IRIS - 2000

A SCIENCE FACILITY FOR STUDYING THE DYNAMICS OF THE SOLID EARTH

THE GLOBAL SEISMOGRAPHIC NETWORK

THE PROGRAM FOR ARRAY STUDIES

THE DATA MANAGEMENT SYSTEM

a Proposal to
The National Science Foundation
by

IRIS

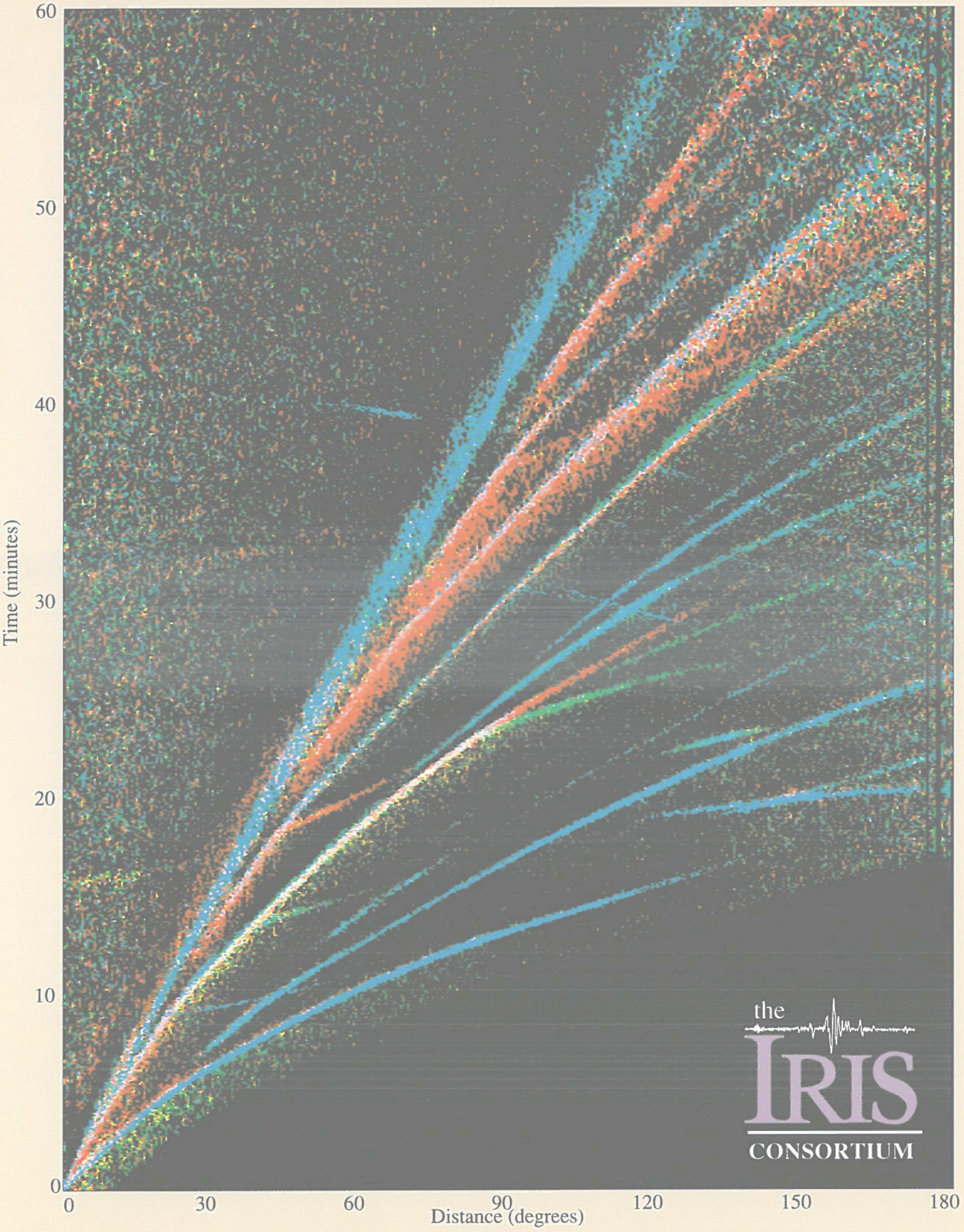
and its 85 Member Institutions

August 1995

IRIS 2000

A Science Facility for Studying the Dynamics of the Solid Earth

EXPLORING THE EARTH THROUGH SEISMOLOGY



INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY
A UNIVERSITY BASED CONSORTIUM
FOUNDED IN 1984
SUPPORTING RESEARCH IN SEISMOLOGY
THROUGH FACILITIES FOR
INSTRUMENTATION
AND
DATA COLLECTION, ARCHIVING AND DISTRIBUTION
WITH FUNDING PROVIDED BY
THE NATIONAL SCIENCE FOUNDATION AND
THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Image produced at IGPP, U. C. San Diego by L. Astiz, P. Earle and P. Shearer

This is an image of over 27,500 stacked 3-component broadband seismograms from 834 earthquakes with $M > 5.7$ and depth < 70 km that occurred from 1988 to 1994. Seismic phases are shown with different colors depending on their polarization. Blue shows vertical motion, green is radial-horizontal and red is transverse-horizontal motion. The data were recorded by the IRIS Global Seismographic Network (GSN) at stations operated by the United States Geological Survey, Albuquerque Seismological Laboratory and Project IDA, IGPP, University of California, San Diego.

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IRIS 2000: The IRIS Proposal

A Science Facility for Studying the Dynamics of the Solid Earth

July 1, 1996 - June 30, 2001

submitted to

The National Science Foundation

by the

85 Member Research Institutions of the

The IRIS Consortium
1616 North Fort Myer Drive, Suite 1050
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A Science Facility for Studying the Dynamics of the Solid Earth

Summary

The Earth's core, mantle and crust are an interrelated system in which the cooling of the planet creates convection in the mantle that, in turn, shapes our landscape and defines our natural resources. To understand how this system works, we must explore beneath the Earth's surface.

Seismology is engaged in a grand experiment to image the interior of the Earth, analyze geological processes, and map seismic events. The result will be illumination of our planet's inner workings on a variety of scales, including thermal convection throughout the mantle, the internal structure of mountain belts, and shallow deformation associated with active faults. Through seismic imaging we can relate mantle strains at the North American plate boundary to the geological processes that govern earthquakes, volcanoes, and mountain-building in the western United States. Glimpses of a new paradigm for geology are now emerging that address convection and dynamics issues where the kinematics of "plate tectonics" could only shrug and admit its inadequacy. Only through the continued development of seismic facilities and the expansion of a comprehensive data archive can seismology continue its contribution to exploring this scientific frontier.

Over the past decade, 85 research institutions have joined together to build the data base for the next generation of discoveries in seismology. With a fixed network of seismic observatories that encircles the globe, and portable instruments deployed continuously in dozens of field campaigns worldwide, millions of seismograms are now delivered to educators, students and researchers each year.

In 1984, 22 universities created the Incorporated Research Institutions for Seismology (the IRIS Consortium) to develop national facilities for the study of the solid Earth. Seismology is a data-driven discipline, and the instrumentation for global seismology and seismic imaging of the crust and lithosphere was inadequate at the time to address the central scientific problems. With funding coordinated through the National Science Foundation, and close cooperation and support from the U.S. Geological Survey, the Air Force Office of Scientific Research, and the Department of Energy, IRIS now provides a national focus for the development, deployment, and support of modern digital seismic instrumentation.

IRIS is a comprehensive and cost-effective mechanism for collecting and distributing seismic data. Rather than having individual universities and investigators develop and maintain disparate instrument programs, the entire research community now operates a standardized facility. From its membership, IRIS draws on a broad spectrum of technical expertise, and is encouraged to develop facilities and services that are both versatile and convenient. On behalf of its member institutions, IRIS operates a global network that in 1996 will approach 90 permanent broadband stations. To complement the permanent stations, a stable of more than 300 portable data acquisition systems is used in temporary deployments throughout the world. Data from both facilities are available to the international seismological community through a standardized, quality-controlled archive, along with tools to provide unrestricted access to these and other data collected by the Consortium.

The IRIS Consortium is building on a strong tradition of cooperation in seismology. The collection of data from a global network relies on the local support of universities and governments around the world. Complex field programs often involve scientists, technicians and students from a number of organizations. The efficient exchange of data requires coordination of formats and access methods. In cooperation with commercial firms, international partners and other U.S. agencies, notably the U.S. Geological Survey, the Consortium seeks to provide Earth scientists with the highest quality resources for exploration of the Earth's interior.

The investment of a decade in establishing and expanding IRIS facilities is now yielding the data necessary to address many fundamental questions in Earth science. With its initial instrumentation goals in view, though not yet fully achieved, the Consortium must advance towards completing the facility while looking to the future. Plans presented in this proposal include technical developments unforeseen in 1984, that will make permanent network operations and large portable experiments both less expensive and more reliable. By improving the efficiency of its core operations and broadening its base of support, IRIS will be able to address new challenges, such as three-dimensional surveys of the structure beneath mountain ranges and the enhancement, through the use of sensor arrays, of faint reflected waves from the core-mantle boundary.

The Consortium is evolving beyond a simple instrument facility and data archive. As a natural result of active collaboration within its membership, standing committees, and working groups, IRIS serves as a forum for articulating the role of seismology and solid Earth science in educational and national policy issues. With rapid and easy access to seismic data, a new generation of seismologists is more fully aware of the entire spectrum of seismic applications, ranging from basic Earth structure to earthquake hazard mitigation and monitoring a comprehensive nuclear test-ban treaty.

The original IRIS goals were to develop three distinct but related facilities:

The Global Seismographic Network (GSN)

- a network of standardized, very broadband, digital seismic stations distributed globally to monitor seismic activity (including earthquakes, underground nuclear explosions, and volcanic activity) and to study the structure of the Earth's interior. The original design goal was uniform coverage of the Earth's surface, achieved by 128 stations on a 2000 km global grid. The GSN currently has 80 stations, with most planned continental stations in place. International partnerships share in the creation of a uniform global network and provide enhanced coverage in many areas. An accelerated deployment of the GSN was made possible by special funds, provided by the Air Force Office of Scientific Research, for applications in nuclear monitoring and research. One unanticipated benefit of this acceleration is the unprecedented data set recorded for the 9 June 1994 Bolivian event, the largest deep earthquake (M=8.3, depth=636 km) in the last 20 years. The Bolivian data have already resolved long-standing disputes about the mechanical behavior of mantle rocks at high pressure and fueled further debate about the relationship between mineral phase changes and deep earthquakes.

The Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL)

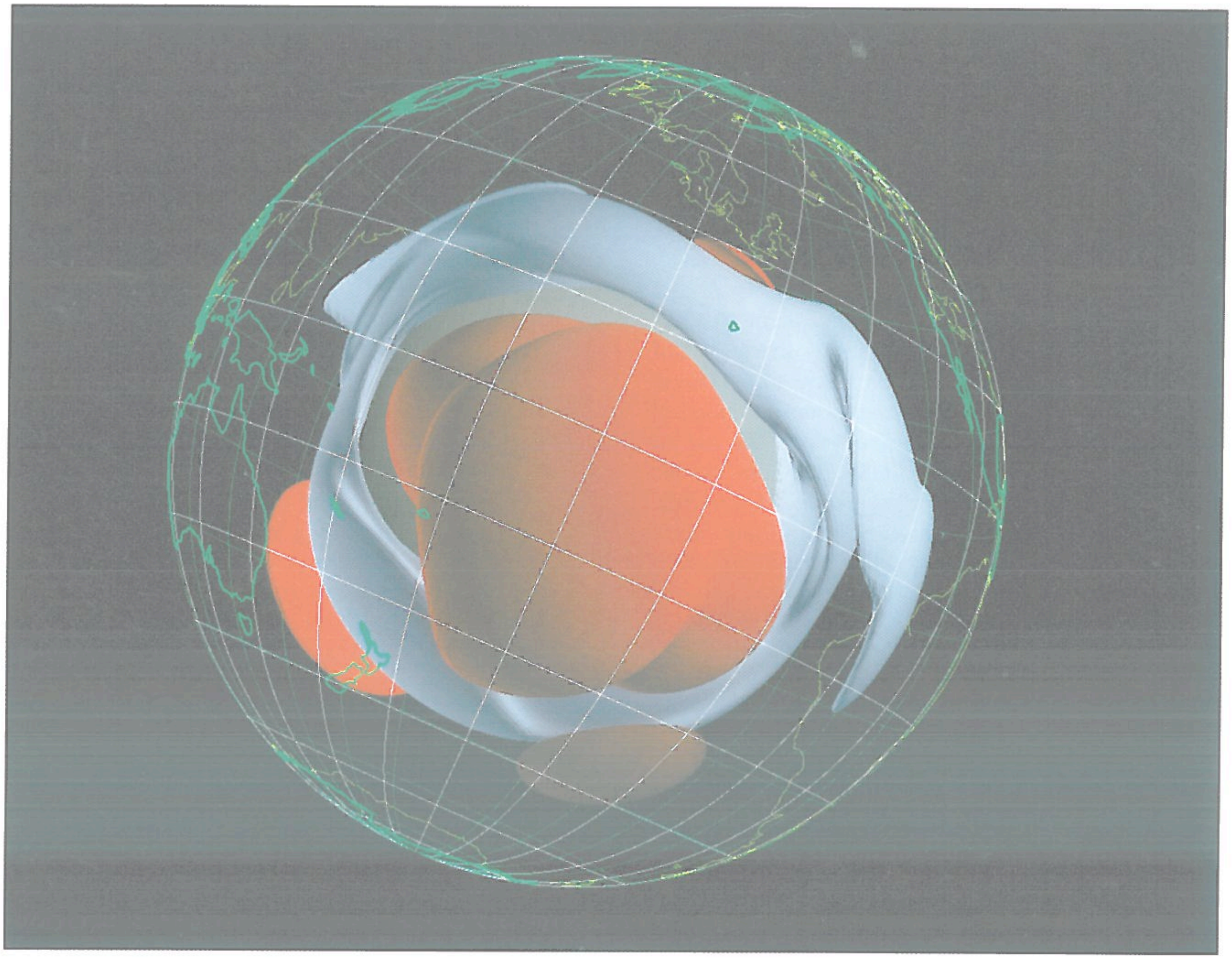
- a facility comprising high-performance portable seismic instruments and support personnel which individual researchers borrow for temporary campaigns to study the fine structure of the Earth, record aftershocks from major earthquakes, or examine other seismic activity of high interest. The original goal of PASSCAL was 1000 field recording units, with a total of 6000 recording channels, seismic sensors, and field computers. The PASSCAL program has acquired more than 1500 channels, roughly 25 percent of its original goal. The instruments are used in more than 25 NSF-funded projects each year. The flexible PASSCAL portable data acquisition system has provided the platform for several innovations in sensor deployment and seismic imaging studies. Current applications of PASSCAL instruments bridge a range of length scales from rock outcrop to the entire planet. In passive mode, two broadband PASSCAL deployments in 1994 were fortuitously placed above large, deep earthquakes in Fiji and Bolivia, and collected data to map fault rupture and aftershock pattern in unprecedented detail. In active-source mode, PASSCAL deployments have probed the manner in which the crust responds to plate tectonic strains in the Western US, revealing, for instance, spectacular crustal detachment faults beneath some mountain ranges.

The Data Management System (DMS)

- a distributed facility for the collection, quality control, archival and timely distribution of seismic data to the research community. The DMS is the open gateway for all researchers and students to access IRIS data and software. The DMS includes near-real-time data retrieval links to many stations of the GSN and cooperating networks, so researchers and government agencies can quickly characterize seismic events of special interest. At one time, many adhered to the view that each observational seismologist would require a complete data archive, with all the attendant overhead of tape storage, file management and downstream quality control. The success of the DMS can be measured by the fact that this option is now rarely contemplated except by research groups with special data sets e.g. regional array operators. Instead, a new generation of seismologists treats the IRIS DMS as its own seismic data archive, retrieving data as needed. In addition, the DMS has evolved into a clearinghouse for software, helping researchers to process data readily and communicate with colleagues through a common analysis language. For example, data from a PASSCAL deployment of 12 broadband stations across the Tibetan Plateau, designed to study its structure, have now been utilized in at least 23 research papers by groups outside the original research team to investigate a diverse range of topics unrelated to its original goals.

Core Program Maintenance and Growth

Over the past ten years, the three core programs succeeded in setting standards and applying new technologies to establish a firm foundation for modern seismological research. All three programs have achieved or exceeded the technical standards set forth in the original IRIS proposal. While limitations in funding have prevented each from growing to the size originally proposed, the GSN and DMS are now approaching the targets set in 1984.



Shear Wave Heterogeneity in the Mantle

The increased density of stations and enhanced quality of waveform data, has greatly improved the resolving power of seismic imaging in delineating deep Earth structure. The three-dimensional model S12_WM13 of Su et al., 1994 is based on an inversion of 27,000 long-period seismograms and 14,000 travel time observations. Many surface tectonic features, such as ridges, trenches and continental "roots" are reflected in short wavelength heterogenities extending to depths of 300 km or more. In the deep mantle, consistent long-wave length mega-structures are emerging, some of which also appear to be related to surface features. These include the "Pangea Trough," "Great African Plume" and "Equatorial Pacific Plume Group". This three dimensional view of the model S12_WM13 shows shear wave velocity anomalies from a depth of 1000 km to the core-mantle boundary. Red represents the isosurface of velocity 0.35% slower relative to PREM, blue is the isosurface for of seismic velocity 0.35% faster. A plume of slow velocity rising from the CMB is seen beneath the central Pacific surrounded by a ring of high velocity . Figure provided by Wei-jia Su and Adam Dziewonski, Harvard University.

As the programs evolved, there was significant merging of resources, with increased interactions between the core programs that strengthened the overall impact of IRIS, improved its efficiency, and led to new opportunities in collaborative and interdisciplinary science. Funding for treaty verification through the Joint Seismic Program (JSP), in particular enhanced the core programs and provided new observational capabilities.

To realize the scientific potential of the current facility, the highest priority in the next five years is to maintain and operate the established IRIS core programs. Emphasis will be placed on improving services and data collected, and on reducing operational costs. Acquisition of hardware for data collection by GSN and PASSCAL will continue. As attention shifts to more difficult sites on islands and on the seafloor to provide coverage in the world's oceans, the rate of GSN station installation will decrease. The PASSCAL program still requires significant growth to satisfy the growing pressure on this program from funded field experiments and to fulfill the need to provide complete sampling of seismic wavefields. New lower-cost instruments need to be acquired, designed to optimize the efficiency of large field experiments. Towards the end of the next five years, development must begin on a new generation of PASSCAL instruments to replace the aging and heavily used current pool.

Core Program Enhancement

While focusing on maintenance of the core programs, it is essential that we continue to develop and enhance IRIS facilities in response to the evolving demands of the research community. These changes will require innovation and the exploitation of new technologies to make the logistics of desired experiments more practical and to open new areas of scientific exploration. Two areas, Telemetry/ Arrays and Information Services, have emerged as logical candidates for evolutionary enhancement of the existing core programs. Both of these have impact across the IRIS core programs and are natural extensions of technical capabilities that have developed over the past ten years.

Advanced telemetry and communications Recent advances in telecommunications, including the explosive growth of the Internet, suggest true real-time access to data from remote stations will become significantly more economical and widespread over the next few years. The use of telemetry in the PASSCAL and GSN programs has the multiple advantages of providing enhanced scientific capability, improved data quality, and significantly decreased costs for station maintenance and data collection. As digital communications technology improves and costs decrease over the next five years, we intend to position IRIS to take advantage of various emerging modes of communications on local, regional and global scales. A full integration of communications capabilities - from data collection by GSN and PASSCAL, through data access and distribution within the DMS - will provide seismologists with greater flexibility in experiment design and greater ease of data collection.

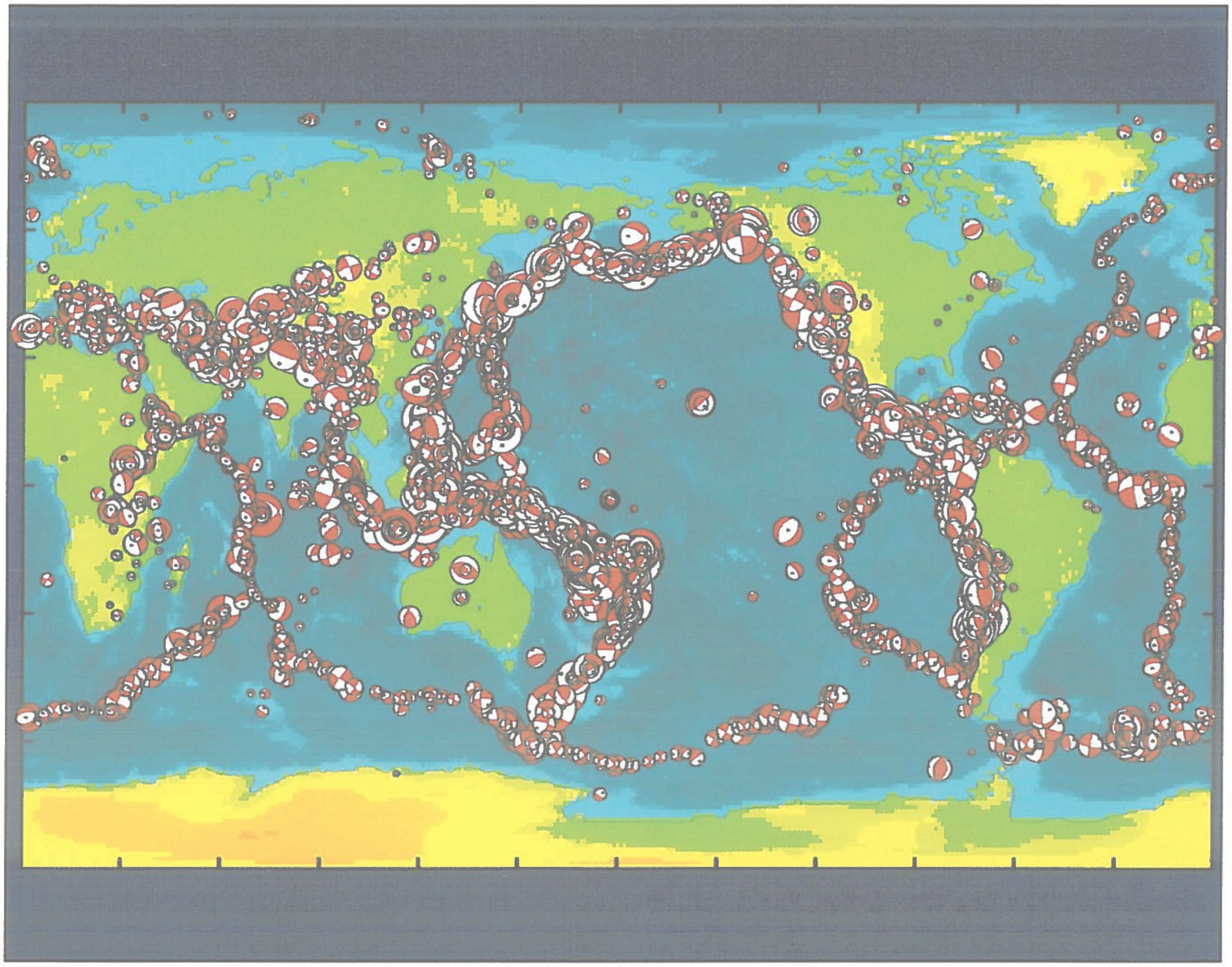
Real-time data collection - The DMS SPYDER^{TM} system, which retrieves waveform data from GSN and cooperating-network stations immediately after significant earthquakes and events such as nuclear test explosions, has demonstrated the impact of data telemetry in the routine determination of event source parameters and in monitoring the quality of station operation. Similar advantages accrue from remote data collection in extended PASSCAL deployments. We propose to combine emerging communications technologies with existing capabilities in GSN and PASSCAL instruments to provide access to data from any IRIS instrument, anywhere in the world, in real time.

Arrays - If PASSCAL instruments are linked via radio telemetry to a central data concentrator, an array is created. While simple in concept, profound benefits in both data management and analytical power accrue with the evolution from single stations to arrays. Telemetered arrays based on PASSCAL data acquisition systems, developed as part of the JSP array studies program, have shown the power of broadband network and array techniques in studies of regional seismicity and teleseismic wavefields. A central challenge in seismic data analysis is extracting a weak signal from noisy background, whether to detect P-waves from a small, distant seismic event or to extract, from the signal of a larger event, the subtle scattered wave from a buried geologic interface. Identification of such signals is enhanced by simultaneous analysis of data from closely spaced seismometers in an array, using computer processing to steer the array like an antenna. Analysis of array data yields a more comprehensive view of the wavefield than analysis of single-station data, and data telemetry is essential to the success of routine operations. Local telemetry in the PASSCAL instruments will naturally lead to increased utilization of array processing techniques. Array technologies developed by PASSCAL can find critical application in regional telemetered networks and aftershock studies.

