and 7 December, 1983. The Bylaws of IRIS were finalized following the incorporation of the consortium by the initial university members (See Section 6.2).

The organization of IRIS is outlined in Figure 6.1. The membership of the corporation, which is composed of a representative of each member institution acting through the Board of Directors, will empower a small, elected Executive Committee to exercise many of the powers of the Board of Directors. The Board of Directors is the primary policy making body of the corporation and is responsible for overseeing the work of its committees and the corporate offices. The Executive Committee of the Board shall have, with few exceptions, all the powers of the Board. Its role is envisioned as that of a Steering Committee and abbreviated Board. It will make necessary decisions between meetings of the Board. The Standing Committees, bodies concerned with the initial programs of IRIS, are largely responsible for the detailed structure of the scientific plans and the writing of proposals. The constitution and structure of the Standing Committees may change from time to time at the pleasure of the Board of Directors. The Advisory Council is a body of experts elected by the Board to provide the Board of Directors and any of its committees with experienced counsel. Figure 6.2 illustrates the initial structure for the Standing Committee and its subcommittees approved by the Standing Committee on its first meeting.

The membership of the Board of Directors and the corporation is restricted to institutions of graduate education and research in the United States. This clearly includes most universities in this country, but excludes government agencies, quasi-government national laboratories and non-U.S. institutions.. Such organizations may be affiliated with a university, but are probably contractually unable to become members of the corporation. Representatives of the national laboratories, government agencies, and foreign organizations may become affiliated with IRIS through appointment to the various committees. Members of the Executive and Special Committees must be Directors, but membership in the other committees is unrestricted.

6.1.1. The Incorporation Process

At the 7 December 1983 meeting of the *ad hoc* Senate the following resolution was adopted:

> The Senate resolves that a corporation of research institutions be formed to seek funding for major research efforts in the earth sciences, which will include the development and deployment of a permanent global digital network and a portable regional network and the establishment of one or more national seismic data and computation centers, and the Senate empowers the Board of Trustees to begin the process of incorporation.

A group of scientists involved in seismic studies of the continental lithosphere met in Madison, Wisconsin on January 13 and 14, 1984. This group, representing 36 U.S. educational and research institutions formed a consortium and elected its Board of Trustees. A resolution similar, in principle, to that quoted above was passed at the meeting. Subsequently, the "Lithospheric" Board of Trustees agreed that both the "Global" and "Lithospheric" programs should join under the same corporate umbrella. The overall structure shown in Figure 6.1 was approved by both Boards. IRIS was incorporated during the spring of 1984 and its first meeting was held in Cincinnati on May 13, 1984. By November, 1984 the membership of IRIS includes 36 Universities.

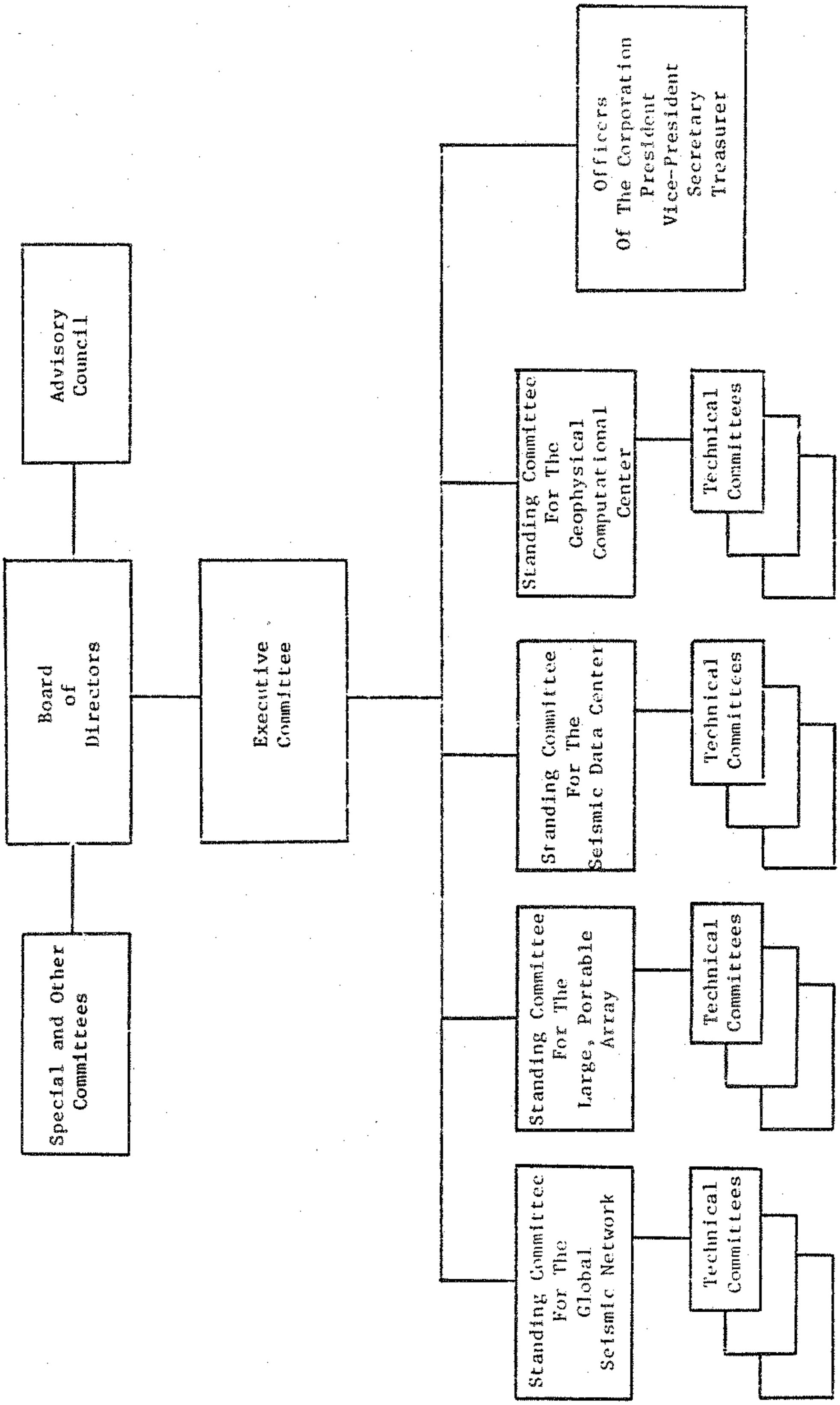

Advisory Council
Board of Directors
Special and Other Committees
Executive Committee
Officers Of The Corporation President Vice-President Secretary Treasurer
Standing Committee For The Geophysical Computational Center
Technical Committees
Standing Committee For The Seismic Data Center
Technical Committees
Standing Committee For The Large, Portable Array
Technical Committees
Standing Committee For The Global Seismic Network
Technical Committees