Information Services, Software Support and Educational Outreach Through the IRIS GSN and partnerships with other national and international networks, the DMS has become the gateway through which the seismological community gains access to global seismic waveform data. Because of the vast quantities of data already archived from the global networks, the extension of established DMS services to other types of seismic data, geophysical time series and educational materials will put relatively small increased demand on IRIS facilities while providing Earth scientists and educators with convenient access to various data resources. Many other agencies, most notably the USGS, as well as non-US groups, provide "value added" information (eg. earthquake catalogues and maps) and we propose to work closely with them to develop linked databases and enhanced user access.

One of the main strengths of the Consortium is that it provides an avenue for the flow of modern seismological data to all researchers. This has allowed the single investigator at a small university, as well as the seismologist in a large research university, to conduct new research. A natural evolution is toward providing tools - both software and access to special purpose hardware - to all researchers to process the data. There have been preliminary efforts in the DMS, PASSCAL and JSP programs directed toward stimulating the community development of a software framework for data manipulation and time series analysis. These developments show how the research community can benefit from standardized and centrally-maintained software that eases access to data and provides basic processing tools, while remaining flexible enough to encourage innovation and experimentation.

The facilities structure of IRIS makes it an excellent forum for addressing important issues in science education. In the last five years IRIS has worked closely with some of our member institutions to develop initiatives for education in the Earth sciences. This mission is multifaceted, encompassing the training of undergraduate students, providing public access to information on seismic events and bringing dynamic Earth science to the K-12 classroom. IRIS proposes in the next five years to continue its support of educational services. IRIS will emphasize



Global Seismic Energy Release

Since 1 January 1977, researchers at Harvard University have been measuring the "centroid moment tensor," or CMT, source mechanisms for all earthquakes and other seismic sources with magnitudes M>5.5. This dataset, comprising over 12000 events, is available to researchers over the Internet. Graphed here atop a world map is a superposition of all CMT source mechanisms, plotted at their epicenters. Because the source moment tensor is directly related to strain release by brittle fracture within the Earth, the routine compilation of seismicity has facilitated attempts to model the long-term deformation of the lithosphere, both globally and regionally. Such seismic methods offer a complement to quasi-continuous strain measurements made by geodetic instruments, such as the Global Positioning System. In its first decade, the CMT project relied on computer tapes of seismic data from the Global Digital Seismic Network, or GDSN, often delivered several months behind real time. At the present time, near-real-time dialup access to several dozen stations of the Global Seismographic Network and cooperating networks allows a "Quick" CMT source mechanism to be determined within a few hours of most events with M>5.8. This near-real-time data access is facilitated by cooperation between IRIS and the National Earthquake Information Center (NEIC) of the U. S. Geological Survey. The NEIC informs the IRIS DMS of earthquake "alerts" as they occur. In return, the NEIC uses worldwide seismic data, retrieved via dialup by the SPYDER system of the DMS, to evaluate and improve its earthquake locations. In the next five years IRIS proposes to telemeter data from selected GSN stations to the DMS in real-time. By providing the NEIC such a source of real-time global data, IRIS can contribute to the rapid production of an "open" worldwide seismic bulletin, reliable to much smaller Richter magnitude than at present. Figure provided by Goran Ekstrom, Harvard University.

how its members can increase their involvement in education and outreach and will develop resources within the DMS for use in classroom activities.

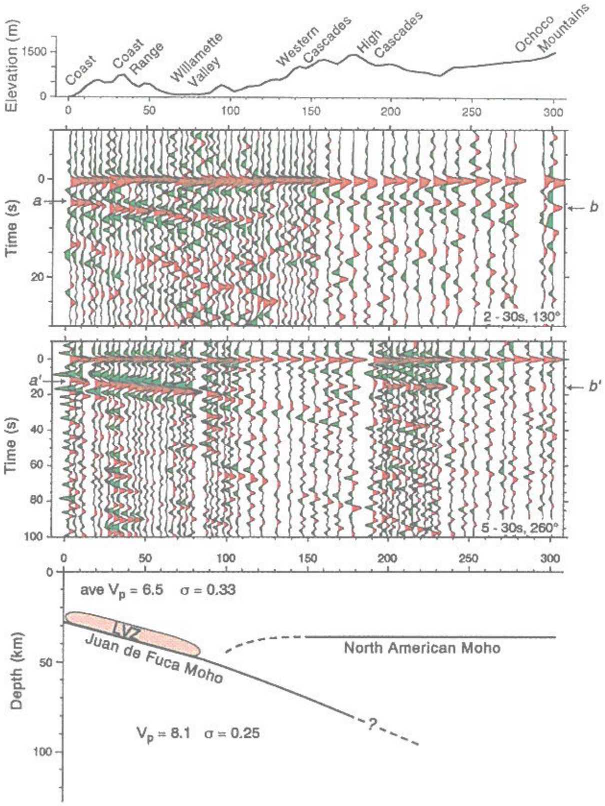
New Initiatives

IRIS proposes three initiatives as outgrowths of the initial core programs. These are development of broadband seismic observations on the ocean floor, coordinating a facility for imaging the shallow crust, and enhancing the GSN as a network for the global collection of other types of geophysical measurements. We seek encouragement from NSF to pursue these initiatives through seed funding and authorization to seek additional support from other agencies and Divisions within NSF.

Broadband Ocean Seismology – The oceans, which cover 70% of the Earth's surface, cause significant gaps in global coverage of the GSN. This prevents detailed mapping of the Earth's structure and limits resolution of features such as hot spots, subduction zones, mid-ocean ridges, and secondary convection at the base of the cooling oceanic plate. Stations on remote islands still leave much of the seafloor unsampled. Moreover, the geologic processes that form islands make such sites unrepresentative of the world ocean. To attain true global coverage, we need to develop seafloor seismic stations. IRIS proposes to work closely with the NSF Division of Ocean Sciences, other federal agencies and international groups in developing an Ocean Seismic Network, as an extension of the GSN, and a portable broadband facility for seafloor studies.

Shallow Seismic Imaging – Considerable attention is now being focused on the problem of imaging the uppermost crust at scale lengths of centimeters to meters. This "shallow imaging" is important for engineering, environmental, hydrological and wave propagation studies and is becoming an integral part of research and education at many IRIS member institutions. Shallow imaging also constitutes a frontier research area, as the physical properties encountered in the upper few hundred meters of the Earth vary more strongly than anywhere else in the solid Earth. IRIS recently received support from DOE to initiate a pilot project to acquire specialized multichannel recording equipment for use in shallow imaging and, as an adjunct to PASSCAL, facilities for crustal studies. We propose to work with NSF and other funding agencies to establish IRIS services in this area to encourage the acquisition of shallow imaging equipment by IRIS and its member institutions. Working through the PASSCAL program to coordinate these resources in joint experiments, we plan to help establish common standards for data exchange and processing.

Global Geophysical Observatories – The GSN provides the framework for the first Earth-based geophysical observatory system, capable of retrieving global data in a timely fashion. IRIS proposes to use the GSN as a platform for other geophysical observations such as continuous GPS, geomagnetic field, barometric pressure, temperature, and potentially a variety of other environmental and geophysical parameters. Funding is requested from NSF to develop a "proof of concept" network using selected GSN stations. Prototype geophysical observatories will be chosen from those with good communications and in areas designated as scientifically important by other geophysical organizations. We seek authorization to work with NSF, NASA, DMA and other agencies to acquire funding for expansion to additional sites.



Illuminating the Lithosphere from Below
The body wave coda of teleseismic phases contains important information on lithospheric structure near the recording station. Receiver functions - based on the identification of near-receiver converted phases - have been used for a number of years as a simple technique for interpretation of crustal and upper mantle structure beneath individual stations. With large numbers of PASSCAL stations in profiles recording the same teleseismic events, it is possible to improve the interpretation of receiver functions by correlation of converted phases from station to station. Profiles of receiver functions can be presented and interpreted in a manner similar to conventional reflection profiles. These data show the subducting Juan de Fuca plate illuminated by two earthquakes recorded during the 1993-94 deployment of PASSCAL instruments in Cascadia. More detail on this experiment can be found in Section II of this proposal. Figure provided by John Nabelek, Oregon State University

Funding Strategy

In its first decade, the IRIS Consortium has received approximately 50% of its funding from the NSF Earth Sciences Program. Other key sources of funding and cooperative support have been the Department of Defense (DOD), the USGS and the Department of Energy (DOE). Cost sharing from host institutions helps to support operations at IRIS facilities and University Network stations. Private support from the Cecil and Ida Green Foundation provides assistance in the development of the IRIS/IDA program. Significant indirect support has come from non-US partners in providing station support for the GSN. The USGS has been a collaborative partner with IRIS in developing the GSN and the portable Seismic Group

Recorder (SGR) facility at Stanford University. DOD funding, in support of nuclear monitoring research, has accelerated the installation of the GSN and supported operation of seismic facilities in the former Soviet Union. DOE is funding the purchase of multichannel-system shallow imaging systems.

These external funding sources are complementary to the NSF support. They demonstrate both the multiple applications of seismic data and the reputation the IRIS Consortium has developed as a credible and reliable scientific facility. In this five-year proposal, we request direct NSF support, coupled with funding for the GSN from the US Geological Survey, for the continued operation and moderate expansion of IRIS core programs. We also request endorsement through a funding authorization to seek alternative funding sources for further expansion and the development of major new initiatives.

One of the major successes of IRIS is the Consortium's ability to promote international partnerships. These partnerships have allowed IRIS access to regions of the world where in the past it was often impossible to operate. In addition, these partnerships have provided a mechanism for economy. IRIS has memoranda of understanding with a number of international groups to jointly operate and monitor GSN stations. Coordinated siting plans and agreements for data exchange with members of the international Federation of Digital Seismographic Networks complement the coverage of the GSN and allow IRIS resources to be directed where coverage is most needed.

IRIS 2000 - A vision of the future

We submit this proposal with the firm belief that seismology is an essential tool for solving fundamental problems in Earth structure and dynamics. With increasing concern about the Earth and its environment, geoscientists have a responsibility for providing a clear and accurate understanding of Earth processes, and an assessment of the possible benefits or threats to modern society. Without a fundamental understanding of scientific issues, human decision-making can fall prey to short-term solutions that create long-term problems. Through the collection of pertinent data, we can aid in transforming creative speculation into scientific "fact." The role of IRIS is to provide data and other services to researchers so that they can more easily develop and test their ideas about the origin and evolution of our planet.

In the past decade, the practice of seismology in the United States changed dramatically, often catalyzed by IRIS activities. We expect these changes to continue, if not accelerate. In the 21th century, we expect that:

— Seismologists will become less specialized as easy access to different types of data becomes routine. The labor required to collect or to analyze a specific dataset will decrease, and opportunities will increase to compare different types of data (e.g., active-source refraction profiling and passive-source receiver functions) and to cast seismological problems in a broader geological context. The application of new tools to significant broad scientific problems is bound to lead to breakthroughs.

— Other Earth scientists will increasingly view seismology as a tool for their own use, as it becomes easier to conceive and execute integrated field experiments and to interrogate and analyze data through a globally linked network of multidisciplinary data libraries.

— Scientific understanding of earthquakes will be greatly advanced by the combination of high-resolution imaging, geodetic observations of real-time deformation which accompanies and causes earthquakes, and theoretical studies based on fundamental rock physics. Improved resolution of the geometry and dynamics of structure and fault systems will provide tools for three-dimensional hazard assessment. Public awareness of earthquakes and their effects will improve as seismologists collaborate with engineers and policymakers to apply enhanced knowledge of seismicity and the dynamics of earthquake rupture to practical applications in building design and hazard reduction.

— International cooperation in the operation of global geophysical observatories will lead to rising intellectual and operational standards for seismology and environmental monitoring. The proliferation of global data telecommunications will foster an effective "neighborhood watch" to contribute to the monitoring of nuclear test-ban treaties, using openly available data from IRIS and other networks.

— Riding on the expansion of the Internet into high schools, classroom exercises in earthquake location and characterization will become feasible. Students will analyze worldwide data from an event that occurred only hours before, and gain experience in scientific observation and hypothesis-testing with an immediacy that few current science labs can match.

We believe that IRIS has laid the foundation for a stable, coordinated facility which can sustain the routine demands of the research community yet retain the ability to exploit technical innovation and stimulate intellectual inquiry. Prospects for the future will depend on the commitment of federal and state governments to both basic and applied science, the success of our community in continuing to produce committed scientists with exciting ideas, and the ability of scientists to use the data both to frame creative hypotheses and to test them adequately.

Proposal Structure

This proposal has four parts:

Part I is the core proposal for IRIS activities 1996-2001. A brief review of the history and major accomplishments of IRIS is presented along with a budget summary.

Part II documents the scientific accomplishments of IRIS. This section contains contributions from scientists at many IRIS-member institutions and elsewhere, showing some of the major advances in Earth science which have come about as a result of the use of IRIS facilities.

Part III is a detailed implementation plan. The status and goals of the core programs and new initiatives are summarized.

Part IV presents the Budget Plan for 1996 - 2001.

Further information on IRIS can be found through the IRIS Home Page on the World Wide Web (http://www.iris.edu). A variety of other publications, listed in Section III and available from IRIS or NSF can provide the reviewer with additional information.

A Program Plan through the Year 2000

Introduction

Science and technology in the 20th century have worked hand in hand to provide continually enhanced views of the evolution, structure and dynamics of our environment, from the fundamental building blocks of matter to the furthermost reaches of the universe. The interplay between science and technology feeds on the demands of observational science for *data.*

This proposal to the National Science Foundation is a request from the academic seismology community to support the maintenance and growth of the data collection and distribution facilities required to insure that our science can remain healthy and vigorous into the next century.

The Earth is a complex system, large in size and slowly evolving in time. Continents move thousands of kilometers over millions of years. Motions in the core produce a magnetic field that goes through major changes on time scales of millennia. Faulting in large earthquakes extends for hundreds of kilometers and repeats in the same place only every few hundred years. The proper study of these phenomena requires patient observations that are stable over long periods of time and distributed throughout the globe.

With recent advances in technology and vastly improved access to many parts of the world, there has been an explosive increase in the quantity and quality of data available to Earth scientists. As a result, our understanding of the structure and dynamics of our planet have changed dramatically.

- The "radially symmetric" Earth is dead. Our planet is no longer viewed as a series of onion skin layers - simple concentric shells of crust, mantle and core. The intense investigations of the lithosphere that accompanied the plate tectonics revolution starting thirty years ago revealed fundamental differences in structure between continents and oceans, and significant regional variations within the fabric of both. Now, higher and higher resolution images of the deep interior reveal an Earth that is heterogeneous on many scales. This heterogeneity is a signature of compositional and physical processes. The Earth scientist is beginning to develop a picture of the entire Earth system from crust to core.
- Beyond the relatively shallow penetration of the crust in deep mines and boreholes, the most direct evidence we have about the physical properties of the Earth's interior comes from seismic determinations of velocity and density. Enhanced estimates of the Earth's interior structure, coupled with improved knowledge of the chemistry and physics of Earth materials at high temperature and pressure, are leading to detailed models of motions in the mantle and core. These models shed light on fundamental questions concerning the origin of the Earth's magnetic field, the fate of subducted slabs, and the heat engine that drives plate tectonics.
- Although plate tectonics provided a revolutionary model to explain how the surface of the Earth evolves, an understanding of whole Earth tectonics - linking surface deformation to the dynamics of the entire mantle and core - has been inhibited by our limited ability to resolve structure beneath the lithosphere. Detailed tomographic images of the mantle, studies of the distribution and mechanics of deep earthquakes, improved knowledge of the evolution of the magnetic field, and high resolution descriptions of the shape of the geoid now are revealing the complex and inter-related processes that drive the dynamics of the Earth, from the deep interior to the surface.
- Seismology has long been one of the primary methods for probing sedimentary basins in the development of petroleum resources. Active source techniques developed in the petroleum industry now are used widely by the research community as powerful tools not only in exploration of the shallow crust but for studies of the structural geology of the entire lithosphere.
- Our understanding of the structure and evolution of active and complex geological environments, such as western North America and the southern margin of Asia, is in an exciting state of flux. Seismology opens a third dimension to surface geology in the identification and description of "exotic terranes", rafted over great distances and merged into the complex architecture of the lithosphere.
- Earthquakes are no longer characterized by seismologists simply in terms of location, time and

magnitude. Complete descriptions of the earthquake source now include details of the geometry of the fault and its slip distribution. The dynamic characteristics of faulting, including rupture direction and duration, can now be determined for all large earthquakes globally and for even moderate earthquakes in areas with enhanced regional networks.

- Our understanding of seismicity - the distribution of earthquakes in space and time - is now at a level where the earthquake history and knowledge of faults in well-studied regions can be interpreted to provide reliable, long-term forecasts of earthquake potential. Estimates of seismic hazard are used by civic authorities in urban planning and the development of building codes, and as a basis for response to earthquake emergencies.

- Seismologists are now able to provide records of ground motion during strong earthquakes and use these records to estimate the motions expected in future events. Such estimates provide the engineering community with essential information for the safe design and construction of buildings and major facilities. Studies of how fault slip occurs are also changing the way engineers design buildings.

- Recent destructive earthquakes have dramatically shown that damage, especially in large urban areas, depends not only on the distance from a fault and the earthquake's size, but is strongly controlled by local ground conditions. Seismologists, working closely with geologists and engineers, are using their knowledge of the earthquake source and wave propagation and their ability to probe shallow surface layers, to better understand and predict the influence of local geology on the amplification of ground motions.

- Growing environmental awareness is leading to increased concern about the interaction between modern society and the "solid" Earth. The highly fractured and complex shallow veneer of the upper crust is the source of many of our natural resources, especially water and minerals, and the repository for much of our fluid and solid waste. High resolution seismic imaging provides a valuable tool for hydrology and structural geology in characterizing the near surface environment.

- Seismology draws Earth scientists into the international political arena as well. With the end of the Cold War, a complete ban on the testing of nuclear weapons, an essential component in the international control of weapons of mass destruction, now appears more likely than at any time in the past 50 years. That seismology can provide a fundamental and reliable tool to monitor treaties controlling underground nuclear explosions is no longer in question, but significant challenges remain in implementing an acceptable international monitoring system.

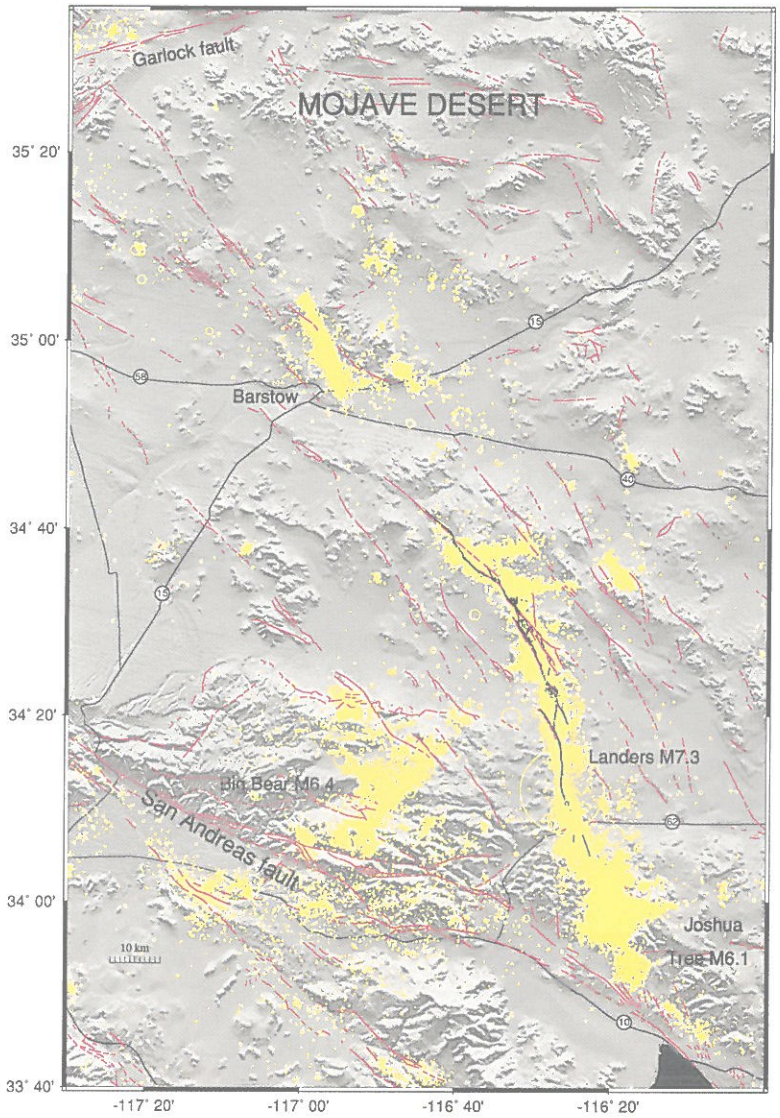
- The public, and children especially, are fascinated by earthquakes, plate tectonics and the way our planet works and evolves. This natural interest in the Earth can bring excitement to science in the classroom, taking advantage of seismology's close ties with almost all areas of basic science and mathematics. Improved public awareness of seismology and the fundamentals of earthquake science also must be a cornerstone in programs for earthquake hazard mitigation.

Progress within each of these areas depends on high-fidelity observations of Earth motion from seismometers. Sophisticated technology has been developed to measure Earth motions accurately with the dynamic range required to observe seismic events both large and small, near and distant. Technology has enabled seismologists to make these high-quality measurements in adverse field conditions, remote from power and transportation lines. Technology has also enabled seismologists to archive, distribute and analyze vast quantities of this new seismic data. The IRIS Consortium was created to manage, exploit and, in some cases, drive technological advances to provide geoscientists with the data for their science. This proposal requests funding authorization to support this activity.

IRIS - The Consortium

The Incorporated Research Institutions for Seismology, or IRIS, is a nonprofit corporation headquartered in Arlington, Virginia. The 85 member institutions of the IRIS Consortium comprise virtually all US academic institutions with a research effort in seismology. Each member institution is represented on the IRIS Board of Directors. An Executive Committee provides overall direction and policy. Standing Committees guide the development and operations of IRIS programs. A full time staff, including a President, Program Managers and Business Office, implement these programs both through IRIS operated facilities and through sub-awards at universities and government labs. Over the past decade, IRIS has worked with US federal agencies and international partners to develop and maintain the technical resources for seismology to contribute to advances in Earth science.

As a *consortium of research universities,* IRIS looks to its members to provide advice and direction on IRIS activities. Through on-going interactions with scientists at member institutions and through formal structures such as workshops, annual meetings, symposia and newsletters, the research community interacts with IRIS and, through the Consortium, expresses its evolving needs to funding agencies. From the enthusiasm and experience of its members, IRIS derives excitement and vision to guide its role in supporting Earth science and encouraging forefront research.



Rapid Response to the 1992 Landers, California Earthquake
On 28 June 1992 Southern California was awakened by its largest earthquake in 40 years. The M=7.4 Landers earthquake caused surface ruptures as large as 6 meters in a 85-km arc across the Mojave Desert east of Los Angeles. Within hours, seismologists were supplementing fixed regional-network seismic observatories with a dense network of portable seismic equipment from the IRIS-PASSCAL RAMP program and the Southern California Earthquake Center (SCEC) to record aftershocks and determine the structure of this previously unappreciated seismic zone. A compilation of major events and aftershocks of the Landers sequence is superimposed on a topographic map of the Mojave Desert region. In the last decade seismologists have recognized the importance of earthquakes on faults subsidiary to the San Andreas Fault in California. These events suggest mounting stress levels in the "locked" segments of the San Andreas, from Parkfield to Palm Springs (last large rupture in 1857) and in the Coachella Valley to the south (no large historical rupture). In fact, aftershock patterns of some events in the Landers sequence show a "cross" pattern consistent with the surrounding crust being loaded to near failure. In particular, the M=6.6 Big Bear earthquake followed the Landers rupture by only three hours. Though the Big Bear event was far from the Landers rupture, it occurred in a crustal volume where ambient stress would be increased slightly by the Landers fault movement. Ambient near-failure stress levels are consistent with earthquake rupture models in which overpressured fluids within the fault zone diminish the frictional resistance of crustal rock to faulting. Figure provided by Hiroo Kanamori, California Institute of Technology.

As a *corporation*, IRIS provides a structure for the stable operation of its facilities and a mechanism for developing programs and bringing the wishes of its members to fruition. Through its professional staff, committees and sub-awardees, IRIS provides continuity in institutional and personal resources for operational and developmental activities.

As a *major facilities program* for National Science Foundation, IRIS seeks to work closely with the NSF Earth Sciences Division and its Program Managers to develop a program focused on the support of facilities on which NSF funded research is based. Since a large segment of IRIS support is provided through the Air Force Office of Scientific Research and many operational aspects of IRIS are closely integrated with programs at the US Geological Survey, interactions with AFOSR and USGS are also essential in maintaining an effective program.

All three aspects of IRIS structure contribute to the development of this proposal. The overall proposal is the Consortium's request to NSF for the facilities program the university community sees as essential to support strong and innovative research in seismology and contribute to the development of Earth Sciences over the next five years and into the 21st century. The budget and implementation plan reflect the professional input of the IRIS Program Managers and sub-awardees, with direction from the Executive Committee and appropriate Standing Committees, based on IRIS experience in operating the facility over the past ten years. The budget strategy presented below outlines our proposal for how IRIS and NSF can cooperate to maximize the use of available funding resources to secure a facility that will best serve a vigorous research community in the years ahead.