Figure 6.1

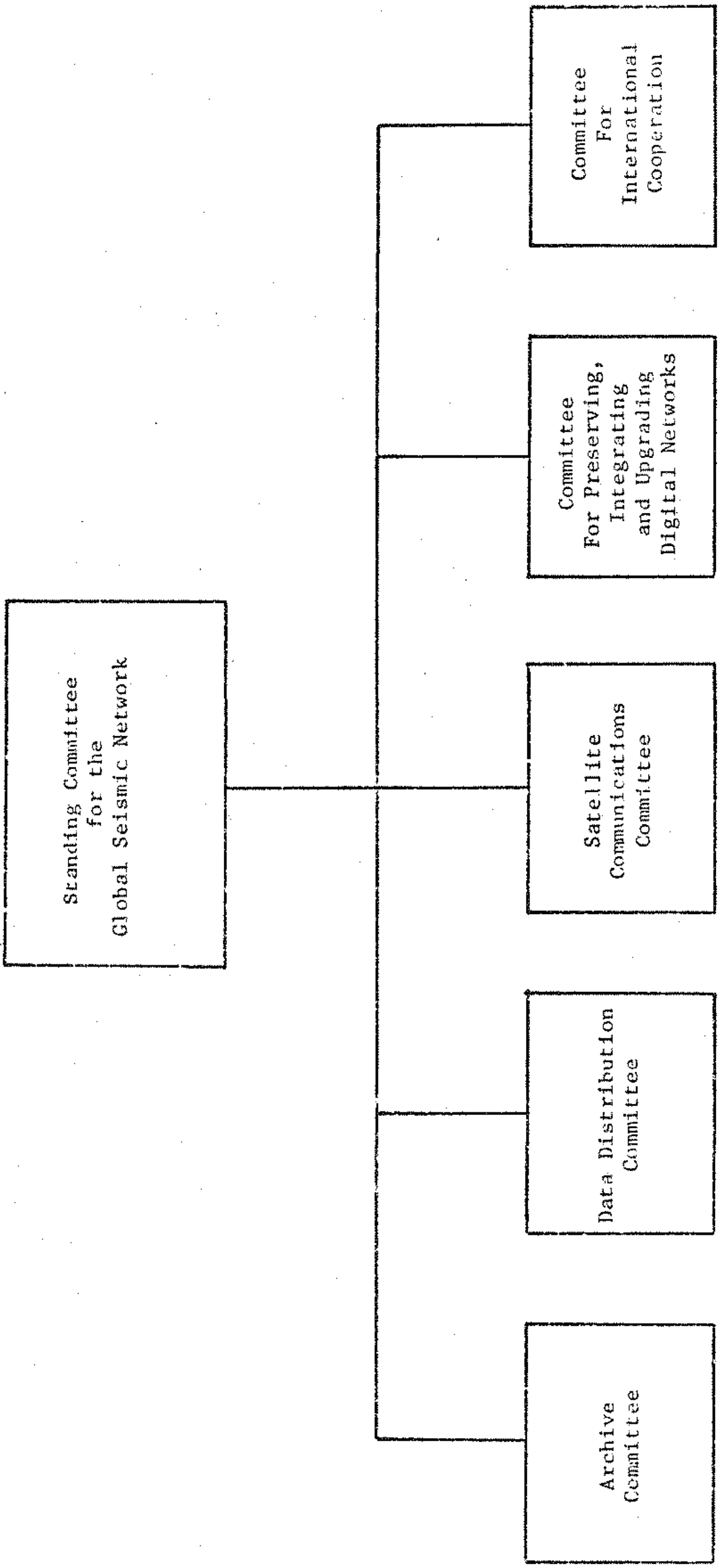

Standing Committee
for the
Global Seismic Network
Committee
For
International
Cooperation
Committee
For Preserving,
Integrating
and Upgrading
Digital Networks
Satellite
Communications
Committee
Data Distribution
Committee
Archive
Committee

Figure 6.2

6.2. Bylaws of the Incorporated Research Institutions for Seismology

This section presents both an outline and details of the Bylaws, consistent with Delaware law, that were approved at the first meeting of the corporation. (Delaware, unlike most states, does not require that the corporate headquarters be located within the state.)

Membership of the various committees is outlined in Figure 6.3 and the chairmanship and the acceptable voting majority of each committee are found in Figure 6.4. Generally, most committees will reach other decisions by a majority vote although a change to the Bylaws and admission of new members requires the affirmative vote of two-thirds of all current members of the Board of Directors.

BOARD OF DIRECTORS

One member appointed by each institution of graduate instruction and research, indefinite terms.

EXECUTIVE COMMITTEE

Chairman and Vice-Chairman of the Board of Directors and five other members of the Board of Directors.

SPECIAL COMMITTEES

Formed to deal with specific issues; for example: nominations for election to offices, membership in the Corporation, financial matters, etc. Members appointed by the Chairman of the Board from among the Directors with approval of the Board.

ADVISORY COUNCIL

Elected by the Board of Directors. Members need not be Directors.

STANDING COMMITTEES

Members appointed by Chairman of the Board of Directors, with approval of the Board. Members need not be directors.

CORPORATE OFFICERS

Chairman and Vice-Chairman of the Board of Directors
President, Vice-Presidents, Secretary and Treasurer

Figure 6.3

Membership of the Board and Its Committees

BOARD OF DIRECTORS

Chairman and Vice Chairman elected for two year terms.
Chairman may not succeed himself or herself.
Two-thirds majority vote of full membership on amendments to Bylaws.
Majority vote on all decisions if a quorum is present.
Quorum composed of a majority of members of the Board.

EXECUTIVE COMMITTEE

Chairman and Vice-Chairman of the Board serve ex officio.
Five Directors elected by the Board from its membership for two year terms.
Quorum composed of a majority of its members.
Majority vote on all matters.

ADVISORY COUNCIL

Chairman elected every three years.
Chairman may succeed himself or herself.
Members serve three year terms.

CORPORATE OFFICERS

Chairman and Vice-Chairman of the Board serve ex officio.
Other officers elected by vote of the Board of Directors.
Two year terms.
Eligible for reelection.
Other than Chairman and Vice-Chairman of the Board the officers need not be members of the Board.

Figure 6.4

Chairmanship, Terms of Office, and Voting Majorities

6.2.1. Bylaws of the Incorporated Research Institutions for Seismology

INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY
A Delaware Not-for-Profit Corporation

BY-LAWS

ARTICLE I

Name

SECTION 1. The name of the Corporation is INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY

ARTICLE II

Member Institutions

SECTION 1. Membership. The following named educational and not-for-profit institutions shall be initial members of the corporation, subject to their notifying the Corporation of their acceptance of membership:

California Institute of Technology
Carnegie Institution of Washington
Georgia Institute of Technology
Harvard University
Lamont-Doherty Laboratory
Memphis State University
Michigan Technological University
Northwestern University
Pennsylvania State University
Princeton University
St. Louis University
Texas A & M
University of Alaska
University of California, Berkeley
University of California, San Diego
University of Colorado
University of Hawaii at Manoa
University of Illinois, Urbana
University of Southern California
University of Texas, Austin
University of Texas, Dallas
University of Texas, El Paso
University of Utah
University of Washington, Seattle
University of Wisconsin
Virginia Polytechnic Institute

Any of the following named educational and not-for-profit institutions shall be permitted to become additional members of the Corporation without vote of the Board of Directors upon notifying the Corporation of acceptance of membership and payment of the initial membership fee prescribed by Article VII on or before the date of the first annual meeting:

Boston College
Brown University
Cornell University
Indiana University, Bloomington
Louisiana State University
Old Dominion University
Oregon State University
Massachusetts Institute of Technology
Montana State University, Bozeman
New Mexico Institute of Mining & Technology
Purdue University
Rice University
Southern Methodist University
Stanford University
State University of New York, Binghamton
State University of New York, Stony Brook
University of Arizona
University of California, Los Angeles
University of California, Santa Barbara
University of California, Santa Cruz
University of Kentucky
University of Michigan
University of Nevada
University of North Carolina
University of South Carolina
University of Wyoming
Woods Hole Oceanographic Institution

SECTION 2. Election and Vacancies. Other educational and not-for-profit institutions with a major commitment to research in seismology and related fields, including single or multiple campuses of multi-campus university systems, may be elected as additional members or to fill vacancies in the membership by the affirmative vote of two-thirds of the members of the entire Board of Directors.

SECTION 3. Resignations. Any member may resign at any time by giving written notice to the Chairman, President or Secretary of the Corporation. Such resignation shall take effect at the time of receipt of the notice, or at any later time specified therein. Any resigning member shall remain liable for any unpaid portion of the initial membership fees and any other membership fees, assessments or charges levied by the Board of Directors pursuant to ARTICLE VII of the Bylaws before the giving of such notice.

ARTICLE III

Board of Directors

SECTION 1. Powers. The affairs of the Corporation shall be conducted under the authority of the membership through the Board of Directors. To this end and without limitation of the foregoing or of its powers expressly conferred by these Bylaws, the Board of Directors shall have power to authorize such action on behalf of the Corporation, make such rules or regulations for its management, create such additional offices or special committees and select, employ or remove such of its officers, agents or employees as it shall deem best. The Board of Directors shall have the power to fill vacancies in, and change the membership of, such committees as are constituted by it.