IRIS and the Earth Science Community

IRIS has become much more than an instrument facility; it has become a focal point for university-based seismological activities. The fundamental problems of Earth science require synthesis of information and activities of other fields, organizations, and institutions. Therefore, IRIS strives to coordinate, cooperate, and work with a variety of activities within the Earth sciences and thus maximize the impact of its contributions on the larger global and societal problems it is helping to solve.

The number of organizations with which IRIS coordinates its activities is quite large. Some of the principal organizations are the United States Geological Survey (USGS), the Southern California Earthquake Center (SCEC), the Council of the National Seismic System (CNSS), the University Navstar Consortium (UNAVCO), and the UNIDATA program center of the University Consortium for Atmospheric Research (UCAR).

IRIS has formed a strong and important partnership with the U.S. Geological Survey to operate the Global Seismographic Network. Many PASSCAL experiments are cooperative ventures between university and USGS researchers. IRIS cooperates with the SCEC data center at Caltech in data distribution and software developments, in RAMP programs organized by SCEC, and in common goals for instrument standardization. The CNSS coordinates the activities of the USGS National Seismic Network and the university-operated regional seismic networks. IRIS is a full member of the CNSS and participates in the areas of information exchange and data distribution. We feel that the future developments in PASSCAL telemetry can benefit from and contribute to telemetry techniques within the CNSS.

NSF has provided significant resources to UNAVCO and UNIDATA. IRIS is aware of these activities and has informal contacts established with both organizations. It is our intention to increase the exchange of ideas and capabilities with these two organizations, especially in data management and distribution. By coordinating activities rather than duplicating them, the impact of NSF funding is maximized.

Several scientific organizations are also focused on similar problems in the Earth sciences. Programs such as CSEDI, Active Tectonics, and Continental Dynamics are fields whose interests overlap with those of IRIS. Much of the coordination is a natural result of individuals who are active in IRIS and those organizations simultaneously. IRIS views continued cooperation and coordination as essential for optimizing the utility of IRIS facilities.

National and International Partners

US Geological Survey
Memorandum of Understanding for joint support and operation of the Global Seismographic Network, cooperation in data exchange, and scientific cooperation in PASSCAL field programs.

NASA
Memoranda of Understanding in collocating GPS & GSN instrumentation at FLINN/GSN stations.

Alfred Wegner Institute for Polar Research, Germany
Contribution of instrumentation for joint GSN/AWI station at Spitzbergen, Norway

Australian National University, Australia
SPYDER data access node in Australia.

Bundesanstalt fur Geowissenschaften und Rohstaffe (Geological Survey), Germany
Contribution of instrumentation for joint GSN/BGR station at Graefenberg, Germany.

Central Weather Bureau, Taiwan
Cooperation in use of IRIS Database Management System

Earthquake Research Institute of the University of Tokyo, Japan
SPYDER data access node in Japan, Memorandum of Understanding in cooperation for undersea cable re-use; Joint ownership with IRIS of Trans-Pacific Cable-1.

Federation of Digital Seismographic Network
Member of FDSN and first Federation archive for continuous waveform data.

GEOFOrschungsNetz (GEOFON), GeoForschungsZentrum, Germany
Memorandum of Understanding with IRIS & USGS in cooperation for five joint GSN/GEOFON seismic stations including data exchange, instrumentation, and maintenance support; SPYDER data access node in Germany; Cooperation in use of IRIS Database Management System.

Geological Survey of Canada
Memorandum of Understanding in cooperation for operation of GSN stations at Alert and Flin Flon, and data exchange

Geophysical Institute of the Czech Academy of Sciences, Czech Republic
Memorandum of Understanding for cooperation in rescue of historical broadband data.

GEOSCOPE Program, University of Paris, France
Memorandum of Understanding for coordination of siting plans and data distribution; contribution of instrumentation for joint GEOSCOPE/GSN station at Kipapa, Hawaii

Institute of Dynamics of Geospheres, Russia
Data exchange agreement.

Institute of Geological and Nuclear Sciences, New Zealand
SPYDER data access node in New Zealand

Instituto Geografico Nacional, Spain
Contribution of instrumentation for joint GSN/IGN station at Taburiente, Canary Islands.

King Abdulaziz City for Science and Technology, Saudi Arabia
Agreement for cooperation in establishing a seismic station in Saudi Arabia.

Kyrghyz Institute of Seismology, Kyrghyzstan
Agreement for operation of K-NET and Ala Archa GSN station

Lithoprobe Program, Canada
Cooperation with PASSCAL in scientific field experiments.

MEDiterranean NETwork (MEDNET), Istituto Nazionale di Geofisica, Italy
Contribution of instrumentation for joint GSN/MEDNET station at Bhannes, Lebanon

Mexican National Seismic Network, Mexico
Contribution of instrumentation for 2 joint MNSN/GSN stations at Tepich, Yucatan and Isla Socorro.

National Nuclear Center of Kazakhstan, Kazakhstan
Agreement for seismic stations, arrays, field programs, data exchange, and research

Observatories and Research Facilities for European Seismology, Netherlands
SPYDER data access node in the Netherlands.

POSEIDON Program, Japan
Contribution of instrumentation for joint GSN/POSEIDON stations on Sakhalin Island, Russia, and Papua New Guinea.

Russian Academy of Sciences, Russia
Agreement for operation of seismic stations and data exchange

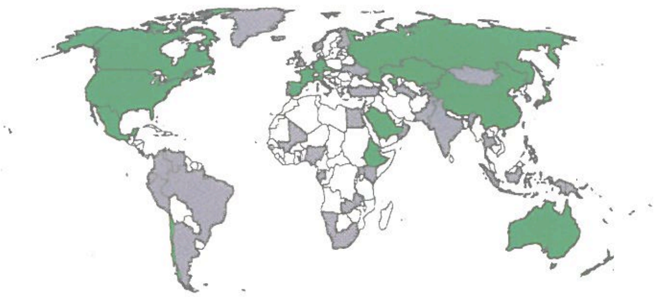
State Seismological Bureau, China
IRIS sponsorship of the upgrade of China digital seismographic network to GSN standards under USGS/SSB protocol; contribution of seismic instrumentation by Chinese.

Synapse Science Center, Russia
Memorandum of Understanding for support of the Moscow Data Center

University of Addis Ababa, Ethiopia
Contribution of instrumentation for joint GSN/Ethiopia station at Addis Ababa.

University of Chile, Santiago, Chile
Sponsorship of data coordination experiment-SALSA, Scientific ALliance for South America.

GSN station host organizations
Over one hundred agreements negotiated by USGS and UCSD/IDA on behalf of the IRIS for the installation, operation, and maintenance of the Global Seismographic Network



International Cooperation
IRIS has developed international partnerships and scientific agreements throughout the world (countries in green) and has established GSN stations in others (countries in purple) through cooperative agreements with host organizations.

We are targeting the use of IRIS resources in developing a more complete understanding of the earthquake process as a significant goal for the next five years. Close interaction with the USGS and regional network operators will be essential in this endeavor. The use of the IRIS Data Management System to help coordinate the distribution of data from the USGS National Seismic Network and regional networks has started and is being encouraged by the CNSS. Broadband stations, many based on GSN or PASSCAL designs, are gradually being installed in regional networks, especially in California and the Pacific Northwest. PASSCAL instruments are being used in a wide variety of earthquake-related studies, especially for recording aftershocks from significant earthquakes. By encouraging the collection and exchange of high quality data, IRIS can contribute to the monitoring of seismicity in the U.S. and to research being carried out by both the USGS and the university community under the National Earthquake Hazard Reduction Program (NEHRP). Standardization of instrumentation and the distribution of information to a broad community are areas in which IRIS makes important contributions to NEHRP.

IRIS Partnerships — a Cost Effective Seismological Facility

As IRIS has grown as a national facility for seismological research, it has entered into partnerships with both national and international agencies and groups whose scientific goals overlap those of IRIS. These partnerships provide an extremely cost effective mechanism to operate a global facility like the GSN, and provide an avenue for US researchers to work in regions of the world which would be otherwise difficult to access. IRIS works in close partnership with the US Geological Survey in the GSN and DMS programs through a Memorandum of Understanding and the GSN Technical Plan, and in the PASSCAL program through informal scientific cooperation on many field experiments. IRIS and its member institutions were the first organizations to install permanent, and open, seismic stations in the USSR. When the Soviet Union dissolved into 15 republics, IRIS worked with the new governments and their science organizations.

IRIS has entered into a wide range of national and international cooperation and partnerships. The accompanying table and map give a précis of these agreements, which range from formal documents to "a handshake," illustrating the flexibility with which IRIS can act in serving and furthering its scientific programs. On the broadest level, each GSN station represents a formal international partnership.

IRIS and Education

In the past ten years, IRIS has developed an infrastructure which forms a very fertile ground for educational initiatives complementary to the activities of large organizations such as the American Geophysical Union, the American Geological Institute and the Federal Emergency Management Agency. All of these organizations play an important role in the general education of the public. However, the intensive interaction between IRIS members, the development of the GSN, and the extensive experience with global data transfer allows IRIS to play a unique role in science education. "There is no need to launch another space shuttle to provide school kids with real, important, surprising data," as one IRIS member expressed it recently.

IRIS has helped support teacher training courses at member universities such as the State University of New York, Binghamton and Purdue University. Other IRIS member universities such as the Michigan, Indiana, Alaska and Tennessee are developing training courses and classroom material, some of which is based on IRIS data. IRIS is working with Alan Jones of SUNY, Binghamton to develop an interactive seismogram display to be included in the new geology exhibit at the Smithsonian's Natural History Museum. A PC-based program collects waveform data for significant earthquakes from the IRIS DMS SPYDER^{TM} system and creates a display of seismograms, annotated with major phases, a map showing the epicenter and station, and a cross section of the Earth showing the paths of the indicated phases. The frontispiece for this proposal is a poster prepared by Luciana Astiz, Peter Shearer and Paul Earle of the University of California, San Diego, showing a global record section from GSN data. A companion booklet is being prepared for teaching purposes which will identify and explain the major seismic phases seen in the poster.

An example of an IRIS-stimulated education program is the Princeton Earth Physics Project (PEPP), which began in 1993. NSF/EHR sponsors this program to develop a high school curriculum rooted in the physics of earthquakes. Through the development of classroom science projects that involve the analysis of digital seismic data, through teacher workshops at IRIS member universities, and, last but not least, through the development of a low-cost school seismometer (a broadband "Volksseismometer"), PEPP attempts to bring real science, coupled with global environmental monitoring, into the classroom. Using the Internet, PEPP will be able to reach millions of 7-12 graders even in remote parts of the country. IRIS works with PEPP to identify researchers at IRIS member institutions to participate in training programs and act as mentors for teachers establishing classroom programs and installing PEPP stations. There is already a long waiting list of teachers who wish to participate. We anticipate the first Volksseismometer to be delivered for installation in 1995; the school network will grow to some 200 participants by 1997, and a network of as many as 1000 schools in the year 2000 is foreseen.

A Strategy for the Future

The primary emphasis of IRIS activities during the next five years will be to consolidate and strengthen the facilities that have been established during the first decade. While we take considerable pride in the quality and extent of the facilities which IRIS has established, we acknowledge that there are areas where significant improvement, especially in quality control, user services and cost savings, can lead to more productive and sustainable operations. At the same time, IRIS must not ignore its responsibility to be diligent in the stimulation of new frontiers.

Continued growth of our science necessarily relies upon advances in technology and the applications of the technology to monitoring Earth processes. IRIS needs to pursue new directions that best promote and support the strategic goals of solid Earth geophysics. These new directions must be innovative, cost-effective, and meet major needs of the community while, to the extent possible, be conceived as natural evolution of the current IRIS core programs

The program and funding strategy we present is composed of the following parts:

I - A Baseline Budget for *Core Program Operations and Enhancements* - This part of the budget acknowledges the importance of maintaining and operating the existing facilities programs as the first programmatic and budgetary priority in this five-year plan. The budget also includes appropriate expansion and enhancements necessary to respond to pressures and trends identified by our members in the research community. This baseline part of the budget is our primary request for NSF support.

II - Proposed *USGS support for GSN Operations* - The Global Seismographic Network is operated in cooperation with the USGS. In the overall Budget Plan we present the cost for operation and maintenance of all GSN stations, including those of the IRIS/USGS part of the network, and indicate the expected level of support to be provided by the USGS for the support of their part of the network.

III - An Accelerated Budget for *New Initiatives* - which identifies areas where augmented funding would significantly accelerate the capabilities of existing and developing programs, especially in global observatories, array technology, ocean seismology and shallow imaging. For these areas, we request consideration of augmented NSF funding and the authorization to seek outside support.

In the following section we provide an overview of the development proposed for the IRIS facilities over the next five years. Additional detail on both the programs and budgets are presented in the Implementation Plan in Part III and the Budget Plan in Part IV of this document.

Core Programs, Enhancements and New Initiatives

Focus and Interactions

IRIS has benefited greatly from the major effort in the early planning stages to develop clear and specific goals and from the ensuing focus on achieving those goals. It is a tribute to the foresight and imagination of its founders that, after ten years, most of the original IRIS goals have stood the test of time and remain valid today. It is a tribute to the staff and the direction provided by IRIS members that many of these goals are now being achieved.

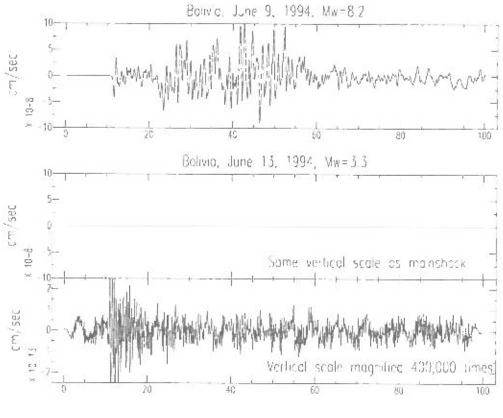
During the first five years of IRIS, primary emphasis was placed on the development of technical specifications for a new generation of instrumentation and data management, the procurement and testing of prototypes and the initiation of embryonic programs. The past five years have seen these programs grow rapidly into productive facilities supporting new and innovative science. The challenge for the next five years will be to maintain the excitement that accompanies growth and expansion as we move into a period requiring more emphasis on sustaining the existing facilities.

As the three IRIS core programs have matured, there have been increasing opportunities and encouragement for interaction between programs. Some of these interactions were obvious and anticipated in the original plan - it was clear that the DMS would closely interact with both GSN and PASSCAL, and that PASSCAL and GSN would have common interests in data logger and sensor development. Other interactions, although not as predictable, have resulted in healthy developments that have often led to innovation and unanticipated advances. A convergence of technologies and scientific interests is leading towards an erosion of spectral boundaries between GSN and PASSCAL. The use of telemetry to provide real time data access is finding application in all IRIS programs. The next five years will see increasing emphasis on coordination between programs both to improve efficiency in operations and to encourage scientific interactions.

Global Seismographic Network

Largely due to the influx of funding in support of nuclear monitoring, and the growth of other broadband networks, global coverage is approaching the original design goals set by GSN in 1984. Most of the continental stations in the GSN siting plan will be installed by the end of the current Cooperative Agreement. The focus of the next five year program, and the largest component of the GSN budget, will be devoted to completing the network and operating and maintaining the existing stations.

The GSN siting plan calls for the installation of 35 additional stations during the five years covered by this proposal. Twenty five of these stations, most of them on oceanic islands, are required to complete uniform global coverage. An additional ten stations are needed to provide enhanced regional coverage in areas of interest to the nuclear verification community.



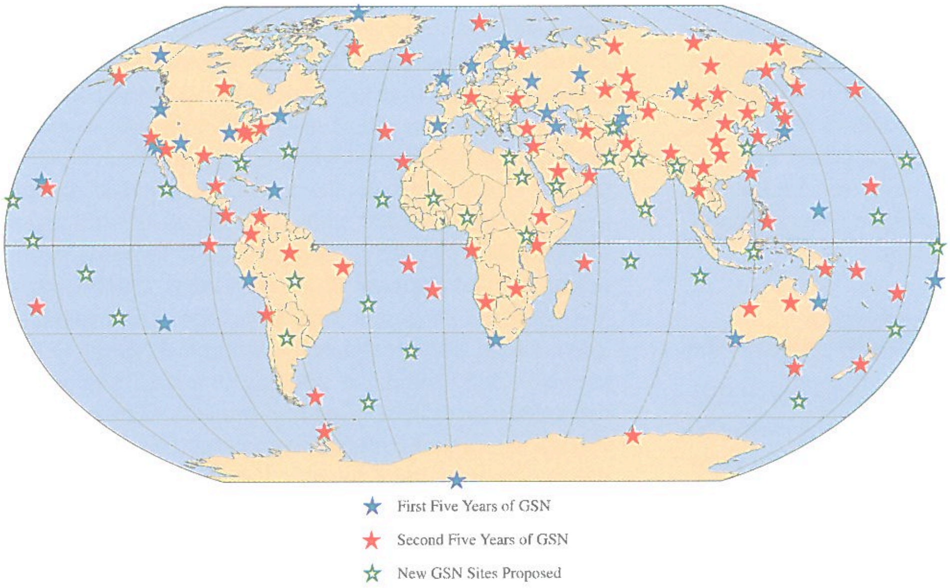
Dynamic Range
With 24-bit data acquisition systems it is possible to record on one instrument almost the entire amplitude range of interest to seismologists, from the background noise at a quite site to strong motions from all but the largest nearby earthquakes. The top trace shows the record of the June 9, 1994 Bolivian deep focus earthquake recorded near the epicenter on a portable PASSCAL seismograph with a broadband seismometer and 24-bit data acquisition system. The bottom two traces show a magnitude 3.3 aftershock on June 13, recorded on the same instrument. The middle trace is reproduced at the same scale as the upper trace for the mainshock. The bottom trace shows the aftershock with the vertical scale magnified 400,000 times. If the mainshock were plotted at the same scale as the bottom trace, it would require a page 6 kilometers high. Figure provided by Terry Wallace, University of Arizona.

The retrieval of data from many of the GSN stations through the SPYDER™ system has been one of the most successful and widely used innovations developed by IRIS. There are emerging developments in the telecommunications industry which, over the next decade, should make it cost effective to realize the long-standing IRIS goal of real-time collection of all data from all GSN stations. In addition to the scientific and societal advantages of having data available within minutes of an earthquake, real time data telemetry can significantly improve station operations and decrease operational costs. Over the next five years, we propose to take advantage of an expanding international Internet and new satellite technology to link as many GSN stations as possible in a real-time, global data collection system. If industry projections for low-cost, worldwide, digital communications systems are met, we will incorporate these towards the end of this five year program; if not, all of the infrastructure will be in place to take advantage of them as soon as they are available.

The GSN provides an infrastructure for station sites, communications and data distribution that can become the basis for a network of global geophysical observations. The development of sites - the selection of locations, developing local contacts, obtaining permission, and building facilities - is one of the more time consuming and expensive aspects of establishing an international network of scientific instruments. Other geophysical disciplines, including geodesy, geomagnetism, gravity and the atmospheric sciences, also have an interest in developing global observational networks. In many cases their current networks are incomplete or outdated. Numerous discussions with both US and international groups responsible for these networks have indicated a strong interest in working with IRIS to take advantage of opportunities for co-location with GSN stations. For a variety of reasons - some financial, most bureaucratic, few, if any, scientific - it has been difficult to obtain commitment and funding from other sources to initiate a program for instrument acquisition and deployment. Because of our confidence in the concept of an integrated network of geophysical observatories, we are proposing, as part of the baseline support for the GSN, to begin with a "proof-of-concept" network of four sites with co-located GPS receivers, magnetometers, atmospheric pressure sensors and other instrumentation. As part of the new initiatives budget, we request authorization to work with other groups and funding sources to develop support for augmented instrumentation at an additional 30 stations.

The GSN siting plan takes advantage of virtually all of the islands available for station locations in remote areas of the world's major oceans. Large areas of ocean remain, however, with no islands, where the only option is to install

GLOBAL SEISMOGRAPHIC NETWORK



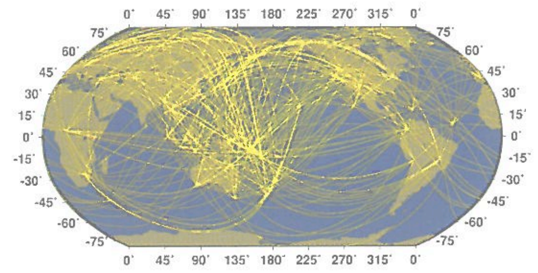
Growth of the Global Seismographic Network
GSN stations installed during IRIS's first five years are shown in blue, GSN stations installed during the second five years (expected through the summer of 1996) are plotted in red. Open green stars show locations of proposed new GNS stations. Many sites are international and national cooperative sites with other networks and organizations. A more complete discussion of the history and planned activities of the GSN and its interaction with members of the Federation of Digital Seismograph Networks can be found in Section III of this proposal.

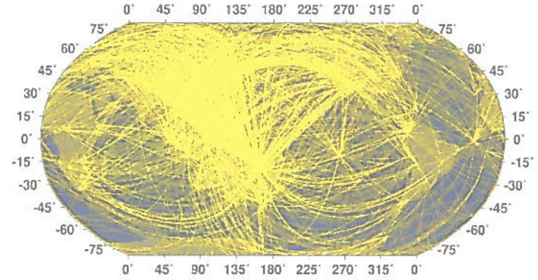
seafloor instruments. The original IRIS plans anticipated that an oceanic component of the GSN would be needed to provide coverage in these areas, but first priority was given to completion of the land based stations. With that goal in sight, serious planning has now gone into the initiation of a development program for an Ocean Seismic Network (OSN). As described in the section on Broadband Seismology in the Oceans in Section III of this proposal, initial development, partly supported through IRIS, has started and a program plan has been prepared. The plan reflects both the long standing plans to establish permanent observatories in the deep ocean and a growing interest in developing a PASSCAL-like program to support temporary deployments of broadband seismometers on the seafloor. Current activities include the testing of modes of seismometer emplacement and the development of prototype recording systems. Various technologies are being considered for data recovery, including the use of abandoned telephone cables. IRIS is proposing as part of its baseline budget to continue to support the OSN development efforts and to work with the OSN to develop funding for implementation of the full OSN program through NSF Ocean Sciences or other agencies and programs. The full budget for this effort is included in the New Initiatives component of the GSN budget.

The GSN is a closely linked partnership with the USGS. The USGS Albuquerque Seismological Laboratory installs, operates and maintains 60% of the GSN stations. The operating agreement between IRIS/NSF and the USGS for operation of the GSN, as outlined in a Memorandum of Understanding and the Technical Plan for the GSN, is that IRIS would provide equipment for upgrade of existing stations and equipment and installation costs for new stations. The USGS would be responsible for the on-going maintenance and operational costs for those stations that they operate under the IRIS/USGS component of the GSN. The operational costs for the full GSN have been prepared for this proposal and are presented in the budget section. The budget plan is constructed with the assumption that the USGS will contribute to the long term operation and maintenance for their component of the GSN at a cost of $3M per year.

GSN Program Highlights

- Operate and maintain a global network that will reach 139 stations in 2001. Special emphasis will be placed on increasing efficiency of operation and overall quality of network performance.
- Continue to work with the USGS and the nuclear monitoring community to develop long-term, stable funding for support of operation of the GSN. In addition, as the multi-use nature of the GSN increases, other agencies will be expected to contribute to the operational support.
- Install 35 new stations to complete uniform global coverage and provide regional densification in areas


Great-Circle Paths to 1984 GDSN for Events with $M_S > 6.2$


Paths to 1994 GSN,CDSN,GTSN for Events with $M_S > 6.2$

Mapping the Earth: 1984 versus 1994
Our ability to map internal Earth structure depends critically on the distribution of great circle paths from earthquake sources to seismic observatories. We compare the path coverage for two years: 1984, the year that IRIS was founded and 1994, to reflect the impact of the accelerated deployment of the Global Seismographic Network. Plotted are the short-arc great-circle paths from all earthquakes with surface wave magnitude Ms greater than 6.2. Events of this size or larger are appropriate for global tomographic studies using surface waves. For 1984, we used the (then) 28 stations of the Global Digital Seismic Network, or GDSN. For 1994, we used 93 stations of the combined GSN, Chinese Digital Seismic Network (CDSN), and the Global Telemetered Seismic Network (GTSN), all of which endeavor to submit quality-controlled data to the Data Management Center within 60 days of recording. There are more large events in 1994 (38) than in 1984 (24). In 1984, data coverage in the Western Pacific and the U. S. is quite dense, with good azimuthal sampling (important for detecting seismic anisotropy), but many regions (Russia, South Pacific, Antarctica) are either unsampled or traversed long paths in a narrow azimuth range. In 1994, the western and northern Pacific, Eurasia and North America are well covered, and several paths traverse Antarctica. The southern Atlantic and Pacific Oceans, however, are not sampled adequately, motivating the future deployment of island and seafloor seismic observatories. Figure provided by Jeffrey Park, Yale University.

of concern for nuclear monitoring. Acquire portable instrumentation for use in temporary deployments.