SECTION 2. Composition. The Board of Directors shall be composed of one member from each of the member institutions. The chief executive officer of each such member institution shall designate one Director, who shall be the holder of an academic appointment in the department or other organizational unit of such member institution with the primary responsibility for the earth sciences.

SECTION 3. Term of Office. Each member of the Board of Directors shall continue in office until his successor is chosen and qualifies or until he dies, resigns or is removed by the chief executive officer of his member institution.

SECTION 4. Resignation. Any Director may resign at any time by giving written notice to the Chairman, President or Secretary of the Corporation. Such resignation shall take effect at the time of receipt of the notice, or at any later time specified therein.

SECTION 5. Alternate Directors. The chief executive officer of each member institution may appoint from within the member institution an alternate Director to serve for the term specified by such appointment. In the absence of a Director from any meeting of the Board of Directors, his or her alternate may, upon written notice to the Secretary of the Corporation from the Director or from a duly authorized representative of the member institution of the Director, attend such meeting and exercise all the rights, powers and privileges of the absent Director.

ARTICLE IV

Meetings of the Board of Directors

SECTION 1. Annual Meeting. The annual meeting of the Board of Directors for the election of officers and for the transaction of such other business as may properly come before it shall be held on the first Wednesday in December in each year, or on such other date within thirty (30) days after the first Wednesday in December as the Board of Directors may designate.

SECTION 2. Special Meetings. Special meetings of the Board of Directors may be called by the Chairman of the Board of Directors or by the President and shall be called by the Secretary upon the written request of at least four Directors or one-fifth (1/5) of the membership of the Board, whichever is greater.

SECTION 3. Place of Meetings. The Chairman of the Board of Directors or the President shall designate the place of the annual meeting or any special meeting, which may be either within or without the State of Delaware and which shall be specified in the notice of meeting or waiver of notice thereof.

SECTION 4. Notice of Meetings. Notice of such meeting of the Board of Directors shall be given to each Director by the Secretary, or by an officer directed by the Chairman of the Board of Directors or the President to give such notice, by delivering to him or her personally, or by first-class mail, postage prepaid, addressed to him or her at the address of his or her member institution, a written or printed notice not less than thirty nor more than sixty days before the date fixed for the meeting. Notice of any meeting need not be given to any Director, however, who submits a signed waiver of notice, whether before or after the meeting. The attendance of any Director at a meeting without protesting prior to the conclusion of the meeting the lack of notice thereof shall constitute a waiver of notice by him or her. When a meeting is adjourned to another place or time, it shall not be necessary to give any notice of the adjourned meeting if the time and place to which the meeting is adjourned are announced at the meeting at which the adjournment is taken.

SECTION 5. Quorum. Except as may be otherwise expressly required by law, the Certificate of Incorporation or these Bylaws, at all meetings of the Board of Directors or of any committee thereof a majority of the Directors or members of such committee then serving in such position shall constitute a quorum. If a quorum is not present, a majority of the Directors present may adjourn the meeting without notice other than by announcement at said meeting, until a quorum is present. At any duly adjourned meeting at which a quorum is present, any business may be transacted which might have been transacted at the meeting as originally called.

SECTION 6. Voting. Each Director shall be entitled to one vote. Except as otherwise expressly required by law, the Certificate of Incorporation or these Bylaws, all matters shall be decided by the affirmative vote of a majority of the Directors present at the time of the vote, if a quorum is then present.

SECTION 7. Action Without a Meeting. Any action required or permitted to be taken by the Board of Directors or any committee thereof, may be taken without a meeting if all members of the Board of Directors or of such committee consent in writing to the adoption of a resolution authorizing the action. The resolution and the written consents thereto shall be filed with the minutes of the proceedings of the Board of Directors or the committee.

SECTION 8. Participation by Conference Telephone. In any meeting of the Board of Directors or any committee thereof, any one or more Directors or members of any such committee may participate by means of a conference telephone or similar communications equipment allowing all persons participating in the meeting to hear each other at the same time. Participation by such means shall constitute presence in person at a meeting.