- Continue to develop communication channels with the goal of providing real-time access to all data from all GSN stations.
- Work with the DMS, USGS and the nuclear monitoring community to facilitate the use of GSN data in the operational activities of the USGS National Earthquake Information Center and the International Seismic Monitoring System.
- Develop four sites as a "proof-of-concept" for a global geoscience network of multi-disciplinary observatories. Instrumentation will include GPS receivers, magnetometers, atmospheric pressure sensors and strong motion accelerometers, in addition to broadband seismometers. Work with other groups to develop funding for 30 additional observatories.
- Continue support of development of instrumentation for broadband seismology on the ocean floor. Work with the Ocean Seismic Network and international community to develop funding for a network of permanent ocean bottom observatories and a marine facility for portable broadband instruments.
- Continue to support the development of enhanced capabilities for global seismic instrumentation with emphasis on software for event detection and parameter estimation.

Program for Array Studies (PASSCAL)

There have been a number of exciting, and sometimes conflicting, evolutionary changes in the needs of the research community served by PASSCAL since the original goals for this program were defined 10 years ago.

In the first ten years of IRIS, PASSCAL acquired a single all-purpose instrument aimed at serving the entire seismological community's need for portable experiments. The availability of this flexible datalogger and a new generation of broadband seismometers fostered the development of portable broadband passive source (i.e. earthquake) experiments. As many of the examples in Section II of this proposal show, these experiments are at the cutting edge of studies imaging the upper mantle. The same instruments are also used to field active source reflection and refraction experiments utilizing large numbers of channels (500-1000) for high resolution imaging of the crust and lithosphere; although in most cases, the PASSCAL instruments constitute no more that a third of the available seismographs used in these experiments. In both natural and active source studies, the number of seismograph channels available has increased dramatically in comparison to that available before the founding of IRIS. However, as documented in the PASSCAL implementation plan in Section III of this proposal, the current PASSCAL inventory is unable to satisfy the needs of funded field programs and there is a compelling need to increase the number of instruments to support both active and passive projects.

The primary emphasis for PASSCAL in this 5-year program will be to continue to support the existing instrumentation facility, and to develop and acquire new instrumentation in order to increase significantly the number of available channels.

Instrument Acquisition

The range of experimental deployments for PASSCAL instruments is broad, but two basic classes (short-term, active source and long-term, passive source) dominate the current usage. There is emerging interest in applications in array studies and shallow imaging, and these are likely to increase in importance in the future.

Short-term, active source

Sensors - high frequency (1-100 hz), usually single component
Experiment duration - days to weeks
Re-deployment - instruments may be moved daily
Primary requirement - large number of channels, high station density, rapid deployment
Current instrument usage - 3-channel PASSCAL instrument, SGR's, Canadian PRS
Support - Stanford Instrument Center
Limitations - more channels required; current PASSCAL instrument difficult to use in rapid deployment mode

Proposed support - The need for large numbers of channels (low cost) and easy deployment (light weight and simplicity) requires the acquisition of a new class of instrument. Simple, single channel data loggers are being developed for use in the exploration industry which appear to meet the basic requirements for this application (weight of one pound, cost of approximately $1500 per channel). We propose to begin acquisition of these instruments for evaluation during the first year of the new cooperative agreement and acquire a total of 1050 channels during the five year period. This instruments will satisfy most moderate scale active source experiments. The relatively short duration of these deployments will allow multiple experiments to be supported per year. For very large experiments, requiring even more channels, the active source community will continue to utilize the rest of the PASSCAL pool of instruments, especially the 3-channel recorders. As the number of simple single-channel instruments increases, some of the 3-channel recorders will become increasingly available for natural source experiments. It is also expected that any instrumentation acquired for shallow imaging (see below) can also be used for special purpose high-resolution recording in active source experiments.

Long-term, natural source

Sensors - broadband (10's sec - 10 hz), 3-component
Duration - months to more than a year
Re-deployment - stations usually remain static
Primary requirements - broadband, large data volume multiple data streams
Current instrument usage - 6-channel PASSCAL
Support - Lamont Instrument Center
Limitations - would be greatly enhanced by telemetry and more rugged intermediate period sensors

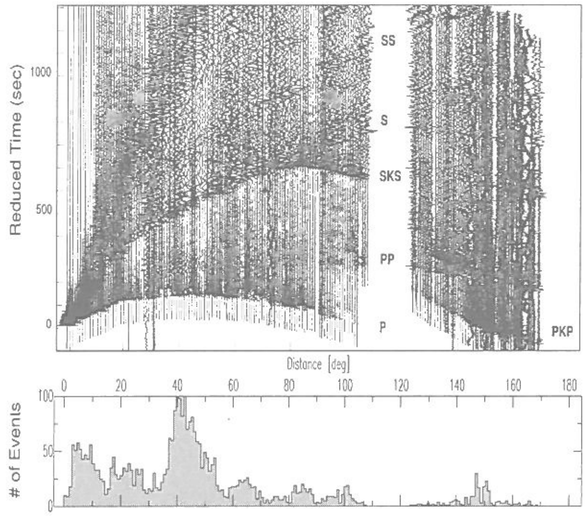
Proposed support - The current 6-channel PASSCAL recorders are well suited to long-term, broadband experiments. The development of telemetry for remote access to data during long-term deployments will greatly facilitate the collection of data and monitoring of station operation. Many passive source experiments do not require the extremely long period response provided by current broadband sensors and we are proposing to acquire a total of 150 less expensive and more rugged intermediate period (10's of sec) sensors for these applications. Acquisition of 50 additional 6-channel instruments is proposed and, as noted above, increasing numbers of 3-channel instruments will be available for passive source experiments as new single-channel instruments are acquired.

Arrays

In the PASSCAL context, an array is simply multiple PASSCAL data acquisition systems with telemetry added, to transmit data to a central recording system. As described in more detail in the PASSCAL, Array and Telemetry sections of Part III, this relatively simple extension to the current facility provides increased flexibility in experiment design and greatly enhanced analytical capability. Much of the development work for array design has already been carried out by the array studies group under the Joint Seismic Program. An initial 20-element broadband array has been acquired under the JSP, which will become the first array element under the PASSCAL program.

As part of the core program, we are proposing that telemetry and central recording equipment be purchased for six 20-element arrays, and that an array instrument center be established to support these systems. Under the core program support, the data loggers and sensors for these arrays will be made available from the existing PASSCAL instrument pool. The PI will have the option of deploying instruments in autonomous mode, as arrays, or as combinations of both.

In the new initiatives part of the budget plan, we propose to acquire additional sensors and data loggers to fully populate the 20 arrays, independent of the existing hardware. Since the arrays are especially suited for studies of the details of regional wave propagation and seismicity, it is anticipated that additional support for this expansion of the array capability might come from agencies responsible for nuclear monitoring research and earthquake hazards studies. The new initiatives budget specifically targets the acquisition of a full 20 element array to augment the existing IRIS RAMP facility (Rapid Array Mobilization Plan) for aftershock studies. Without telemetry, a RAMP deployment in a remote area provides data only after a time consuming trek around the network to service the instruments. With telemetry, seismicity and fault zone



PASSCAL Augments the GSN
The deployment of temporary networks of broadband PASSCAL instruments in remote areas can be a demanding but rewarding experience. The effort involved in planning and implementing complex field programs has encouraged collaborative projects between multiple PI's with diverse experimental goals. The year-long deployment of twelve stations in the 1991-92 Tibetan Plateau Broadband Seismic Experiment is an example of such a program. The original PI's (Tom Owens and Francis Wu) and colleagues have used a variety of techniques - travel time and attenuation tomography, shear wave splitting, receiver function analysis, locations and fault plane solutions of regional seismicity, etc. - to study the structure and seismicity of the Tibetan region. As the detailed coverage in this record section from the Tibetan experiment indicates, temporary broadband experiments also have the potential to contribute to studies of global earth structure. Traces selected are the highest signal-to-noise ratio trace in each 100 km source-receiver separation bin for which data are available. The histogram plots the total number of recorded events in each 100 km bin. The data from this and other long-term PASSCAL deployments are being merged with GSN data in the IRIS DMS archive, providing the entire seismology community with a rich source of data for detailed studies of Earth structure and sources unrelated to the goals of the original PI's. Figure provided by Tom Owens, University of South Carolina

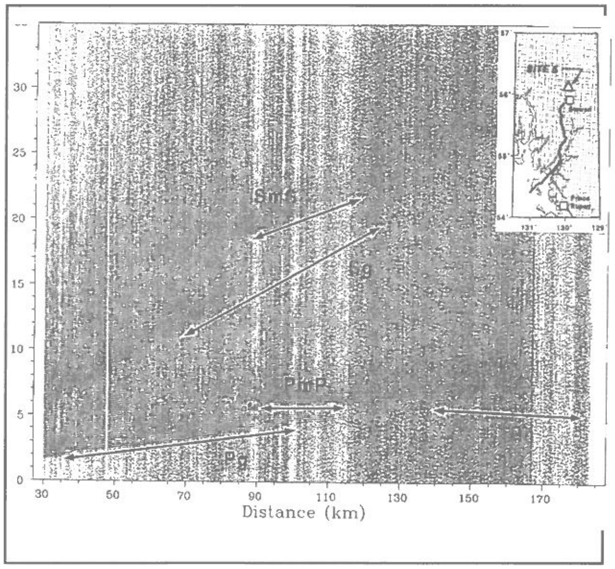
deformation can be monitored in near real time, a factor of critical importance during an aftershock sequence.

The development of array capabilities as an enhancement to the basic PASSCAL instruments was carried out under the JSP with applications in both local, phased arrays for studies of seismicity and wave propagation (Pinyon and Geyokcha) and regional networks for earthquake monitoring (Kyrghyzstan). We anticipate that these developments will also find application, outside of IRIS, as components of permanent regional seismic networks in the US and overseas.

Shallow Imaging

The use of seismic imaging to study shallow structures (depths of 5-1000m) has become increasingly important for studies in many areas such as hydrology, waste disposal, earthquake site evaluation, archaeology, neotectonics, and Neogene (climate) stratigraphy. These practical applications are likely to become an increasingly important component of seismology. New developments in theory and analysis are required to take full advantage of what seismology has to offer; particularly in the integration of data from ground penetrating radar, electrical, and seismic methods. Shallow imaging will become a very important component, perhaps even the dominant component, of the new jobs available for graduates of the IRIS institutions. IRIS must plan an effective program to take advantage of these changing circumstances.

Seismic imaging of the upper 1 km of the crust, as well as detailed investigations in integrated crustal/upper mantle experiments, require the use of sensors recording from 6 Hz to 100 Hz deployed at spacings of 0.25 to 25 meters. This type of experiment is not easily done with present PASSCAL facilities. Commercial systems for shallow seismic imaging consist of strings of (24-256) geophone channels recorded by a portable multichannel datalogger. Many IRIS institutions have purchased this type of equipment for teaching purposes and small scale research projects. IRIS has recently received a grant from DOE to purchase two 60 channel systems. These systems will form the core of a PASSCAL facility to support shallow imaging.



PASSCAL instruments in offshore - onshore experiments
This record section from the ACCRETE project in southern Alaska indicates the quality of data that can be obtained from the combination of standardized PASSCAL instruments with the powerful and repeatable energy source provided by the air-gun array on the R/V Ewing. In 1994, offshore-onshore experiments, combining the Ewing air guns and hydrophone arrays at sea with PASSCAL instruments and chemical explosions on land, were carried out along much of the western coast of North America, from California to Alaska. The results of many of these experiments, and a unique application of marine techniques in the BARGE experiment in Lake Mead, are described in more detail in Section II of this proposal. Figure provided by John Diebold, Columbia University and P. Hammer, University of British Columbia.

The facility will provide the incentive for IRIS members to coordinate the use of existing university systems and develop common mechanisms for data exchange. IRIS can assist in this coordination by:

- Providing discounts for bulk purchases of equipment
- Acting as a clearing house to coordinate the sharing of instrumentation held by individual members.
- Providing the IRIS community with access to relevant software packages and arranging for inexpensive bulk purchase of commercial software.
- Developing software to allow users to integrate data from commercial instrumentation into IRIS data formats.

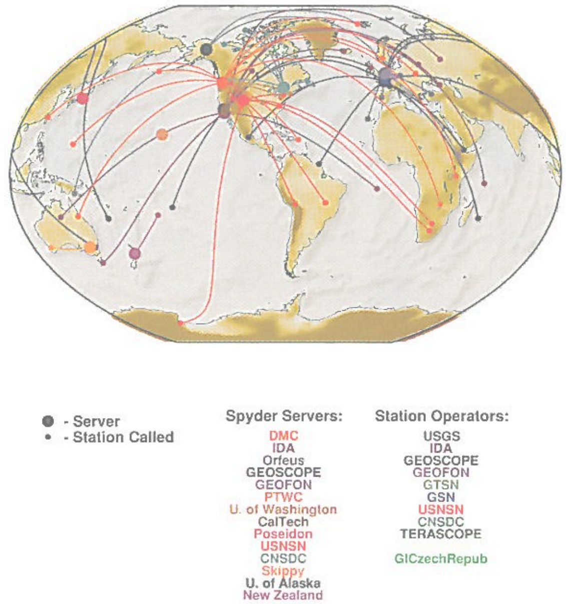
Based on experience with the DOE multi-channel equipment and the new single channel simple instrument, a decision will be made in the second year of this 5-year program as to the appropriate balance of single-channel and multi-channel instruments to support shallow imaging and active source crustal and lithospheric investigations.

New Instrument Development

By the end of the next five-year program, the PASSCAL instrument will be technologically obsolete, having reached its natural lifetime for replacement and re-engineering. To continue for the next five years without preparing for a transition to new technology would leave us with archaic, unreliable instrumentation. The wear-and-tear on the instruments in the field, coupled with the march of technology clearly demands an ongoing program in instrument modernization and replacement. New technologies in telemetry, mass storage, low power, and time keeping, invite us to undertake a transition to true, coherent arrays. During the last two years of this plan, funds are requested to start developing a new generation of PASSCAL instrumentation.

PASSCAL Highlights

- Support of the current facility will continue through the two Instrument Centers at Lamont and Stanford.
- PASSCAL will work closely with the DMS to improve IRIS-wide capabilities for management of data from both active and passive source experiments.
- The 6-channel instruments will remain the backbone of support for long-term broadband experiments. Fifty additional instruments of this type will be acquired to provide a total of 170.
- A new class of single-channel instruments will become the core facility for short-term active source experiments. As the inventory of these instruments increases, the need for the current 3-channel instruments by the active source community will decrease and consequently more 3-channel instruments will become available for longer-term passive experiments, especially utilizing telemetry in array deployments. The three channel instruments will, however, remain available for scheduled use in very large scale active source experiments. One thousand channels of "simple" instruments will be purchased along with an additional sixty 3-channel



SPYDER™ and Near-Real Time Data Collection
The SPYDER™ system, developed by the University of Washington and the IRIS Data Management System, has proven to be one of the most popular means of accessing data from the GSN and cooperating stations from other networks. SPYDER™ is based on a combination of dial-up and Internet communications to access selected segments of waveforms from significant earthquakes in near real time. SPYDER™ is activated by USGS NEIC earthquake "alerts" broadcast over Internet. For events of magnitude 5 or greater, the appropriate time window for each station is determined and a request sent either directly to the GSN site, or to a secondary node in the SPYDER™ system, which in turn contacts the station and retrieves waveform data. Data are returned automatically to the DMC where a special user interface provides information on data available, and convenient tools for previewing and retrieving data.. In mid-1995, there are 77 stations available via SPYDER™, of which 46 are IRIS GSN stations. Data from SPYDER™ are typically available within minutes to hours of an event.

instruments, for a total of 390 3-channel instruments.

- Arrays, with dimensions up to 10's of km and based on the existing 3- and 6-channel hardware, will find increasing application in specialized studies of the seismic wavefield and sources. These may be in special long term deployments for studies of wave propagation and regional seismicity, or as enhanced nodes within larger-scale deployments of PASSCAL instruments for teleseismic observations. As part of the baseline budget, six sets of telemetry equipment only will be purchased to support up to 120 of the existing 3- or 6-channel data acquisition systems. An array center will be established to support the operations and further development of the array systems. The augmented budget requests support for one complete array system for RAMP use in aftershock studies and for seismometers and data acquisition systems to fully populate the arrays as independent systems.
- In addition to telemetry associated with the arrays, PASSCAL will develop communications capability for remote data acquisition from independent instrument deployments in long-term broadband experiments. This development will be coordinated with similar activities under GSN and DMS.
- As an augmentation to the PASSCAL program under new initiatives, we request authorization to seek additional support for instrumentation for shallow imaging and active source studies. Depending on experience during the early phase of this program, this instrumentation could take the form of multi-channel (shallow imaging) systems or additional one-channel recorders.
- In the final two years of this 5-year program, development will begin on a new generation of PASSCAL instruments.

Data Management System

As IRIS has matured, there has been an evolution in concept of data services as emanating not from an archive in a Data Management *Center*, but rather from a Data Management *System*, consisting of a number of coordinated and inter-connected nodes.

The concept of a Data Management System is reflected in the distributed nature of the facilities that comprise the DMS. The core facility is the IRIS Data Management Center in Seattle. GSN data flow to the DMC through Data Collection Centers (DCC's) co-located with the GSN operational centers in San Diego and Albuquerque. Additional nodes include programs at Harvard University and the University of Washington that aid in quality control along with a Data Analysis Center in Moscow. The Joint Seismic Program Center at the University of Colorado is being integrated into the DMS as a focus for software development.

The concept of a Data Management System is also reflected in the services it provides. The archive at the DMC is at the core of the program, but DMS responsibilities extend into data collection, quality control, user services, software support and the integration of diverse data sets from GSN, PASSCAL and an increasing number of contributing sources external to IRIS.

During the past five years, the operations and hardware configuration at the DMC have evolved from an interim, experimental system to a stable and efficient operation. For GSN data in particular, the basic functional and operational elements, both personnel and hardware, have been defined and implemented. Increasing emphasis is now placed on refining operations both to improve the efficiency and quality of data flow and to be more responsive to user requests. Now that these operational aspects have stabilized, a primary responsibility for the DMS over the next five years will be to insure the reliable and efficient collection and distribution of data from the GSN and PASSCAL programs. The success of the IRIS DMS philosophy in collecting, archiving and distributing data has led to strong encouragement to extend its mission. We propose significant expansion of the "information services" provided by the DMS, especially in coordinating basic and "value-added" data related to earthquake science and in the management of other kinds of data collected by the solid Earth research community. Essential partners in the coordination and distribution of earthquake data will be the USGS and the recently formed Council of the National Seismic System (CNSS).

The Data Management Center is unique among IRIS core facilities in that, unlike the PASSCAL instrument centers or GSN network operations, it is an IRIS staffed and operated facility. A significant component of the DMS budget is thus devoted to salaries of personnel and the maintenance and replacement of hardware at the DMC. The current staff of ten full time employees consists of a Program Manager, a director of operations, a systems administrator, two software engineers, three data control technicians and one administrative support person. As the DMC operations have evolved, the tasks for this group have shifted from the development of the data management framework to the efficient operation of a large and complex system. The current number of personnel is considered appropriate for the steady state operation of the DMC, but additional staff, especially in the area of programming, is required for the expanded mission in "information services".

Interest in providing data for research and monitoring related to a Comprehensive Test Ban Treaty has been the basis for the recent accelerated expansion of the GSN. The DMS plays an important role in insuring the data from the GSN are available to those involved in operational monitoring and research on nuclear monitoring, both in the government and university communities. In January, 1995, the GSE (Group of Scientific Experts), as part of the United Nations Conference on Disarmament, began GSETT-3, a third test of a global system for seismic monitoring. Many GSN stations are being used as part of this test and the DMS is working with the prototype International Data Center at the DARPA-sponsored Center for Monitoring Research to insure that appropriate access is provided to GSN data. The National Academy of Sciences was commissioned by ARPA to make recommendations on a variety of aspects of the GSETT-3 effort. The report of the Academy Panel recommended that waveform data being collected as part of the prototype International Monitoring System be made available to the research community through the IRIS DMC. Initial contacts have been made between IRIS, the USGS and the United States National Data Center (NDC) for GSETT-3 at Patrick Air Force Base in Florida to establish protocols for access to these data through the DMS.

There has been increasing encouragement for IRIS to work with the USGS and regional networks operators to develop a more focused national program in Earthquake Studies. Over the past few years, led primarily by regional network operators and the USGS, the concept of a National Seismic System has emerged, encompassing the full spectrum of operations related to earthquake monitoring in the U.S., from station operation to cataloging and information distribution. A Council of the National Seismic System (CNSS) has been formed to coordinate the activities, and IRIS has recently become a full member of this group. IRIS brings to the CNSS established strengths in data integration and archiving. There have already been preliminary efforts to use the facilities of the DMS to stimulate data exchange between regional networks. Working through the CNSS, the DMS has started to archive event data from some of the regional networks. Agreement has been reached with the USGS for distribution through the DMS of data from the U.S. National Seismic Network. Temporary deployments of PASSCAL instruments in aftershock studies following significant earthquakes like Loma Prieta, Landers and Northridge complement regional networks in producing high resolution images of seismicity and structure. An important role for the DMS is to work with regional data centers, such as those at the Southern California Earthquake Center and Berkeley/USGS, to insure that all available data, both seismic and non-seismic, related to these special earthquake sequences are readily available.

The coordinated archiving and distribution of national earthquake data will greatly enhance the resources available to the research community involved in earthquake studies as part of the National Earthquake Hazards Reduction Program. The USGS and the CNSS have also initiated an effort to coordinate the production and distribution of national and regional earthquake catalogs. The DMS is working to insure that the appropriate "hooks" exist to couple the earthquake catalogs and waveform data.

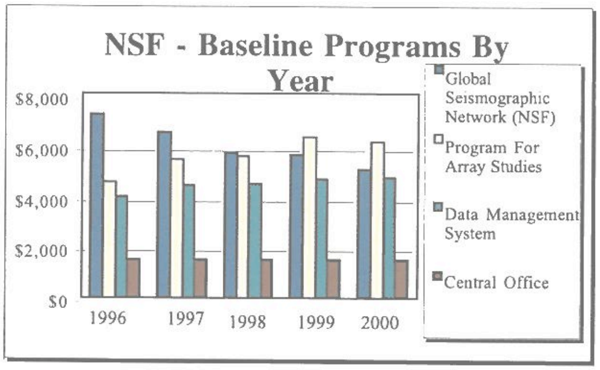
In addition to improving the coordination and exchange of earthquake data, the effort of the CNSS and IRIS in collecting and distributing data from national and regional networks can contribute greatly to studies of Earth structure. As recent work has shown, the high density of regional network stations in some areas allows them to be used as powerful arrays for resolving the details of deep structure and discontinuities, especially in the upper mantle. In the past, a significant impediment to applying these data in structural studies has been the effort required to collate data from diverse networks. Archiving data in a common format at the DMC and integrating them in the database with GSN and PASSCAL data overcomes this problem. As the number of broadband stations in regional networks increases, and as temporary deployments of PASSCAL instruments provide data from areas of sparse regional network coverage, new opportunities will emerge for high resolution tomographic studies of the lithosphere and investigations of deep Earth structure. The DMS can play a key role in bringing these data together in a coordinated, well-documented and easily-assessable archive.

DMS Highlights

- Operation of the existing DMS services will continue. Staffing at the Data Management Center in Seattle will increase from ten to thirteen. The Data Collection Centers at the IDA and Albuquerque operations centers of the GSN will continue to be supported and managed through the DMS. Support will continue of DMS nodes at the University of Washington, Harvard University, the JSP Center at the University of Colorado and the Moscow Data Center.
- The DMS and PASSCAL will work to provide improved data access and quality control for PASSCAL experiments. Data from long term passive experiments will be integrated with GSN data in the main DMS archive. Special facilities, both hardware and software, will be provided to assist active and passive projects in the sorting and manipulation of large datasets.
- Information services will be enhanced, especially in support of earthquake studies. The DMS will work closely with the USGS and the Council of the National Seismic System to help coordinate and facilitate the archiving and exchange of earthquake data. As in the

past, IRIS emphasis will be on waveforms, incorporating data from the USGS National Seismic Network and regional networks, and the USGS will focus on the coordination of earthquake catalogs and parameter data.

- The exchange of information with other data centers and the distribution of data to users will benefit from expanded use of distributed nodes on the Internet. Cooperation with other seismological data centers will be expanded, and links with centers responsible for other types of geophysical data will be established
- Working with the GSN and PASSCAL programs, improved methods of real-time data collection will be established and incorporated into the data flow of the DMC.
- A software framework to support research with IRIS data will be developed. The primary emphasis will on a database management system focused on seismological data and on graphical tools for data display and manipulation.
- The routine handling of data during quality control and archiving at the DMC will be augmented with simple processing tools to provide characterization of waveform data. The results of this processing will be of use in monitoring data quality and in providing parameter data to the NEIC.
- Software and hardware configurations will be developed to facilitate local data base management at universities
- Hardware upgrades will be implemented as required at the DMC and DCC's. Major purchases during this five year period include staged upgrade or replacement of the existing mass store systems at the DMC and DCC's.



Budget Summary

In this proposal we present a five year program for the continuation and enhancement of facilities IRIS has established over the past ten years, and describe new initiatives to extend the support that IRIS provides to the national and international geoscience community.

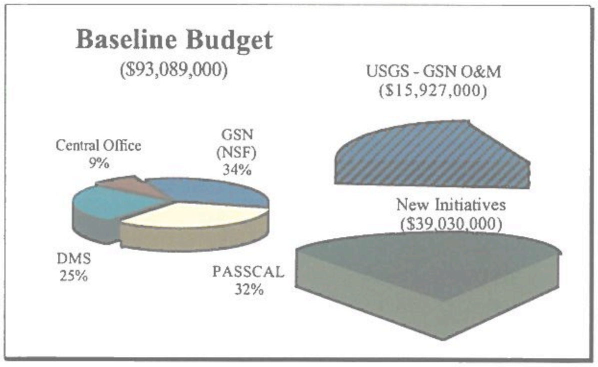
The budget strategy which we propose consists of three parts: baseline support from NSF; a contribution from the U.S. Geological Survey for support of the Global Seismographic Network; and a request for program endorsement and authorization by the National Science Board to seek additional funds from NSF and other agencies to support new initiatives.

In this section we provide a brief summary of the funding request for the next five years. A review of prior funding and details of the budget request for individual program elements can be found in the Budget Plan in Section IV of this document

Baseline Program support from NSF

Support for the completion, operation and enhancement of the existing core facilities is contained in the baseline budget to NSF. The total request is for $93,087,000, an average of $18,617,000 per year. The program components are summarized in the figure below. Approximately one third of the baseline budget is devoted to each of the GSN and PASSCAL programs; one quarter to DMS and one tenth to the IRIS Central Office.

GSN - By the end of the proposed plan, the GSN will grow to a total of 139 stations. Uniform station distribution will be completed over the continental regions of the globe and island sites will provide coverage of most of the world's oceanic areas. In areas of special interest for nuclear monitoring, additional stations will provide enhanced regional coverage. Major effort will be devoted to establishing real-time access to data from all GSN stations.



The annual budget for the GSN decreases through this 5-year plan as the rate of new installations decreases and the network support stabilizes into steady-state operation and maintenance. The total (zero-inflation) request for support of the GSN is $45M of which $30M is proposed from NSF and $15M from the USGS.

PASSCAL - This proposal requests a significant increase in the number of PASSCAL instruments. The inventory of current 3-channel and 6-channel instruments will increase by approximately 40%, to a total of 560. One thousand new, single-channel instruments will be acquired to support active source studies. Specialized multi-channel systems will be acquired for shallow imaging. An array capability will be developed based on telemetry of data from existing PASSCAL instruments. The annual PASSCAL budget increases during the five-year period, from approximately $4M/year to $6M/year, primarily as a result of increased support for the expanding instrument pool at the PASSCAL Instrument Centers.

DMS - With an operational Data Management Center firmly established, the activities of the DMS during this five-year program will focus on enhanced user services and information management. The annual budget for the DMS remains relatively constant at approximately $4.5M/year. Major hardware upgrades at the DMC and associated data collection centers are staged throughout the 5-year plan. In the final two years of this plan, DMS support of communications channels increases significantly as the GSN and PASSCAL programs make increasing use of global telemetry systems for real time data collection.

Central Office - The IRIS Central Office is responsible for overall coordination and management of IRIS programs and for operation of IRIS-wide activities such as publications and workshops. Approximately 10% of the total budget is devoted to Central Office activities.

Operation and Maintenance of the USGS Component of the GSN

The GSN has been developed as a cooperative project between NSF/IRIS and the USGS. The original agreements between the USGS and NSF/IRIS called for IRIS to provide new equipment to upgrade existing USGS stations and installation support and new hardware for new stations. Once stations were established, the USGS would be responsible for the on-going operational costs of the IRIS/USGS component of the GSN (~60% of the total network) and IRIS would continue to provide new equipment for station upgrades. The influx of funding from DOD, as a result of special Congressional interest in a Comprehensive Test Ban Treaty, has accelerated the installation of new GSN stations. Funding for support of USGS activities in this accelerated program - both installation and operation costs - have been provided via interagency fund transfer from DOD to NSF and the USGS. Discussions are now in process, through a special Working Group under the auspices of the White House's National Science and Technology Council (NSTC), concerning the long-term support for global seismographic networks. A primary recommendation of that Working Group is expected to be that, staring in FY97, each agency will be responsible for the support of their own activities in network operations, without the need of interagency transfers. NSF and USGS are currently working together and with the NSTC Working Group to establish a specific plan for future support of the GSN. This proposal is based on the assumption that this process will be successful. The budget includes enhanced NSF support for the GSN and associated data management activities, plus increased support from the USGS of $3M/year for O&M of the IRIS/USGS network.

National Science Board Authorization for New Initiatives

In addition to the baseline support for core programs, new initiatives are proposed in the development of multi-purpose, global geophysical observatories; broadband seismology in the oceans; and extensions to PASSCAL in aftershock monitoring, arrays and shallow imaging. We present budgets for these initiatives for which we request additional NSF support and/or National Science Board approval to seek funds outside NSF. The total request for these new initiatives in $39,030,000.

IRIS 2000
Scientific Contributions

INTRODUCTION

Jeffrey Park, Yale University
Guust Nolet, Princeton University

Earthquakes

EARTHQUAKE SEISMOLOGY AND IRIS

Goran Ekstrom, Harvard University

THE PHYSICS OF EARTHQUAKE RUPTURE

Tom Heaton, United States Geological Survey, Pasadena

Seismic Evidence for an Earthquake Nucleation Phase
William L. Ellsworth, U.S. Geological Survey
Gregory C. Beroza, Stanford University
RAMP Deployment Following the June 28, 1992 Mw 7.6 Landers Earthquake
Frank Vernon, Adam Edelman, University of California at San Diego
Characterization of Fault Zone Physics Along the San Andreas Fault
Jonathan Lees, Yale University
RAMP Deployment Following the January 17, 1994 Mw 6.7 Northridge Earthquake
Frank Vernon, Adam Edelman,University of California at San Diego
Earthquake Hazards Along the Southern Cascadia Subduction Zone
M.T. Hagerty and S.Y. Schwartz,University of California, Santa Cruz
The 1992 Suusamyr Earthquake and Aftershock Sequence
Robert Mellors, Frank Vernon, University of California, San Diego
Gary Pavlis, Indiana University
Prospects for Increased Seismicity in the LA Basin
Susan E. Hough, U.S. Geological Survey, Pasadena
IRIS/PASSCAL Contributions to Understanding Geodynamics and Seismic Hazard Associated with the Cascadia Subduction Zone
Anne Trehu, Oregon State University
Regional Earthquake Sources Studies
Douglas Dreger, University of California, Berkeley
3D Crustal Structure of the San Francisco Bay Area
John Hole and the BASIX Working Group, Stanford University., U.S. Geological Survey, Woods Hole Oceanographic Institution, Pennsylvania State University, University of California, Berkeley
Recording Aftershocks of Significant Earthquakes
Susan Y. Schwartz, University of California, Santa Cruz
Bolstering the National Seismic System
Walter Arabasz and Steve Malone, Council of the National Seismic System
The Berkeley Digital Seismic Network
Barabara Romanowicz and Staff of the U.C. Berkeley Seismographic Station,
University of California, Berkeley

Near-field Phases Recorded on KNET
Robert Mellors and Frank Vernon, University of California, San Diego

The Southwest Pacific Seismic Experiment
Doug Wiens, Washington University

Geometry of the Subducted Nazca Plate Determined With Data from the PASSCAL Seismic Deployment BANJO
P. Silver, DTM, Carnegie Institute of Washington
G. Zandt, University of Arizona
J. VanDecar, DTM, Carnegie Institute of Washington
E. Minaya, San Calixto Observatory, Bolivia

Rapid Earthquake Analysis Utilizes the Internet
G. Ekstrom, A.M. Dziewonski, M.P. Salganik, S. Sianissian, Harvard University

Anomalous Earthquakes on Volcano Ring-Fault Structures
Goran Ekstrom, Harvard University

Lithospheric Structure

IRIS AND THE SKIN OF OUR PLANET

Alan Levander and ILIAD Workshop Participants

The Mendocino Triple Junction Seismic Experiment
Anne Trehu, Oregon State University; Alan Levander, Rice University,
Anne Meltzer, Lehigh University; Simon Klemperer, Stanford University
Bruce Beaudoin, Stanford University; Walter Mooney, US Geological Survey, Menlo Park
Jim Luetgert, US Geological Survey, Menlo Park; Sam Clarke, US Geological Survey, Menlo Park
Gary Carver, Humbolt State University; Kevin Furlong, Pennsylvania State University
Manik Talwani, HARC

The Brooks Range Seismic Reflection/Refraction Experiment
Alan Levander and E.S. Wissinger, Rice University
Gary Fuis, U.S. Geological Survey

The Basin and Range Geoscientific Experiment (BARGE): Intracontinental Lacustrine Seismology
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WAVE PROPAGATION

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Introduction

Jeffrey Park, *Yale University*
Guust Nolet, *Princeton University*

Part II of the IRIS proposal is intended to show how IRIS has influenced the science of seismology. The best way to do so is by example. We invited IRIS members to choose an illustrative aspect of their work and condense this on one page. In addition, we asked a select group of scientists to write essays that reflect their personal view of the role of IRIS. We have used these to structure Volume II into sections that broadly encompass the fields where IRIS has exerted a substantial influence. New discoveries in seismology are nearly always the result of new, sometimes unexpected, observations. These short contributions, with their mix of hard facts and speculation, demonstrate that the infusion of new seismic data from IRIS activities has led both to the resolution of lingering scientific disputes and to provocative new models. The subsections of Part II include:

Earthquake Seismology and IRIS: A better assessment of seismic hazards and the prospects for earthquake forecasting require a better understanding of how earthquakes occur. Are there identifiable precursors to large ruptures? How does the rupture sustain itself, and what makes it stop? How do aftershocks relate to the main event? A decade ago, detailed, broadband, on-scale recordings of earthquake rupture were scarce, and comprehensive aftershock studies were possible only under pre-existing regional seismic networks. Now that data sufficient inquality and quantity can be collected to address earthquake source behavior properly, a wealth of new ideas has sprouted.

IRIS and the Skin of Our Planet: For decades, exploration seismology has used man-made seismic sources to probe the part of the Earth accessible to drilling and resource recovery. To the geoscientist, however, the skin of the earth extends to the base of the tectonic plates, drifting slowly across the viscous mantle. In order to extend the structural intuition of the field geologist fully into the third dimension, academic seismologists have extended the methods of resource exploration to greater depths and longer baselines, as well as adapting broadband seismology to explore below the crust, discerning regional heating events and flow-induced mineral orientations. The contributions in this section suggest that we stand at the threshhold of major integrative breakthroughs in the uplift of mountains and plateaus, the subsidence of sedimentary basins, and the ancillary geologic processes that create mineral resources as a byproduct of active tectonics.

Global Seismic Tomography: A major consequence of NSF support for IRIS has been the solidification of the first controversial images of the Earth's deep interior. Seismic tomography has been extended from a glimpse of the broadest-scale of thermal convection to detailed examinations of whole-earth dynamics, the peculiar style of chemical recycling throughout the Earth's interior that makes our planet unique in the Solar System. With sufficient data to corroborate inferences within dependent types of observations, seismologists now anticipate close study of smaller-scale boundary-layer processes near subducting slabs, oceanic ridges, the core-mantle boundary and the mid-mantle transitions of mineral assemblages.

A Role for IRIS in Public Policy: The Global Seismographic Network and the Data Management System of IRIS spearhead international efforts that are rapidly transforming seismic monitoring activities around the world. It might be argued that seismic observatories would have evolved anyway, given the momentum of technical innovations, of the growing recognition that our society is becoming more vulnerable to the sudden impact of seismic disruption, and of the continued relevance of seismic networks for the monitoring of a test ban treaty. Nevertheless, the unselfish collaboration of more than 80 institutions within IRIS, with strong support of NSF and DOD, has initiated, accelerated and strengthened this evolution. Moreover, the data management system developed by the IRIS community is still unique worldwide, both for its open nature and rapid access to high quality digital data. The contribution in this section show the success of this fertile interplay between "pure" science and the more public role of seismic monitoring.

Wave Propagation Studies: The increased quantity of reliable data has pushed theoreticians to develop managable approximations to wave propagation theory that incorporate velocity anisotropy and lateral heterogeneity, even at small scale. New observations of peculiar seismic waveforms, from well-calibrated and reliable instruments, force researchers to re-examine the simplifying assumptions that guided earlier work. The heretofore incoherent coda that follows major seismic waves can be broken down into isolated scattered waves by analysis of seismic array data. The shape of seismic waveforms, as well as their arrival time, can be used to constrain attenuation and diffraction effects from deep geologic structures. Geologic structures on the outcrop scale can be modelled statistically to fill the volumes of rock between prominent reflectors in active-source reflection/refraction studies. Data from IRIS facilities have transformed formerly esoteric wave-propagation topics into realistic tools to learn something new about the Earth.

Seismology as a Cornerstone in the Earth Sciences: There are few problems addressed nowadays by seismologists that do not overlap significantly with problems in other earth science disciplines. The connection between tomography, viscous flow and mineral physics in the deep earth was among the earliest exploited. The symbiosis of these disciplines is illustrated by this subsection's essay and one-page contributions. Deep-earth imaging also suggests a connection between mantle turnover, thermal anomalies at the core-mantle boundary, and the history of the reversals of the Earth's magnetic field. Nearer the surface, the intellectual boundary between structural geology and crustal imaging has blurred, as the disciplines collaborate to reconstruct continental dynamics. More tenuous connections are being made between studies of earthquake and metamorphic processes, both of which depend, in an poorly-known manner, on the migration of crustal fluids. The use of seismic data to explore our planet's third dimension will continue to complement other branches of earth science, as long as this data is relatively easy to collect, distribute and analyse. This condition can be met if IRIS remains active and continues to interact productively with scientists at its member institutions.

Earthquake Seismology and IRIS

Goran Ekstrom
Harvard University

A defining characteristic of the discipline of earthquake seismology is the seeming unpredictability and uniqueness of the individual objects of our study. We are still far from reaching a comprehensive understanding of earthquakes based on first principles, and have little opportunity to perform controlled experiments which can isolate the specific physical conditions which control their occurrence. Instead, descriptions of the tectonic processes which result in seismic activity, and kinematic and dynamic models of the seismic source, are largely developed and refined in response to the accumulation of earthquake observations. To the seismologist interested in the geological conditions and processes which lead to the generation of earthquakes, the occurrence, recording, and analysis of a single earthquake can provide sufficient information to reach a conclusion on the existence or extent of a geologic structure or a regional pattern of deformation. For the seismologist studying the mechanics of seismic ruptures, a well-recorded earthquake can provide new constraints on hypothetical source models. Better seismological data sometimes help to verify or falsify competing hypotheses, but equally often lead to a gradual evolution of conceptual and physical models. The complexity and variability of earthquakes put the collection of high-quality observations at the heart of our science.

IRIS facilities have made possible progress on a wide range of scientific problems related to the earthquake source. In addition to the advantages resulting from the improved quality and greater quantity of seismological data that are collected by IRIS instruments, a profound change has also occurred in how seismological data are shared, managed, and distributed with the aid of IRIS facilities.

The purpose of this essay is threefold: First, to highlight the technological and organizational achievement which led to the successful 'capture' by IRIS instrumentation of two unique deep earthquakes in 1994. Second, to discuss how IRIS facilities can contribute to the resolution of some current controversies in earthquake source theory. Finally, to describe how the growing volume of high-quality seismological data is allowing us to monitor global seismicity and strain release in new ways, and how the rapid dissemination and analysis of these data can result in societal benefits.

Bolivia and Fiji - The Great Deep Earthquakes of 1994

Two spectacular successes of the IRIS instrumentation program are evidenced by the datasets collected for the Bolivia and Fiji deep earthquakes of 1994. On-scale recordings of these earthquakes were made on both the permanent Global Seismographic Network and two serendipitously located temporary PASSCAL field experiments. These unique datasets can test current hypotheses for the nature of deep seismicity, and the mechanics of deep seismic ruptures. Based on the recent observations, we now know that deep earthquakes can have very active aftershock sequences, and that aftershocks sometimes appear to occur outside of the core of the subducted lithosphere. The observations for the Bolivia earthquake also suggest a very slow apparent rupture velocity, but large local slip. From the recordings of the GSN, we can conclude that any volumetric change associated with the earthquake is insignificant in comparison with the deformation in shear. There is so far no evidence for an infra-seismic rupture initiation or precursory moment release. These observations contradict many earlier studies of large, deep earthquakes (often limited by lower quality data) and motivate a critical reassessment of both conventional wisdom and of specific physical models for deep seismic ruptures.

One reason for the successful recordings of the Fiji and Bolivia earthquakes was the foresight shown in the design of IRIS instrumentation. The wide dynamic range of both the GSN and PASSCAL recorders allowed the earthquake to be recorded on-scale, not only at locations around the world, but also right above the hypocenters. A second reason is, of course, that the temporary PASSCAL deployments were in the field in the first place, with other scientific objectives. The lesson that might be learned is that by utilizing a versatile instrument which is capable of recording many kinds of signal, a windfall of unique scientific data was possible. With cheaper, but more limited, instruments this opportunity could easily have been lost.

Earthquake Source Models

In recent years, studies of the earthquake source have focussed on explaining details of the seismic rupture, and much further work can be expected in this area. After the early realization that earthquake ruptures are highly variable and heterogeneous, and that theoretical source models in most instances fail to reproduce the complexity exhibited by real earthquakes, much of the interpretive efforts have been devoted to the mapping of individual seismic ruptures in time and space. The hope is that in addition to being able to retrieve the source process of single earthquakes, characteristics may be found which apply to earthquake ruptures in general. The nature of slip and stress heterogeneities on the fault plane, their persistence over time and over several earthquake ruptures, as well as the interaction between these asperities and barriers and the propagating rupture front is a continuing focus of observational and theoretical work. A related issue concerns the slip at an individual point on the fault, and the process of rupture healing. Several recent observations suggest that slip occurs very rapidly after initially failure, which has important implications for maximum ground motions near the fault. However, several observational and theoretical studies have also concluded the opposite. Additional examples must be recorded and studied to determine if a general pattern exists.

Local data are clearly more directly useful to discriminate between source behaviors and source models. However, since local and teleseismic data have different relative sensitivity to slip at different depths below the surface, both datasets are important for mapping the slip across the entire fault plane. In addition, since geodetic data have yet different sensitivity to the earthquake strain, the experience is that improved resolution of slip history of the fault can emerge from combined nearfield/farfield/geodetic analysis.

Earthquake Initiation

Another topical question related to the seismic source is the nature of earthquake initiation. Do earthquakes 'know' how big they will be at the time of rupture nucleation? Two classes of studies now argue for the existence of earthquake preparation zones which, in some sense, scale with the eventual earthquake size. Studies of global observations at very low frequencies have concluded that for some large earthquakes, low levels of accelerating moment release precede the seismically observable rupture, constituting a slow precursor. A second class of observations of near-field ground velocity have been interpreted to indicate that the initiation phase of seismic ruptures scales with the final moment release, and are therefore inferred to be related to a process which reflects the size of the eventual earthquake. Both of these finding are controversial, but their potential implication for earthquake warning make it important to test these predictions by close examination of data for a large number of well-recorded earthquakes.

A conclusion that can be drawn is that in the future, researchers, even more than today, will want to integrate a variety of data sets, some of which are unrelated to IRIS facilities, in their investigations of the seismic source. In addition to seismic data of various kinds, other data, such as strain and geodetic data, as well as electromagnetic and resistivity data, would also be of interest owing to their potential connection to earthquake generating processes. IRIS has the opportunity to coordinate the access to these diverse types of data for the seismological community.

A fundamental task of observational seismology is the comprehensive characterization and quantification of seismicity. Continuous broadband digital recording at more than 100 seismic observatories around the world provides the basic data source for monitoring global earthquake activity, and an increasing number of regional broadband networks make similar efforts possible on a geographically smaller scale. The Harvard CMT project, and similar projects at the Earth Research Institute in Japan and at the USGS, use GSN data to calculate moment tensors routinely for earthquakes with magnitudes greater than magnitude 5 or 5.5, providing a continuous record of seismic strain release around the world. In these cataloging efforts, each individual earthquake is seldom of immediate interest. It is the accumulation over time of a uniform catalog which is of particular value. These compilations find uses in global and regional tectonic studies, in statistical seismicity studies, and in studies of earthquake interaction through stress migration. Catalogs also serve in that they define 'normality' — outliers, which probably result from some unusual physical boundary conditions, can be identified and studied in greater detail.

What kind of progress can we expect in this basic cataloging aspect of earthquake seismology over the next decade? It seems clear that, even on the global scale, we are far from the limit in terms of optimal analysis of smaller earthquakes. It is true that noise puts a lower bound on what can be achieved, but the current magnitude thresholds primarily reflect our limited ability to model wave propagation in the heterogeneous Earth. For example, intermediate period surface waves are routinely observed at large distances for moderate and small earthquakes, but their complex propagation cannot yet be predicted with great confidence, and they are therefore not yet suited for source studies. The same situation exists for other parts of the wavefield, and in particular at regional distances. Advances in the determination of Earth structure, and the incorporation of more complex Earth models in the calculation of model seismograms, will lead to improvements both in the quality, but, perhaps more dramatically, in the quantity of earthquake information that can be derived on a routine basis. For example, if the magnitude threshold for routine global moment tensor analysis can be lowered to M_w=4.5, the number of source mechanisms would be approximately 5 times greater (approximately 3000 earthquakes per year) than currently. Such a rapid accumulation of seismic strain observations should be of particular value for tectonic studies of remote areas with modest seismicity levels.

Real-Time Seismology

The real-time access to global seismological data offered by IRIS has had a significant impact on how seismologists can contribute relevant scientific information following severe earthquakes. Even in areas of dense seismographic networks, such as in California or in Japan, it is clear that immediately following a damaging local earthquake, the basic earthquake information derived from more distant recordings can sometimes both be more reliable, and more rapidly available, than local results. This can be due to the physical failure of local networks, clipping of important waveforms, or saturation by aftershocks of the local earthquake processing capacity. Because of these problems, teleseismic analyses of several recent earthquakes, including the Landers, Northridge, and Kobe earthquakes, have been able to contribute valuable information rapidly, such as fault location (depth) and geometry, slip estimates, and rough estimates of rupture histories. In combination with local seismographic and geodetic data, real-time assessment of the fault slip and associated ground motion is likely to be of increasing value for the relief efforts in future earthquakes. The development of instrumentation and analysis systems which can integrate the local, regional, and teleseismic data for rapid scientific response to the next severe earthquake will be an important goal for the future development of IRIS facilities.

One application for which the rapid availability and analysis of seismic data is of direct importance, concerns the tsunami problem. While it continues to be extremely difficult to provide adequate warning for local tsunamis, it is becoming possible to predict the distant effects of tsunamigenic earthquakes in a useful fashion. The important ingredients for calculations of tsunami amplitudes are the fault geometry and depth, the amount of slip, as well as adequate modeling of water wave propagation across ocean basins and in the near-shore environment. Since tsunami travel times can be several hours, it is now technically possible to predict their distant effects with some accuracy before the arrival of the wave. There is a growing understanding that some earthquakes, such as the Nicaragua earthquake in 1991, may have a much greater tsunami excitation potential than could be predicted from their body and surface wave magnitudes, owing to their long source duration and unusual shallow depth. This makes even more important the integration of data and analysis techniques which can identify such unusual source characteristics shortly after an event.

In conclusion, it is likely that over the next several years, significant advances of our understanding of tectonic processes, seismicity, and the earthquake rupture process, will result from innovative analyses of the unprecedented volume of high-quality data generated and distributed by IRIS facilities. Many future investigations will benefit from a closer integration of IRIS global and portable data collection programs with existing regional and local seismographic networks, as well as with geodetic and other geophysical observatories.