ARTICLE V

Officers

SECTION 1. Officers and Qualifications. The officers of the Corporation shall consist of a Chairman and a Vice Chairman of the Board of Directors, a President, a Secretary, a Treasurer and such other officers as the Board of Directors may from time to time establish and appoint. Officers, except for the Chairman and the Vice Chairman of the Board, need not be Directors.

SECTION 2. Chairman. The Chairman of the Board of Directors shall, when present, preside at all meetings of the Board of Directors and shall perform such other duties and exercise such other powers as shall from time to time be assigned by the Board of Directors.

SECTION 3. Vice Chairman. The Vice Chairman of the Board of Directors shall preside, in the absence of the Chairman, at all meetings of the Board of Directors and shall perform such other duties and exercise such other powers as shall from time to time be assigned by the Board of Directors.

SECTION 4. President. Except as otherwise provided by the Board of Directors, the President shall be the chief executive officer of the Corporation, and unless authority is given by the Board of Directors to other officers or agents to do so, he or she shall execute all contracts and agreements on behalf of the Corporation. It shall be his or her duty, insofar as the facilities and funds furnished to him or her by the Corporation permit, to see that the orders and votes of the Board of Directors and the purposes of the Corporation are carried out. In the absence of the Chairman or the Vice Chairman of the Board of Directors, the President shall preside at meetings of the Board of Directors.

SECTION 5. Secretary. The Secretary shall give notice of meetings of the Board of Directors, shall record all actions taken at such meetings and shall perform such other duties as shall from time to time be assigned by the Board of Directors.

SECTION 6. Treasurer. The Treasurer, subject to the control of the Board of Directors, shall collect and receive, and shall have charge and custody of, the funds and securities of the Corporation. He or she shall have such other duties as are customary to the position of Treasurer in a corporation of this type and such as shall from time to time be assigned by the Board of Directors.

SECTION 7. Election and Term of Office. The Chairman and Vice Chairman of the Board shall each be elected by the Board of Directors from among membership of the Board for a term of two years or until his or her successor is chosen and qualifies. The Chairman of the Board shall not be eligible for reelection until another Director shall have served an intervening term, or a portion of a term of more than one year as Chairman. All other officers of the Corporation shall be elected by the Board of Directors for terms of two years or until their successors are chosen and qualify. They may be chosen from among the Directors but need not be, and they shall be eligible for reelection.

SECTION 8. Resignation. Any officer may resign at any time by giving written notice to the Chairman, the Vice Chairman, the President or Secretary of the Corporation. Such resignation shall take effect at the time of receipt of the notice, or at any later time specified therein.

SECTION 9. Vacancies. Any vacancy in any office may be filled for the unexpired portion of the term of such office by the Board of Directors.

SECTION 10. Removal. Any officer may be removed at any time either with or without cause by vote of the Board of Directors.

ARTICLE VI

Executive Committee of the Board, Other Committees and Advisary Council

SECTION 1. Executive Committee of the Board. There shall be established an Executive Committee of the Board comprising the Chairman, the Vice Chairman and five additional Directors each elected by the Board of Directors for a term of two years or until his or her successor is chosen and qualified.

SECTION 2. Powers of the Executive Committee of the Board. Unless otherwise provided by resolution adopted by the affirmative vote of a majority of the entire Board of Directors, the Executive Committee of the Board may have and may exercise all the powers of the Board of Directors, except that it shall not have authority as to the following matters:

(a) the creation of new committees of the Corporation;
(b) the amendment or repeal of the Bylaws, or the adoption of new Bylaws;
(c) the amendment or repeal of any resolution of the Board of Directors, which by its terms shall not be so amendable or repealable; and
(d) the levying or assessment of fees and dues.

At all meetings of the Executive Committee of the Board, the presence of a simple majority of its members then in office shall constitute a quorum for the transaction of business.

SECTION 3. Special Committees. The Board of Directors may create such special committees as may be deemed desirable, the members of which shall be appointed by the Chairman of the Board from among the Directors, with the approval of the Board. Each such committee shall have only the lawful powers specifically delegated to it by the Board.