The Physics of Earthquake Rupture

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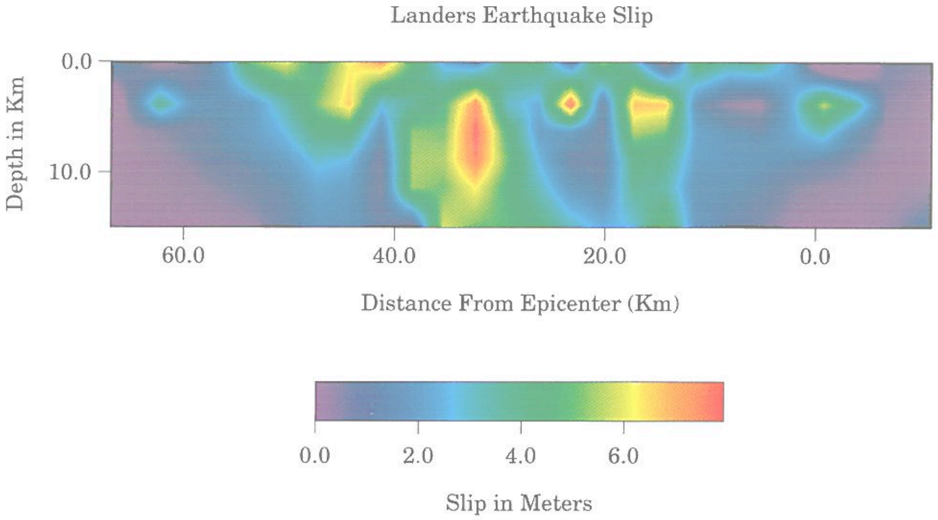
Earthquake rupture physics addresses several unsolved problems, both fundamental and practical. Since earthquakes are one of the principal mechanisms of crustal deformation, understanding the nature of rupture physics holds the key to understanding crustal stress and strength. Furthermore, it has become clear that rupture physics determines the predictability of earthquakes, whether on time scales of decades, hours, or seconds. But perhaps the most important aspect of rupture physics is that it holds the key to predicting the nature of near-source ground motions. Although no modern city has experienced near-source ground shaking from a great earthquake, it is inevitable that this will occur. What will be the nature of the ground motions in such earthquakes and how will modern buildings respond? This is a critical problem that has not yet been solved. The past several decades have seen dramatic improvements in the ability of seismologists to model broadband waveforms from earthquakes. These new capabilities have allowed seismologists to determine the spatial and temporal distribution of slip on faults. Several aspects of these models have challenged existing models of rupture physics. In response, new classes of rupture models have been developed to explain the new observations. The models are dramatically changing many scientists' opinions about crustal strength, earthquake predictability, and the nature of strong motions in large earthquakes. As an example,consider the slip model derived by Wald and Heaton (1994) for the 1992 Landers, California, earthquake (M 7.2). Figure 1 shows the spatial slip distribution derived from simultaneous modeling of strong motion records, teleseismic waveforms and coseismic geodetic deformations. The three types of data are all consistent with a slipmodel that is spatially heterogeneous, that is, there are patches of large slip interspersed with patches of small slip. The heterogeneous nature of spatial slip has been documented often in the past decade. It challenges the notion that similar earthquakes repeat in a characteristic way from one earthquake sequence to the next. It is important to understand the underlying physical mechanism for this slip heterogeneity. Figure 2 shows the temporal development of rupture for the Landers earthquake. Slip proceeds along the fault as a pulse that propagates at about 85% of the shear wave velocity. That is, only a small portion of the fault is slipping at any given instant in time. This behavior of the Landers rupture, which has also been observed for numerous other earthquakes, is inconsistent with standard models, where slip continues for a time sufficient for shearwaves (e.g. a "healing phase") to propagate from the edges of the rupture surface. These observations have motivated a novel class of rupture models in which slip stops long before any information arrive sabout the overall dimensions of the rupture. This "slip-pulse" behavior has been produced by numerical rupture models in which the sliding friction on faults is assumed to decrease with increasing slip velocity. In these models, shear stresses are very high just ahead of the propagating pulse; slip velocity is high and sliding friction is low just behind the rupture front. As the slip velocity decreases from its peak value, the sliding friction increases, causing the rupture to heal. The slip depends on the nature of the sliding friction and the sliding friction depends on the slip, leading to a dynamic feedback system that produces spatially heterogeneous rupture.



Since the friction is low during high-velocity slip, but high when the fault is slowly slipping or locked, the idea of crustal "strength" is a fairly complex concept. The crust appears to have a high strength, so "brittle" earthquake rupture appears paradoxical. In the new rupture models, however, low friction at high slip velocities

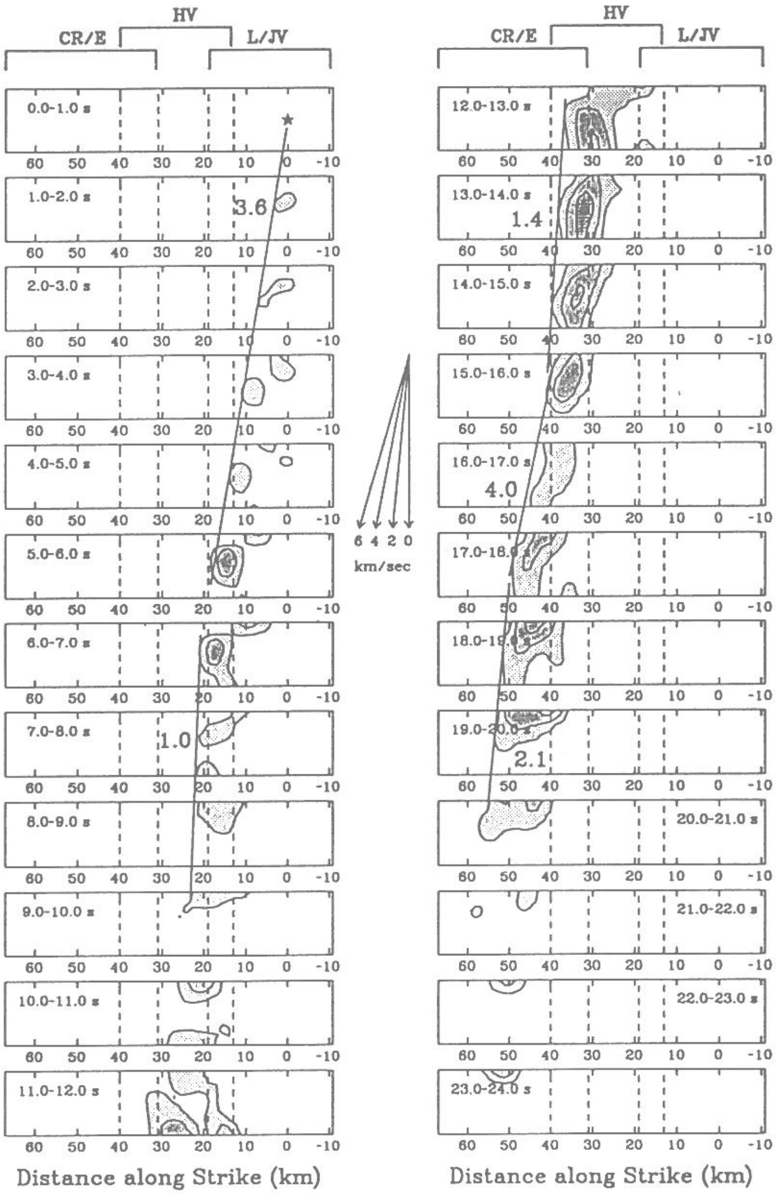


Figure 2. Time progression of the Landers rupture for the combined data model given at intervals of 1 sec as labeled. The contour interval is 0.5 m. For reference, a rupture velocity roset is given with arrows.

allows the crust to fail at relatively low levels of ambient stress. Furthermore, the longstanding heat flow-anomaly problem can be addressed, because the low sliding friction leads to low frictional heating on faults. The nature of rupture physics has implications for the predictability of earthquakes. Dynamic fault rupture occurs millions of times each year, but few of these ruptures grow into large earthquakes. Is is possible to predict which of these ruptures will propagate large distances along the fault? The new class of slip-pulse rupture models certainly complicates our ideas of how to recognize when a fault is "ready" for a large earthquake. Understanding the slip history of large earthquakes is critical for predicting the near-source ground motions for large earthquakes.The 1994 M=6.7 Northridge earthquake and the 1995 M=6.9 Kobe earthquake demonstrate that near-source ground motions can be extremely damaging in a heavily urbanized environment. Better models of earthquake rupture and associated shaking in specific locales would greatly aid our ability to predict seismic hazard. Much larger earthquakes than Northridge and Kobe are certain to strike cities in the western U.S. and in other parts of the world. What will happen when the 1906 San Francisco earthquake repeats itself? Recent simulations of the response of flexible buildings to large displacements at their base suggest that they would suffer unrepairable damage and possible collapse, if the displacements oscillate on the time scale of several seconds. By studying slip models from large earthquakes worldwide, it is possible to predict the near-source ground motions at periods critical to flexible buildings, that is, oscillations longer than 1 sec. These studies may have profound implications for the buildings codes in cities in the western U.S.

Seismic Evidence for an Earthquake Nucleation Phase

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We have used data from modern digital instrumentation to help address the question of whether or not earthquakes are predictable. For an earthquake to occur, a fault must undergo a transition from a locked state to one where slip occurs at speeds of several m/s and rupture propagation velocities of several km/s.

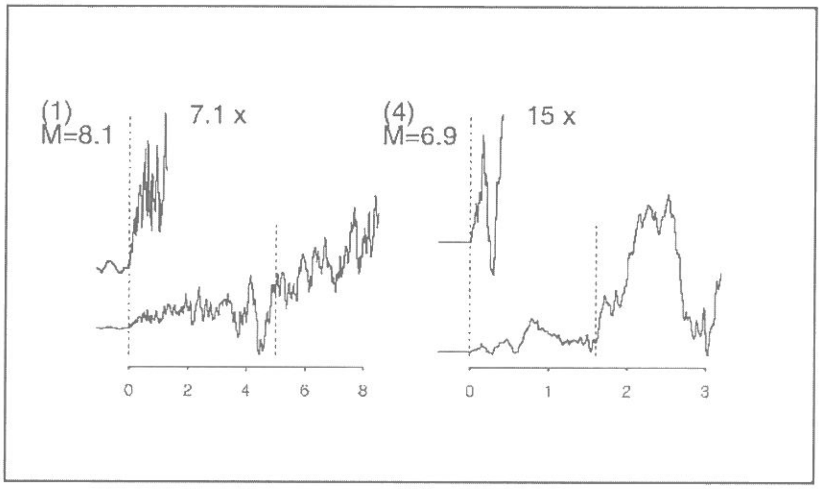


Figure 1. Seismograms recorded near the epicenter of quakes that struck Mexico City in 1985 (M=8.1) and the San Francisco Bay area in 1989 (M=6.9). The seismograms show ground velocity versus time at two magnifications (the upper seismograms in each case show a magnified version of the first arriving waves). The first arrival for both earthquakes occurs at 0 s on the plots. The weak initial motions last for about 5 seconds for the 1985 Michoacan, Mexico earthquake and for about 1.6 seconds for the Loma Prieta, California earthquake.

The abrupt onset of P waves emanating from an earthquake's hypocenter has generally been interpreted as evidence for an abrupt transition; however, near-source, high-dynamic-range, broadband data recorded on the new generation of seismic instruments show that the transition is not so abrupt. We find an interval of weak ground motion, which we term the seismic nucleation phase, at the very beginning of earthquakes ranging from magnitude 2.6-8.1 (Figure 1). Both the size and the duration of the seismic nucleation phase scale with the size of the eventual earthquake, suggesting that the ultimate size of an earthquake is strongly influenced by the nucleation process (Figure 2). We offer two possible explanations of this observation.

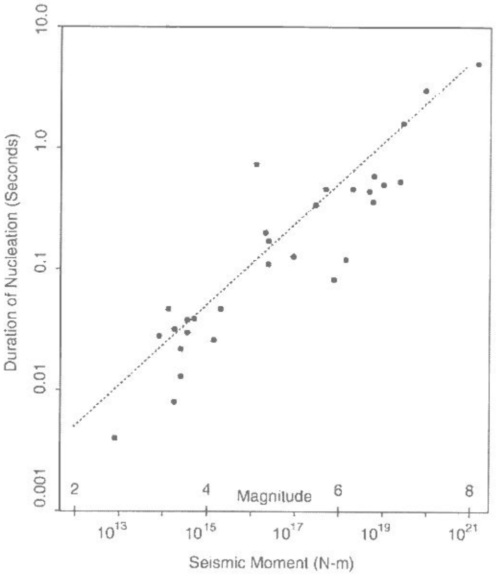


Figure 2. Duration of the seismic nucleation phase is shown versus the seismic moment on a log-log plot for the 30 earthquakes studied by Ellsworth and Beroza (1995). The duration increases as the size of the eventual earthquake increases. The line shows power law scaling with an exponent of 1/3.

One interpretation, is called the cascade model, where the earthquake instability initiates at a point and there is no difference between the beginnings of large and small earthquakes. A large earthquake results when a small earthquake triggers a cascade of increasingly larger slip events.

Another interpretation, is called the pre-slip model, where the earthquake instability begins within a finite area and the beginnings of small and large earthquakes differ. In the pre-slip model, failure initiates with an episode of slow, stable sliding over a limited region that gradually accelerates until the slipping patch reaches a critical size. The process then becomes unstable and fracture propagates away from the nucleation zone at high rupture velocity in an earthquake. In this model the seismic nucleation phase marks the transition from stable sliding to dynamically propagating rupture.

The fundamental difference between the two interpretations is that in the pre-slip model, the seismic nucleation phase is the culmination of a process already in progress; whereas, in the cascade model, the seismic nucleation phase marks the very beginning of the process. In the pre-slip model, earthquakes are predictable, at least in theory, if the slow pre-slip that precedes seismic rupture can be detected. In the cascade model, earthquakes would be much more difficult to predict since they would be triggered by small earthquakes, which happen all the time. Future studies should allow us to test these models and answer the question of whether or not earthquakes are predictable.

RAMP Deployment Following the June 28, 1992 M_w 7.6 Landers Earthquake

Frank Vernon, Adam Edelman
University of California at San Diego

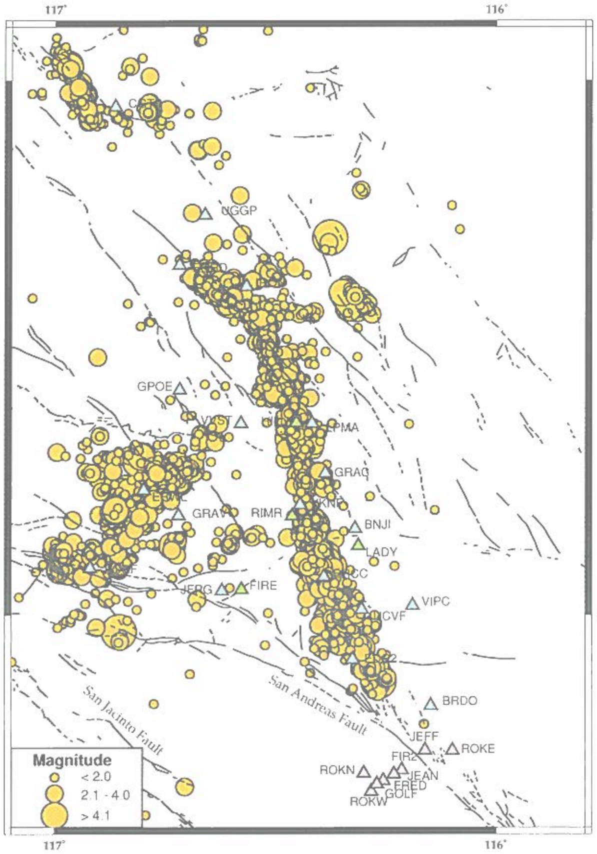


Figure 1. Distribution of Landers earthquake aftershocks recorded by the portable instruments. Station locations are included for reference.

A collaborative study to record aftershocks was undertaken by several Southern California Earthquake Center (SCEC) institutions following the June 28, 1992 Landers earthquake. The Mw 7.6 earthquake occurred at 11:57:34 UTC approximately 10 km north of Yucca Valley along the southern extension of the Johnson Valley fault. The earthquake produced over 70 km of ground rupture, with cumulative right-lateral offsets of 3 to 6.5 m along segments of the Homestead Valley, Emerson Lake, and Camp Rock faults, all of which were involved in the sequence. The primary aftershock activity occurred in a narrow band from 33.6N -116.2W north to 34.5N, -116.6W, with a separate cluster at 35.0N, -117.OW.

Personnel from several institutions participated in the installation and maintenance of the portable stations. The equipment deployed consisted of short period and broadband velocity sensors, and force balanced accelerometers recorded on 16-bit dataloggers. Within 12 hours, four portable instruments were installed and recording data, and an additional 18 were up and running within 48 hours. Instrumentation was provided by the IRIS PASSCAL Instrument Center at Lamont Doherty Earth Observatory, the SCEC instrument center at the University of California at Santa Barbara, the University of California at San Diego, the United States Geological Survey office of Earthquake and Landslide Hazards, the Rocky Mountain Front Experiment, and San Diego State University.

The task of processing these data consisted of three main steps: compilation of portable data, integration of non-PASSCAL data sets, and compilation of station parameter information, including complete instrument transfer functions. Timing corrections and event associations were accomplished utilizing software provided by PASSCAL. Data sets from Lamont Doherty Earth Observatory, San Diego State University, and Caltech's TERRAscope network were then associated with the PASSCAL data set. Recording parameters, response characteristics, and event information were compiled into the CSS 3.0 database format. Both P and S phases were then picked by hand, and an association with the Southern California Seismic Network (SCSN) catalogue was accomplished by comparing the actual phase picks with predicted arrivals generated with the IASPEI91 travel time tables.

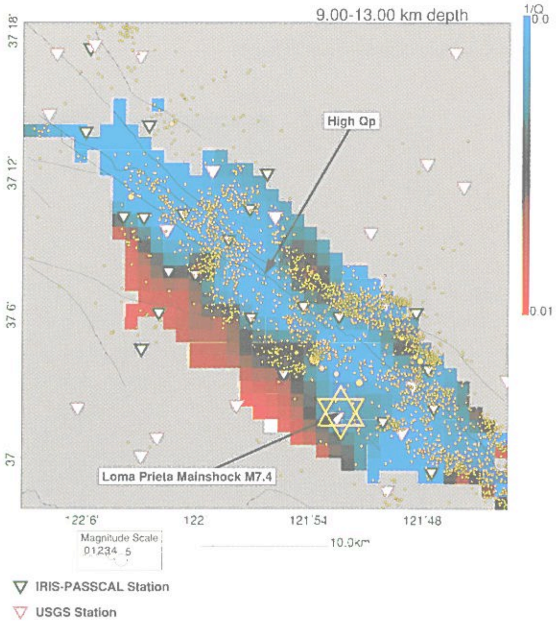
The final data set consists of 4.5 GB of data compromising 2345 events, all of which have been recorded by 5 or more of the portable stations, and associated with a SCSN location. There are 387 of M_L 3.0 or greater, and epicentral distances range from 150 meters to several hundred kilometers. The figure shows the distribution of aftershocks recorded by the portable stations, as well as the station locations. In addition to the waveforms, both P and S-phase arrival picks are included and available from SCEC data center at Caltech, and complete instrument response functions are available in the SEED format data from the IRIS/DMC.

Characterization of Fault Zone Physics Along the San Andreas Fault

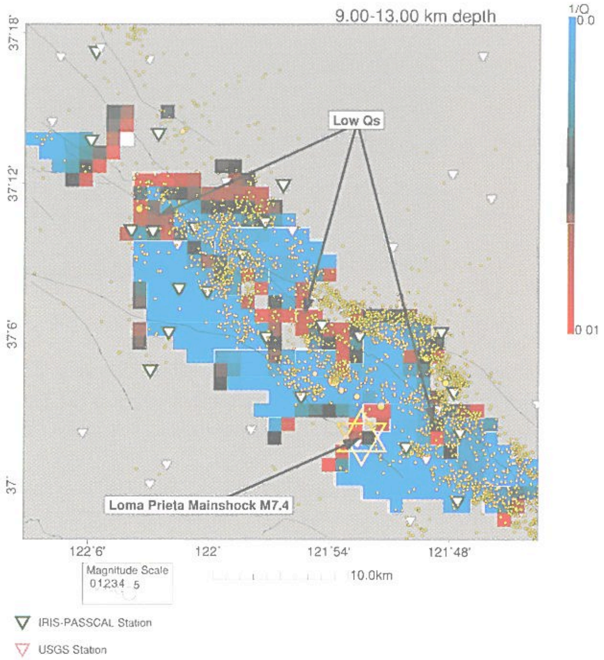
Jonathan Lees
Yale University

We are attempting to characterize the San Andreas fault in regions of large earthquakes by imaging variations of physical properties along the fault. It has been observed in several places along the San Andreas that high velocity regions correlate with large magnitude ruptures (e.g. Parkfield, Loma Prieta, North Palm Springs, Landers and Northridge). A new constraint placed on the physics of the rupture zone is the variation of attenuation (Q) along the fault. Three-dimensional Q variations in the aftershock region of Loma Prieta were derived by tomographic inversion. The data set consists of over 4000 aftershock recordings at 22 PASSCAL stations deployed after the Loma Prieta main shock of 1989. Estimates of attenuation were determined from nonlinear least squares best fits to the Fourier amplitude spectrum of P and S wave arrivals. The linear attenuation inversion is accomplished by using three-dimensional velocity variations derived previously in nonlinear velocity inversions. Low Q is observed near the surface and Q generally increases with depth. The southwest side of the San Andreas fault exhibits lower Q than does the northeast side and this feature apparently extends to approximately 7 km depth. The fault zone, as determined by the dipping plane of aftershock activity, is characterized by slightly higher Qp and lower Qs (Figure 1 and 2), compared to regions immediately adjacent to the fault. These correlate with high-velocity anomalies associated with seismicity at depth. The results are in agreement with earlier observations regarding the association of high-velocity anomalies, seismicity, and fault zone asperities. The pattern of high Qp and low Qs suggests that pores are fully saturated at seismogenic depths in the fault zone. These observations have important implications for the physics controlling the onset of rupture along the San Andreas fault. This analysis could not have been carried out without the IRIS-PASSCAL instruments installed after the Loma Prieta main shock.

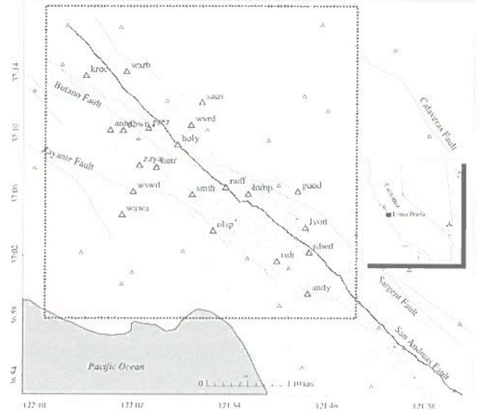
Loma Prieta Attenuation Inversion For P-Waves



Loma Prieta Attenuation for S-Waves

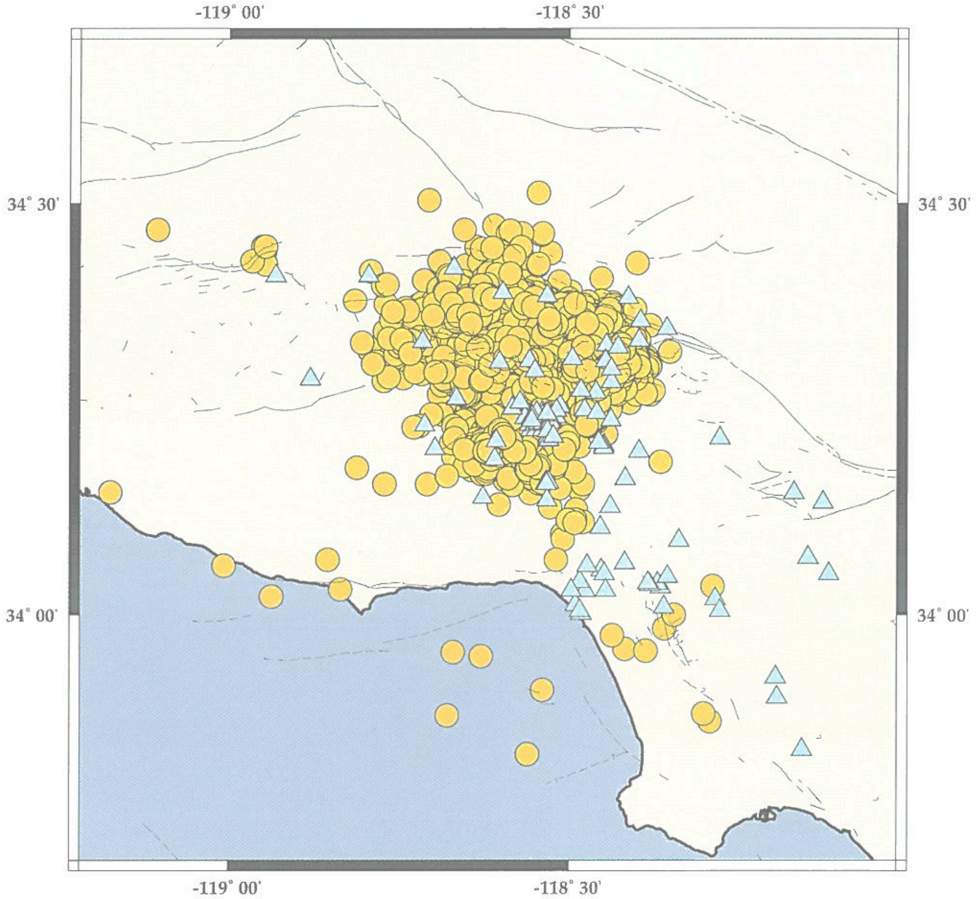


Loma Prieta - PASSCAL Network



RAMP Deployment Following the January 17, 1994 M_w 6.7 Northridge Earthquake

Frank Vernon, Adam Edelman
University of California at San Diego



A collaborative effort to record aftershocks of the January 17, 1994 Northridge earthquake was undertaken by several institutions associated with the Southern California Earthquake Center (SCEC). The MW 6.7 earthquake occurred at 12:50:55 utc on a buried thrust fault approximately 30 km northwest of downtown Los Angeles. The primary aftershock activity occurred in a 20 by 30 km area centered in the town of Northridge.

In the seven weeks following the main shock, over 100 portable instruments were deployed throughout the Los Angeles county area, with coverage extending from southern Ventura county, through the San Fernando Valley, and south into the Los Angeles basin. Instrumentation consisted of both short period and broadband velocity sensors, along with strong motion accelerometers, each recorded on either 12, 16, or 24 bit dataloggers. Instruments were provided by several organizations: the RAMP project at the IRIS PASSCAL Instrument Center at Lamont Doherty Earth Observatory, the SCEC instrument center at the University of California, Santa Barbara, the University of California, San Diego, San Diego State University, the United States Geological Survey offices in Pasadena, Menlo Park, and Golden, Colorado, Lawrence Livermore National Laboratory, and the California Department of Transportation.

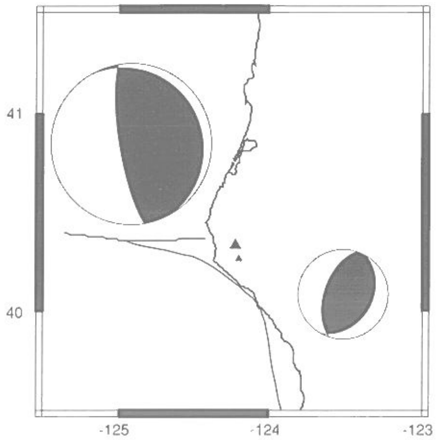
This aftershock deployment was conducted with several scientific objectives. Instruments were deployed directly above the aftershock zone to help constrain aftershock hypocenters. Many sites were chosen to investigate the near surface site effects which produces extensive damage during the earthquake. Strong motion sites that recorded the main shock were instrumented to collect empirical Green's functions for separating source and propagation effects of the main shock. Broadband instruments were deployed to study the long period response of the Los Angeles basin, and a dense array using broadband and short period sensors was deployed to study the response of the San Fernando Valley basin.

Several steps were required to complete the data processing. All raw data was first converted to a common format. Any errors in timing were corrected and all P and S-phases were picked. An associateion with the Southern California Seismic Network (SCSN) catalogue was done, and all data was converted to both SEED and the SCSN database format.

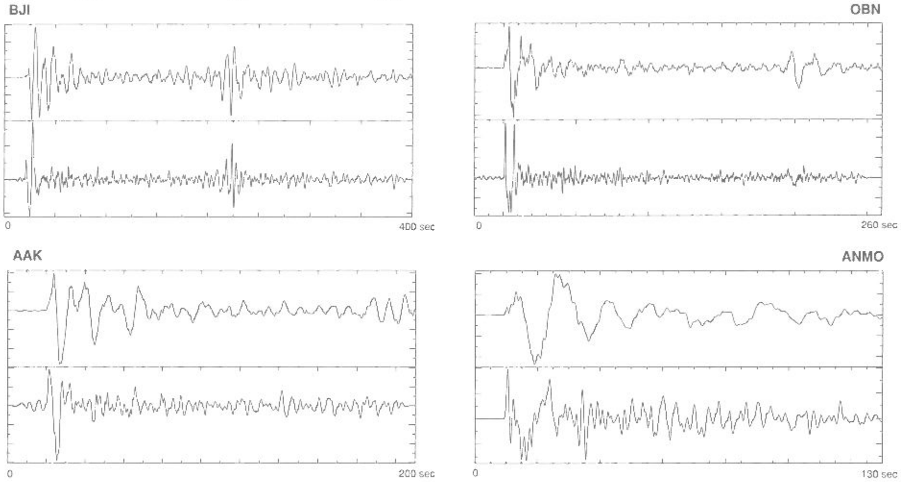
The completed set of aftershock data consists of almost 3GB of data comprising 4817 events, of which 428 were Ml = 3.0 and greater with locations provided by the SCSN. Figure 1 shows the aftershock distribution as well as the portable station locations. In addition to the waveform, both P and S-phase arrival picks are included and available from the SCEC data center, and complete instrument response functions are available in the SEED format data from the IRIS/DMC.

Earthquake Hazards Along the Southern Cascadia Subduction Zone

M.T. Hagerty and S.Y. Schwartz
University of California, Santa Cruz



Map of the Menodino triple junction off the northern California coast. Triangles indicate locations of the 1992 Cape Mendocino (M6.9) and 1991 Honeydew (M6.0) earthquakes. Also shown are focal mechanisms determined from broadband seismograms recorded by globally distributed IRIS stations.



In order to assess the significance of subduction along the Cascadia subduction zone and the potential hazard it poses to coastal California and Oregon, we model seismic waveforms of two recent, large thrust events. Shown in the figures are raw velocity recordings of the 1992 Cape Menocino earthquake (top) and the 1991 Honeydew earthquake (bottom) at four IRIS stations. As these earthquakes did not rupture the Earth's surface, determining their properties accurately is greatly enhanced by the use of global IRIS data.

The 1992 Suusamyr Earthquake and Aftershock Sequence

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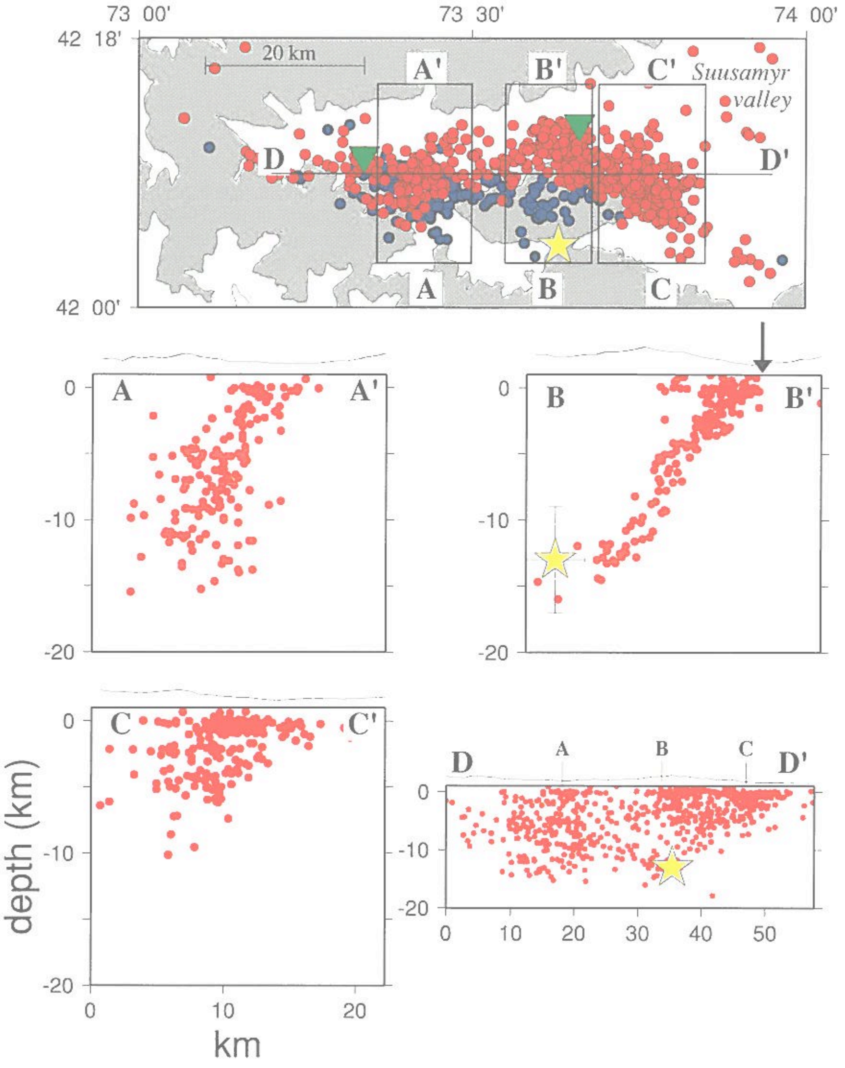
University of California, San Diego
Gary Pavlis
Indiana University

On 19 August 1992, a large (Ms 7.4) thrust earthquake struck the Suusamyr valley of northern Kyrgyzstan. The earthquake killed 90 people, caused severe damage throughout the valley and blocked major transportation routes in the republic of Kyrgyzstan. This earthquake is one the of the largest well-recorded continental thrust earthquakes in recent years. We conducted a study of this earthquake using a combination of aftershock data, teleseismic body waves, and field work. An unusual feature of this earthquake is the very short (less than 3 km) but severe (up to 4 m) surface faulting in relationship to the size of the rupture. In many ways it resembles a larger version of the 1994 Northridge, California earthquake. The goals of this study are to understand the faulting in relationship to the local geology and to explain the limited amount of surface rupture.

The aftershock sequence of this earthquake was recorded by the Kyrgyzstan broadband network (KNET), a 10 station network of seismometers centered around the capital of Bishkek, Kyrgyzstan and operated by IRIS under the Joint Seismic Program. A temporary aftershock network was also deployed from Sept. 15 to Oct. 1 by personnel from the Institute of Physics of the Earth using both IRIS and Russian instruments. The aftershocks were initially located using a standard location program and a selected subset were relocated using a multiple event location method that simultaneously solves for hypocenters and station corrections. The aftershocks show a 50 km zone of aftershocks that dips 45° to a depth of 18 km. The fault plane is clearly resolved and shows a definite 3D structure that closely correlates with local topography.

The main shock was recorded by world-wide IRIS stations. The source parameters were determined by inverting the teleseismic body waves for the focal mechanism, source time function, and depth. The inversion showed that the main shock originated at a depth of roughly 13 km, propagated westward, and consisted of at least two sub-events. The results of the teleseismic inversion closely match the inferred fault structure from the aftershock study.



Comparison of the fault plane with local geology suggests that the shallow extension of the fault may terminate in an anticline along much of its length which explains the lack of significant surface rupture. However, in contrast to other 'blind' earthquakes such as the 1985 Coalinga, California event, the Suusamyr event shows a clear planar distribution of aftershocks. The lack of significant surface rupture has important implications for paleoseismicity studies that depend on surface rupture data to construct earthquake occurrence histories. The Suusamyr event also demonstrates that high-angle basement thrust faults accommodate much of the shortening in the Tien Shan. This constrains the range of possible tectonic models for the region and aids in assessing regional seismic hazard.

Prospects for Increased Seismicity in the LA Basin

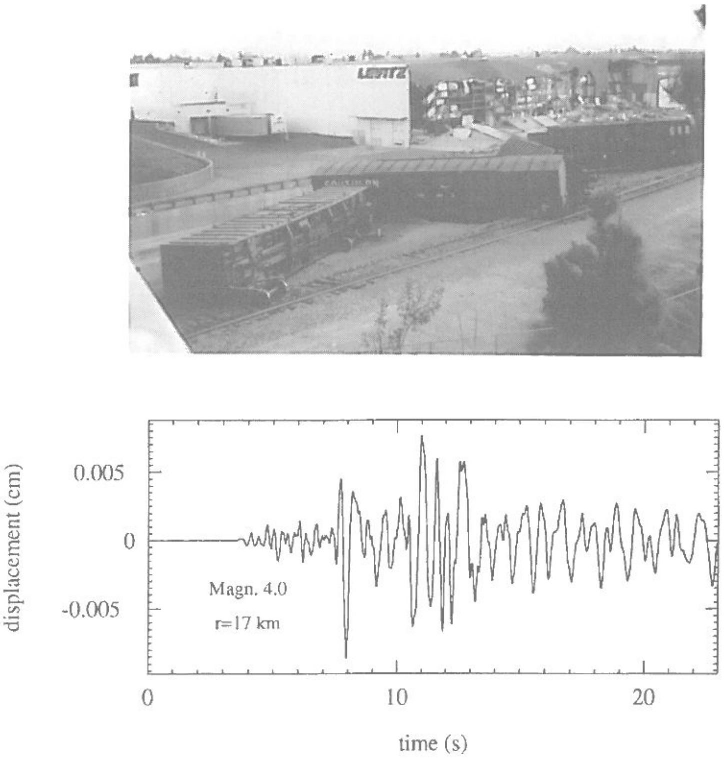
Susan E. Hough
U.S. Geological Survey, Pasadena

In recent years, awareness of earthquake hazard within the greater Los Angeles region has grown considerably, with a shift in focus away from the San Andreas fault and towards the faults that criss-cross the basin itself. Recent studies have used geologic or geodetic information to evaluate the long-term strain rate, with several studies arguing that larger and/or more frequent earthquakes should be expected.

The complex propagation of seismic waves within the deep sedimentary basin that underlies much of the L.A. region has also come to the forefront in recent years, as researchers have developed methods to model 2- and 3-D wave propagation and have amassed a broadband data set with which the issue can be investigated observationally. To investigate potential source zones within or near the LA Basin, it is necessary to develop a general seismotectonic framework for the region. Primarily, this involves developing a tectonic model based in part on source studies of the large and small events that have occurred.

Over the last few decades, the majority of small events within the LA basin have occurred within the aftershock sequences of moderate earthquakes such as the 1987 Whittier event and the 1994 Northridge earthquake. Deployments of portable digital seismic instrumentation provide a unique opportunity to record these aftershock sequences, for the dual purposes of source characterization and detailed propagation studies.

Following the Northridge earthquake, approximately 75 portable digital instruments were installed by institutions comprising the Southern California Earthquake Center. In some cases, a number of instruments are supplied directly from IRIS/PASSCAL. However, the contribution from IRIS/PASSCAL to this type of deployment far exceeds the direct contribution of instruments. By taking the lead in the arena of portable digital seismic instrumentation, and by developing a cohesive and comprehensive project based on these instruments, IRIS/PASSCAL has inspired a remarkable uniformity in the portable seismic instrumentation acquired by academic institutions. The overwhelming majority of recorders used for the SCEC Northridge deployment were Refteks, a fact which has greatly facilitated the compilation and accessibility of a uniform data set.



Top photo shows train derailment caused by the M6.9 Northridge earthquake of 1/17/94. Bottom figure shows a M4.0 aftershock recorded on a portable digital seismometer at 17 km distance. The prolonged duration is due to the generation of surface waves within the San Fernando Valley, which likely provided a significant contribution to damage from the mainshock. The Northridge earthquake caused approximately $20 billion in property damage, yet resulted from a modest rupture of a 10-15 km segment of the thrust fault system along the base of the San Gabriel Mountains at the northern edge of the San Fernando Valley. A rupture of the full extent of one of the LA Basin fault systems could approach 160 km in extent, which would be like 10 Northridge earthquakes, laid end-to-end.

Although analysis of this critical data set is ongoing, a combined data set was made available through the SCEC data center at Caltech approximately 1 year after the earthquake. These aftershock recordings, which include numerous events inthe M4-5 range, will complement the kinds of seismotectonic synthesis studies that now rely only on data from permanent networks. They will be useful in elucidating fault structure, to help us answer one of the uncertainties regarding seismic hazardin the greater LA region: the possibility of earthquakes rupturing across apparent fault segment boundaries. Identified fault systems within the LA region approach the full 150-km width of the region in extent. If the data do not support the interpretation of distinct fault segments, then it is imperative that rupture of an entire fault system (with magnitude approaching 7.5) be considered in any long-term probabilistic assessment of hazard. The maximum permitted magnitude has important consequences for the rate of moderate (but still potentially quite damaging) events such as Northridge.

IRIS/PASSCAL Contribution to Understanding Geodynamics and Seismic Hazard Associated with the Cascadia Subduction Zone

Anne Trehu
Oregon State University

The active and dormant volcanoes of the High Cascades are part of a volcanic arc that extends from southern Vancouver Island, Canada, to northern California. The presence of this arc indicates that oceanic lithosphere is being subducted beneath the North American continent. This interpretation is confirmed by the presence of a well-defined deformation front offshore, which is formed as the flat-lying sediments deposited in the oceanic basin are deformed as they are scraped off the subducting Juan de Fuca and Gorda plates and accreted to the overriding North American plate. Although this region, generally known as the Cascadia subduction zone, is similar in many respects to other subduction zones, the rate of both upper and lower plate seismicity is much lower than is generally found in such tectonic settings. Significant earthquakes in Washington in 1949 in northern California in 1992 and in Oregon in 1993, however, reveal the potential for damage. Results of several recent geologic studies, moreover, suggest that the region may have been affected by several large prehistoric earthquakes, the most recent occurring approximately 300 years ago.

Because of this poorly defined but potentially great seismic hazard, many geophysical studies have been conducted in the past decade to characterize the lithospheric structure associated with this system in order to detect differences between this system and other, more typical, subduction zones. Tomographic studies of mantle velocity structure have shown that a high-velocity subducted lithospheric slab similar to that found beneath other volcanic arcs is present in the upper mantle beneath western Washington and Oregon. Thermal modeling suggests that the low level of seismicity along the plate interface may be due in part to the young age of the subducted lithosphere, the relatively slow convergence rate between the North American and Juan de Fuca plates, and the high regional sedimentation rate. Uncertainties in both the thermal and mantle velocity models, however, are associated with uncertainties in forearc crustal structure and the position of the plate boundary, which was well-known only beneath southwestern Canada prior to a series of recent active and passive

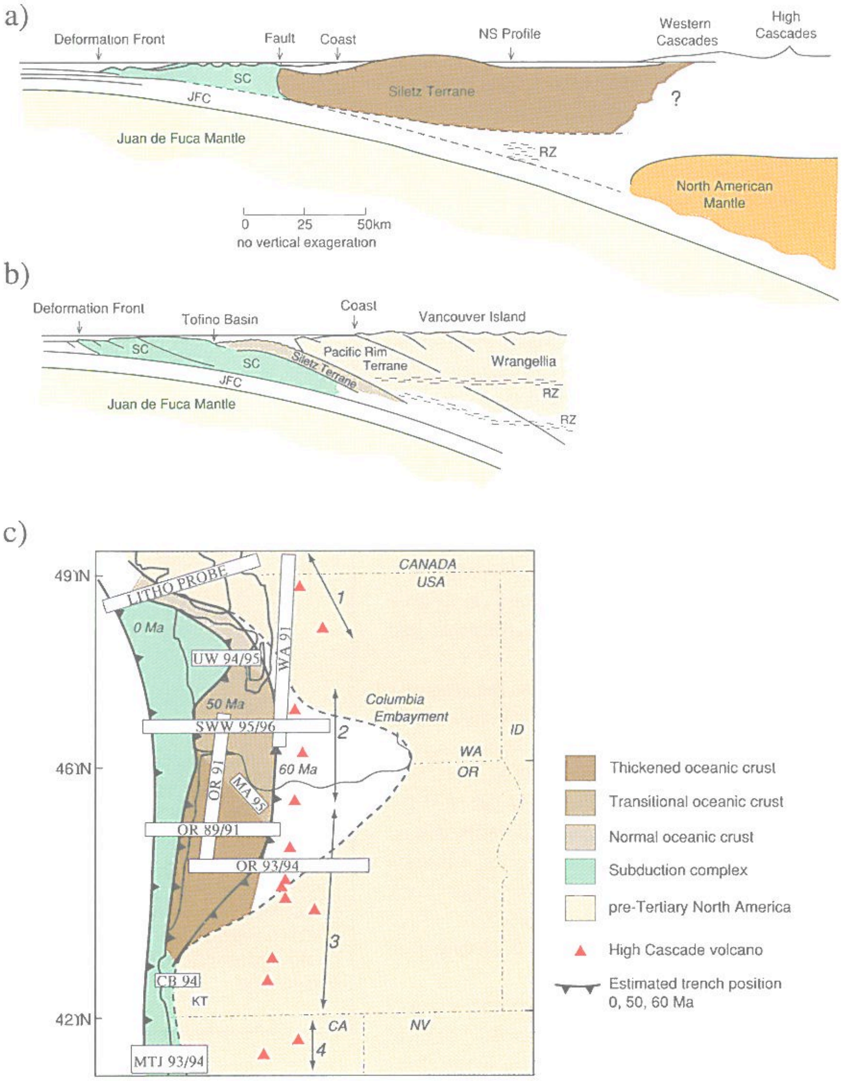


Figure 1 a) Summary of our model of the Cascadia forearc in Oregon, shown with no vertical exaggeration. SC - subduction complex; JFC - oceanic crust of the Juan de Fuca plate; RZ - reflective zone. **b)** Crustal structure of the Cascadia forearc beneath Vancouver Island. The Pacific Rim and Wrangellia terranes are of pre-Tertiary age. **c)** Map of the Pacific Northwest showing regional variations in the thickness of the Siletz terrane. Italic numbers next to arrows show the segmentation of the volcanic arc (Guffanti and Weaver, 1988). This figure shows the minimum extent of the Siletz terrane because its eastern boundary may extend further east beneath the Cascades, its western boundary may have been truncated through strike-slip motion, and its southern boundary may extend beneath the Paleozoic rocks of the Klamath terrane (KT). Locations of recent and planned experiments using portable seismographs are also shown.

source experiments using portable seismographs, many of which were provided by PASSCAL.

To determine whether crustal structure might, in part, be responsible for the anomalous seismicity associated with Cascadia subduction, we conducted active-source seismic experiments in 1989 and 1991 (OR89/91) to image the crustal architecture of the forearc beneath northwestern Oregon and southwestern Washington (fig. 1a) and contrast to it to the structure beneath Vancouver Island as imaged by LITHOPROBE (fig. 1b, from Hyndman et al., 1989). Results from these experiments indicate that the thickness of an accreted oceanic terrane of Paleocene and early Eocene age, which forms the basement of much of the forearc beneath western Oregon and Washington, varies by a factor of at least 4 along the strike of the Cascadia subduction zone (fig. 1c). Beneath the Oregon Coast Range, the accreted terrane is 25-35 km thick, whereas offshore Vancouver Island it is about 6 km thick. These variations are correlated with variations in arc magmatism, forearc seismicity, and long-term forearc deformation. We suggest that the strength of the forearc crust increases as the thickness of the accreted terrane increases and that the geometry of the seaward edge of this terrane influences deformation within the subduction complex and controls the amount of sediment that is deeply subducted (Trehu et al., 1994).

Several recent, ongoing, and proposed experiments using portable seismographs are continuing to test this model and illucidate other aspects of Cascadia arc structure. These include:

1) A NS profile along the western boundary of the Cascades in Washington (WA91) - USGS/Un. Texas at El Paso.
2) Oregon broadband receiver function array across the arc and forearc (OR93/94)
3) Mendocino Triple Junction seismic experiment (MTJ93/94)
4) MCS and onshore/offshore imaging near Cape Blanco (CB94) - USGS.
5) Broadband recording on the Olympic peninsula (UW94/95) - Un. of Washington.
6) High-resolution imaging of the Mt. Angel fault zone (MA94) - Boise State/Oregon State .
7) Reflection/refraction imaging of the arc and forearc beneath SW Washington (SWW95) - USGS/Oregon State/Un. Texas at El Paso.
8) Proposed MCS, OBS and onshore/offshore of forearc offshore SW Washington (SWW96) - USGS/GEOMAR/OSU.

Regional Earthquake Sources Studies

Douglas Dreger
University of California, Berkeley

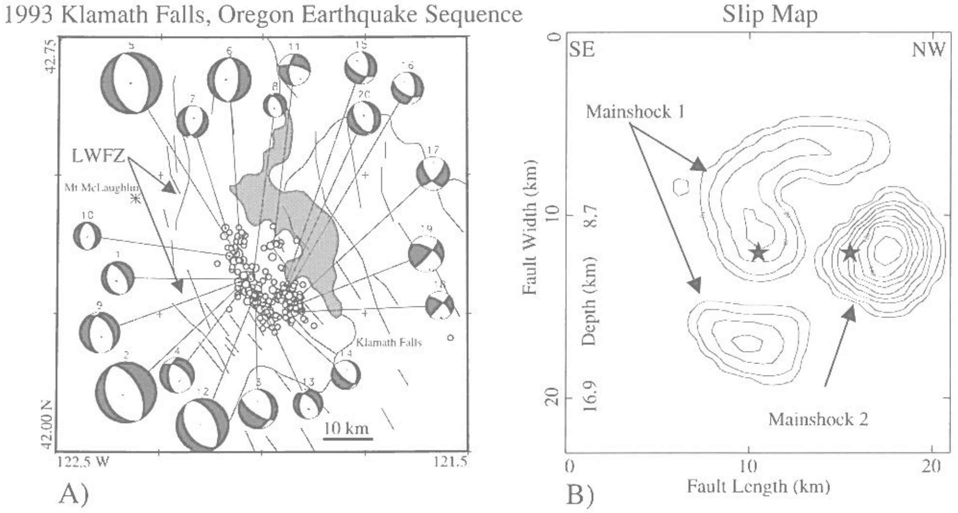


Figure 1. a) Moment tensor solutions for the 1993 Klamath Falls, Oregon earthquake sequence obtained from waveform inversion of long-period, three-component data Events 2 and 5 are the two Mw6.0 mainshocks. Event 12 is a Mw5.4 aftershock. For scale event 8 is a Mw3.5 aftershock. The LWFZ annotation refers to the Lake of the Woods Fault Zone which is the likely causative structure. Note that the bend in the surface faults is manifest in the rotation of the strike of the moment tensor solutions and in the aftershock distribution obtained by Qamar and Meagher (1993). b) Slip maps obtained for the two Mw6.0 mainshocks. Both events ruptured primarily to the northwest although mainshock 1 appears to have to sub-events of major moment release. The first two contours are for 10 and 20 cm of slip. The remaining contours represent 20 cm intervals of slip.