SECTION 4. Standing Committees. By resolution adopted by the Board of Directors, the Board may designate one or more standing committees for each major scientific, educational or research program to which the Corporation provides scientific counsel and advice or management direction. Members of each such committee shall be appointed by the Chairman of the Board, with the approval of the Executive Committee of the Board of Directors, and the Committee shall have only the lawful powers specifically delegated to it by the Board. Each such committee shall serve at the pleasure of the Board. An individual or an institution may be a member of a standing committee whether or not a Director or officer of the Corporation.

SECTION 5. Other Committees. The Board of Directors may create committees other than standing or special committees to be committees of the Corporation. Such committees shall be elected or appointed in such a manner as may be determined by the Board of Directors and shall have such lawful duties as may be specified by the Board. An individual or an institution may be a member of any such committee whether or not a Director or officer of the Corporation.

SECTION 6. Advisory Council. The Board of Directors may establish an Advisory Council to serve as an experienced advisory body to the Board. The members of the Council shall serve for three-year terms and may be elected to subsequent terms. A Chairman of the Advisory Council shall be elected by the membership of the Council for a three-year term and may succeed himself. An individual or an institution may be a member of the Advisory Council whether or not a Director or officer of the Corporation.

ARTICLE VII

Fees and Dues

SECTION 1. Initial Membership Fee.

Each member shall contribute an initial membership fee of two thousand five hundred dollars ($2,500).

SECTION 2. Fees and Assessments. In addition to the initial membership fee, every member shall pay such fees or assessments, annual or otherwise, as may be authorized from time to time by majority vote of the entire Board of Directors; provided, however, that all such fees and assessments shall be levied equally on all members and shall not exceed two thousand dollars ($2,000) per calendar year or a total of ten thousand dollars ($10,000) per member. A member which has resigned from the Corporation shall not be liable for any fees or assessments levied after the effective date of its resignation. Any member which fails to pay any fees or assessments within sixty days after such fees or assessments are payable may be removed from membership for such nonpayment by the affirmative vote of two-thirds of the members of the entire Board of Directors.

ARTICLE VIII

Compensation

SECTION 1. Compensation. The Board of Directors shall have the power to fix the compensation and fees payable to officers and employees for services rendered to the Corporation; provided, however, that no Director shall be paid any compensation for serving as Director. All Directors may be reimbursed for the actual expenses incurred in performing duties assigned to them by the Board of Directors.

SECTION 2. Dividends. The Corporation shall not pay dividends or distribute any part of its income or profit to its members, Directors or officers.

ARTICLE IX

Indemnification

SECTION 1. Indemnification. The Corporation shall have the power to indemnify any Director, officer, employee or agent to the fullest extent permitted, and in accordance with the standards and procedures provided by Section 145 of the General Corporation Law of Delaware; provided, however, that the indemnification provided for herein shall apply only upon the determination by the Board of Directors that indemnification is proper in the circumstances because such Director, officer, employee or agent has met the applicable standard of conduct prescribed by Delaware General Corporation Law Section 145. Such determination shall be made: (1) by the Board of Directors by a majority vote of a quorum consisting of disinterested directors or (2) if such quorum is not obtainable, or even if obtainable if a quorum of disinterested directors so directs, by independent legal counsel in a written opinion. The foregoing right of indemnification shall be in addition to and not exclusive of all other rights to which such Director, officer, employee or agent may be entitled.

ARTICLE X

SECTION 1. Fiscal Year. The fiscal year of the Corporation shall commence on the first day of October and end on the thirtieth day of the following September.

ARTICLE XI

SECTION 1. Seal.. The seal of the Corporation shall be circular in form and shall bear the words and figures: "Incorporated Research Institutions for Seismology — Delaware 1984" or words and figures of similar import. The form of such seal shall be subject to alteration by the Board of Directors.

ARTICLE XII

SECTION 1. Amendments. All Bylaws of the Corporation shall be subject to amendment or repeal and new Bylaws may be made by the affirmative vote of two-thirds of the entire Board of Directors at any annual or special meeting, the notice or waiver of notice of which shall have specified or summarized the proposed amendment, repeal or new Bylaws.