Data from IRIS stations in addition to that from other broadband networks such as the Berkeley Digital Seismic Network, TERRAscope and NSN have lead to improved earthquake source studies for events throughout the western United States. The ease of access to the IRIS data together with data from the continuously recorded or dailup networks have facilitated rapid source analysis procedures. These procedures are allowing the routine determination of more detailed and robust source information, such as centroid depth, scalar seismic moment, fault orientation, rupture velocity, dislocation rise time and slip heterogeneity.

Currently UC Berkeley is operating two automated regional distance moment tensor algorithms which provide preliminary moment tensor information within 10 to 12 minutes following the occurrence of a moderate to large earthquake in central and northern California and we are investigating methods for the determination of finite source information rapidly from regional distance data.

The September 21, 1993 Klamath Falls earthquake sequence serves as an example of the level of source analysis which is now possible using regional distance broadband network data. The Klamath Falls earthquake sequence occurred in a region which has sparse seismicity, and few seismic stations. The closest short-period station was 70 km away and no strong motion instrumentation was operating in the vicinity of Klamath Falls. The two Mw6.0 mainshocks were separated in time by approximately 2.5 hours and were followed by a relatively active aftershock sequence.

Figure 1a shows moment tensor solutions obtained for the twenty largest events which ranged in moment magnitude from 3.5 to 6.0. The focal mechanisms show generally northwest striking normal faults in the southern half of the sequence which rotate to nearly north-south striking events in the northern half, indicating that complexity at the surface persists to seismogenic depth. The moment tensor solutions corroborate the bend in the mapped surface faults and also in the aftershock distribution obtained by Qamar and Meagher (1993), indicating the complexity at the surface persists to seismogenic depth. It is interesting that there were two Mw6.0 mainshocks rather than a single through-going Mw6.2 event. Examination of the rupture kinematics for the two mainshocks reveals that the fault segmentation observed in the surface faults, aftershock distribution and moment tensor solutions may have inhibited a through-going rupture. Figure 1b shows a slip map obtained for the two Mw6.0 mainshocks using an empirical Green's function deconvolution technique.

IRIS and other regional network data provide the capability to investigate regionally recorded earthquakes, especially those outside the dense short-period and strong-motion networks, at a level which was not possible only several years ago. These data are necessary for the continued estimation of seismic moment tensors throughout the western United States, and for developing methodologies for studying finite effects. The rapid access of these data allows quick estimates of the distribution of fault slip to predict near-field strong-ground shaking, thereby providing regional earthquake hazard assessments. The regional stations will provide the only data for the study the many and important earthquakes which occur outside existing dense short-period arrays.

3D Crustal Structure of the San Francisco Bay Area

John Hole and the BASIX Working Group
Stanford Univ., U.S. Geological Survey, Woods Hole Oceanographic Institution,
Penn State Univ., Univ. California Berkeley

As part of BASIX, the Bay Area Seismic Imaging eXperiment, seismic refraction and multichannel reflection data were acquired in the San Francisco Bay area to investigate the crustal structure of the system of major faults that form the plate boundary in this region (Figure 1). While multichannel and wide-angle data recorded along the airgun shot lines constrain structure within the 2D profiles, portable Reftek deployments (Figure 1) and permanent Calnet stations (not shown) provide the ability to extend the models north and south of the Bay and to greater depth beneath the Bay. The dense array of instruments will provide the ability to produce 3D models of crustal velocity and reflector structure. Initial results of BASIX indicate the presence of a strong seismic reflector and velocity contrast in the lower crust (phase 6 in the receiver gather of Figure 2) which may act as a detachment surface linking the major strike-slip faults. The Reftek and Calnet data have allowed the minimum lateral extent of the possible detachment surface to be mapped between the San Andreas and Hayward Faults and across the Hayward Fault (Figure 3), and will ultimately allow the determination of the 3D depth structure of the reflector. The results will provide critical constraints on proposed models for formation of the San Andreas fault system, and in particular on the notion of a major lower crustal detachment. The existence of a detachment and the direction of motion on the detachment have major consequences on the propagation of strike-slip and/or compressional tectonic stresses between the major subvertical faults, and hence have direct application to the study of earthquake hazards in this densely populated region.

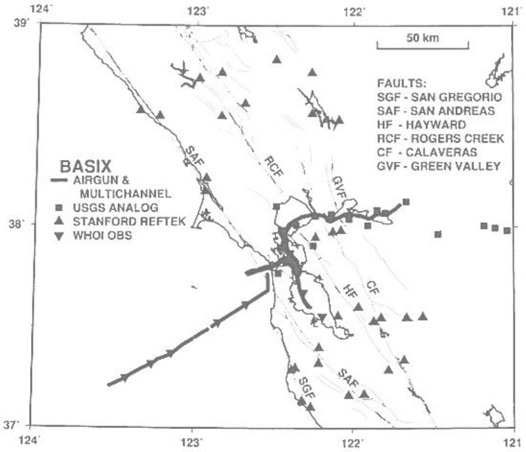


Figure 1.

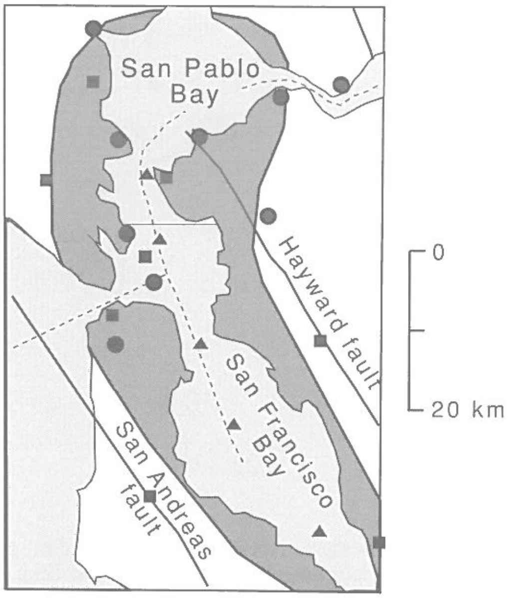


Figure 3.

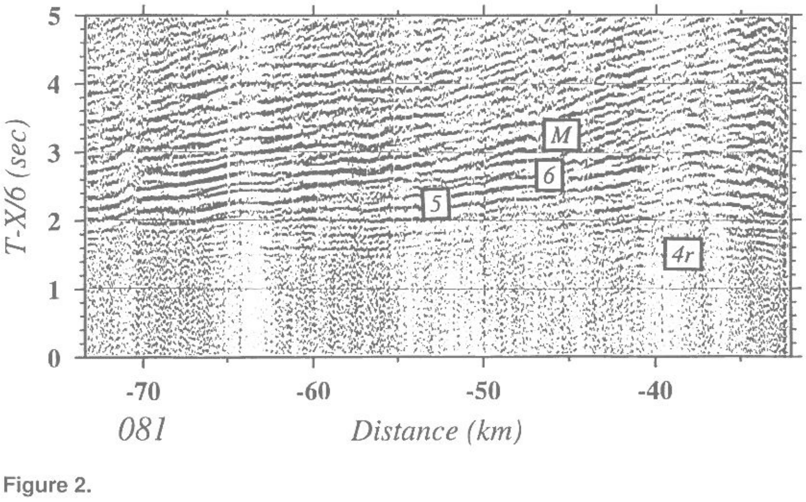
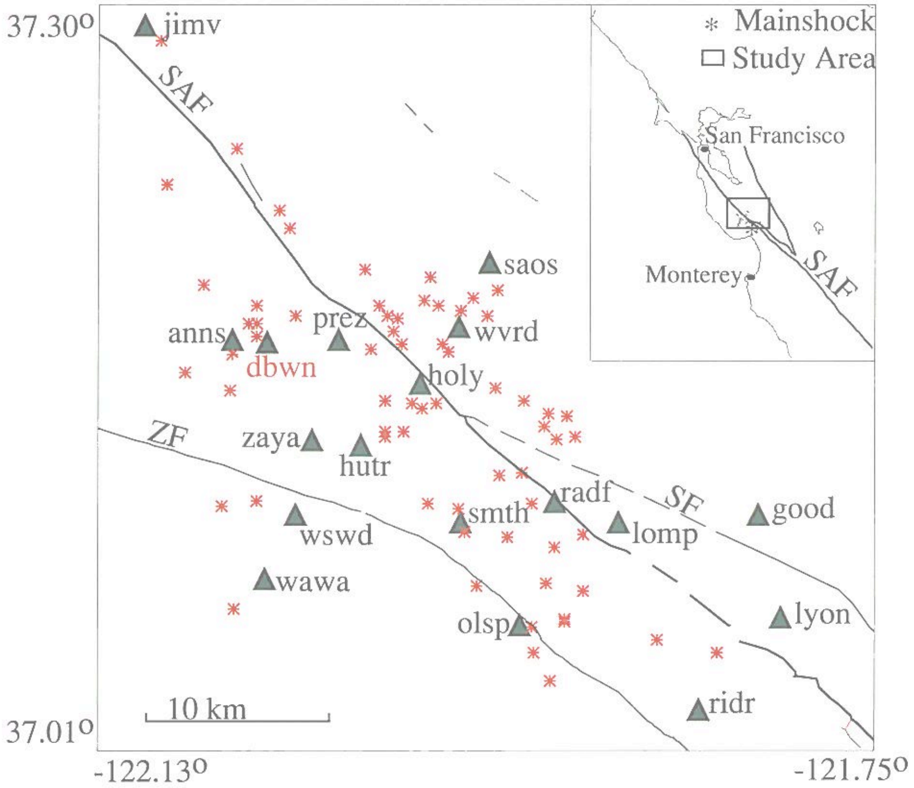


Figure 2.

Recording Aftershocks of Significant Earthquakes

Susan Y. Schwartz
University of California, Santa Cruz



Location map of the IRIS PASSCAL stations (triangles) deployed after the 1989 Loma Prieta earthquake and the larger aftershocks recorded. The star in the insert marks the location of the mainshock, SAF is San Adreas Fault, SF is Sargent Fault and ZF and Zayante Fault.

It has been over five years since PASSCAL portable seismic instruments were first deployed to record aftershocks of the October, 1989 Loma Prieta, California earthquake. Since that first experiment, PASSCAL instruments have been rapidly deployed to record aftershock sequences of many significant earthquakes in the United States and abroad. In more remote regions, the data collected during these experiments were the primary data used to obtain aftershock locations and source parameters, making tectonic interpretations of these events possible. Where regional seismic arrays already existed, the PASSCAL portable stations have provided dense coverage of aftershock zones with high quality three-component stations. This has allowed detailed investigations of the source process of small earthquakes and crustal structure including the nature of seismic anisotropy, the characterization of fault zone trapped waves, the attenuation structure near fault zones, and variations in the amplitude and direction of strong ground motion. In addition, PASSCAL's use of broadband seismic sensors has greatly enhanced the frequency range over which aftershocks can be recorded allowing aftershock waveforms to be inverted directly for source parameters. Although we can not be certain of recording a large earthquake at a close, dense array of high quality instruments, PASSCAL's Rapid Array Mobilization Plan (RAMP), a program to provide portable instrumentation to respond to large earthquakes, assures that the aftershock sequence of such an event can be recorded. Datasets of well-recorded aftershocks should continue to provide us with insight into the earthquake process as well as with rich information about crustal structure in active tectonic regions.

Bolstering the National Seismic System

Walter Arabasz and Steve Malone
Council of the National Seismic System

The National Seismic System (Figures 1 and 2) is an integrated seismograph system linking regional seismic networks throughout the U.S. with the broadly distributed stations of the U.S. National Seismograph Network, operated by the U.S. Geological Survey (USGS). Its purpose is to meet the needs of the nation for timely and accurate information associated with earthquake and volcano hazards—for public safety, research, education, and engineering.

National policy recommendations for a National Seismic System, dating from 1980 and later including a science plan, crystallized in 1993 with the forming of the Council of the National Seismic System (CNSS)—a union of 27 U.S. institutions and agencies which operate the vast majority of seismographic stations in the U.S. The seismic networks forming the CNSS share IRIS's goals related to technologically advanced recording, processing, and distribution of earthquake data. A primary purpose of IRIS is to give seismologists "the best possible tools and data to carry our their research activities." Many of these same researchers simultaneously play a vital public-service role through the CNSS—particularly at regional, state, and local levels—in meeting needs for rapid earthquake alert, earthquake hazard and risk assessment, general earthquake information, and technical and policy guidance to public officials, planners, designers, and other decision makers.

Public funding increasingly challenges the seismological community to use its science and technology to meet societal needs; creative efforts between IRIS and the CNSS can clearly bolster the National Seismic System to the benefit of the nation. Recognizing that the CNSS has no direct funding but relies entirely on the cooperation and limited resources of its member institutions, IRIS can help bolster the National Seismic System in the following ways: IRIS can help develop and transfer key technology to seismic networks, for example in broadband seismometry and digital telemetry, benefiting in turn from the experience of CNSS practitioners. IRIS can provide leadership in defining standards for seismographic systems, including specifications for components and calibration procedures, which the CNSS could coordinate with IRIS, and endorse. IRIS can help develop conversion software to the SEED format that would enable regional seismic networks to provide their short-period data in a standard, easily accessible way, using SEED and the DMC model.

Most networks continue to lack the considerable resources needed to reformat and distribute their data. IRIS can coordinate with and help CNSS network operators in the rapid deployment of portable seismographs after significant earthquakes—especially in many parts of the nation where such recording may be important after moderate-sized mainshocks smaller than those that typically trigger an IRIS RAMP response, say, in California. Importantly, as the National Seismic System advances toward connectivity for the rapid delivery of unified post-earthquake information to all users, valuable information from IRIS researchers involved in near-real-time seismology should become an integral part of the information flow.

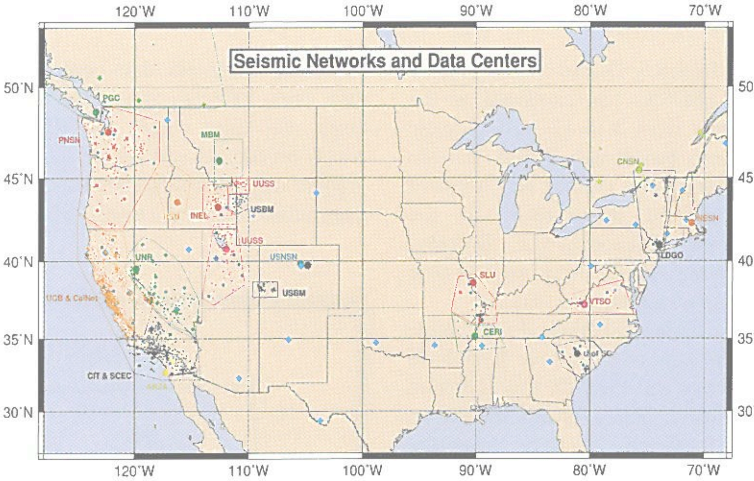


Figure 1. Composite station map of the National Sesimic System, December 1994, showing discrete regional seismic networks (enclosed by polygons), their associated data centers and operating institutions (large dots) and broadly distributed stations of the U.S. National Seismographic Network (cyan-colored diamonds). Approximately 1,430 seismograph stations are shown, including short-period stations (small dots), telemetered broadband stations (diamonds), and dial-up broadband stations (sqaures). Regional resismic networks in Alaska and Hawaii not shown.

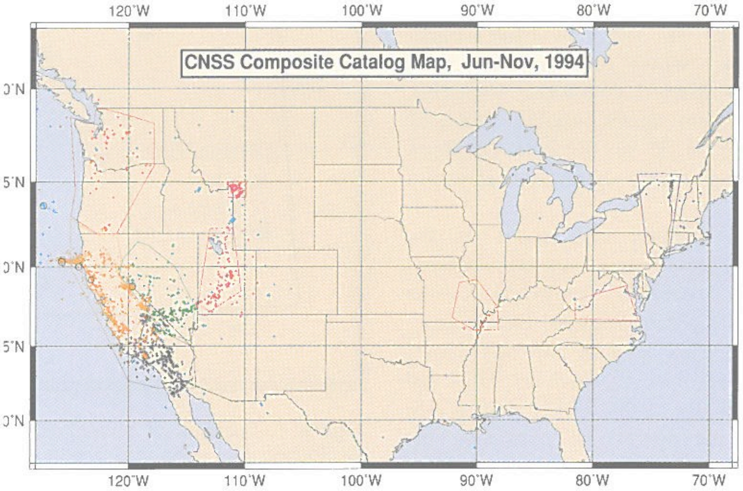


Figure 2. Experimental 6-month composite epicenter map for the contiguous United States, June-December 1994, generated over the Internet from data made available by member institutions of the Council of the National Seismic System (CNSS) via the mechanism, finger quake@machine. Vari colored epicenters chiefly derive from one of the regional seismic networks located within a correspondingly colored polygon; cyan-colored epicenters are from the U.S. National Seismograph Network for events not reported by a regional network.

The Berkeley Digital Seismic Network

Barabara Romanowicz and staff of the U.C. Berkeley Seismographic Station
University of California, Berkeley

The Berkeley Digital Seismographic Network (BDSN) has expanded in the past 4 years from 3 to 12 high-dynamic range, very broadband digital stations located throughout central and northern California and telemetered to the Seismographic Station at U.C. Berkeley in continuous mode, allowing real-time processing of earthquake data.

Each station is equipped with three-component sets of STS very broadband seismometers and FBA-23 strong motion accelerometers and a Quanterra station processor which contains multiple functions, such as detector algorithms and communications protocol for near-real-time telemetry. Station CMB contributes data to the IRIS-GSN network, and 3 stations (CMB, SAO and WDC) also contribute data through a satellite link to the US National Seismic Network. The continuously monitored network is being expanded to include the Hayward Fault Digital Network, which consists of wide dynamic range (0.05-400Hz, 10^{-8}-0.5g), 6 component sondes installed at depths to 250m in 3" to 4" wide boreholes along the highly hazardous Hayward Fault.

The second component of the Berkeley observatory comprises consists of GPS receivers, contributing to the BARD (Bay Area Regional Deformation) network. This network currently counts 10 stations, three of which are collocated with stations of the BDSN. Finally, we are in the process of expanding the pluri-disciplinary character of our regional observatories to include two (and soon three) high sensitivity electric and magnetic field measuring systems, which record two orthogonal electric and three orthogonal magnetic field components in the dc to 10Hz band for purposes of monitoring anomalous fields potentially related to earthquake activity. These systems are co-located with stations of the BDSN and recorded, along with the seismic data, on the Quanterras.

All data are telemetered to the Seismographic Station, through a combination of phone and microwave links. We plan to upgrade the telemetry to frame-relay in the near future, in a cooperative effort with Caltech and Pacbell, which will provide better reliability and increased bandwidth, making it possible to also telemeter GPS and electro-magnetic data continuously to UC Berkeley and to exchange data in real-time with TERRAscope. The broadband and strong motion data are analyzed in quasi real time within the REDI (Rapid Earthquake Data Integration) program, which broadcasts earthquake locations and magnitudes using a pager system and the graphic display system developed by CUBE. We also plan to broadcast automatically determined moment tensors which are currently produced in a test mode.

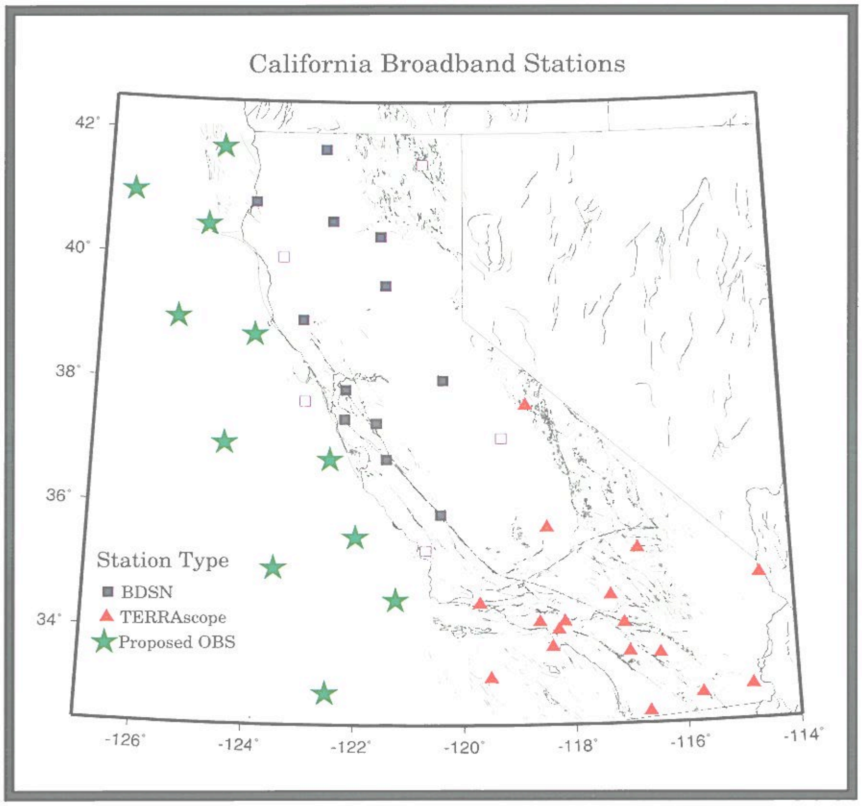
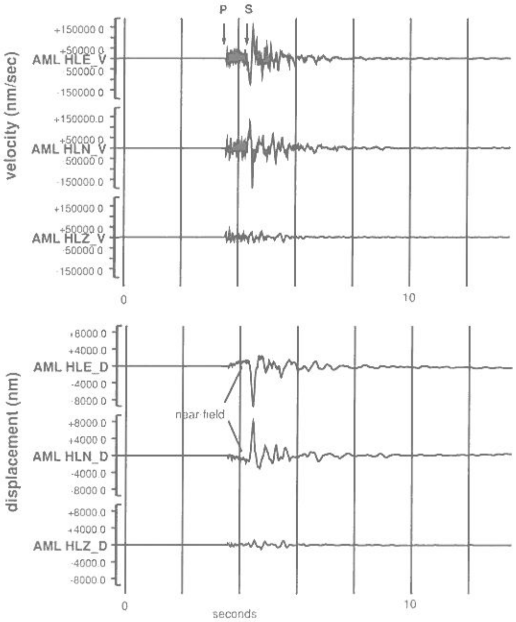


Figure 1. Location of current very broadband stations in California and proposed distribution of permanent ocean bottom broadband sites.

All the data are archived at the Northern California Earthquake Data Center (NCEDC), a mass-store based facility joint with USGS/Menlo Park, accessible through the Internet. The Data Center also provides catalogs of earthquakes in northern and central California produced by UC Berkeley and the USGS/Menlo Park. Plans for the near future include the installation of 2 additional very broad band stations and the relocation of one or more of the most noisy stations in tunnels or custom made vaults. We also wish to promote a longer term and ambitious project to complement the land based very broad band seismic network in California with an ocean bottom component, as shown in the figure above, to remedy the "one-sided" distribution of stations with respect to the active transform plate-boundary, especially in northern California, where there are no islands. The San Gregorio and Hosgri faults cannot be properly monitored with the current network geometry, and the mapping of rupture time and space history for larger earthquakes suffers from inadequate azimuthal coverage. Proximity to the coast suggests that such a deployment is a reasonable technological challenge and could eventually be extended to the whole western US, to provide coverage of the Mendocino triple junction and the Pacific Northwest subduction zone.

Near-field Phases Recorded on KNET

Robert Mellors and Frank Vernon
University of California, San Diego



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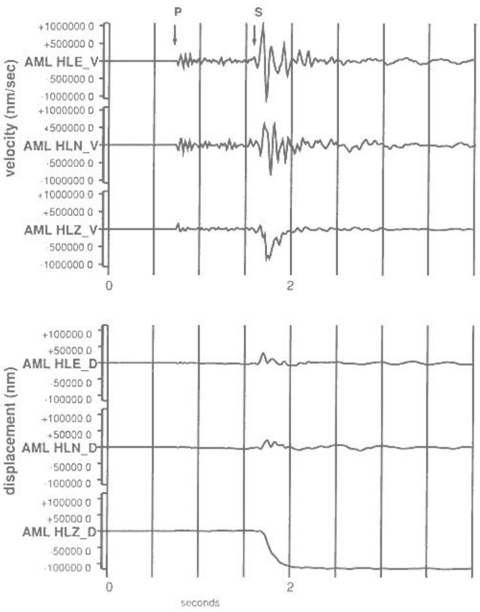

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The advent of broadband seismometers combined with wide dynamic range digitizers has made the on-scale recording of near-field effects from relatively small earthquakes feasible. Near-field terms often appear as ramp-like phases between the arrival of the P and S waves. The relatively longer periods and lower amplitudes of near-field phases require high dynamic range and broadband response. While near-field effects have been recorded for years by strong motion instruments, these records are often due to large earthquakes and the size of the rupture adds to the complexity of the signal.

Since 1991, IRIS (as part of the Joint Seismic Program) has operated a 10 station network (KNET) around the city of Bishkek in Kyrgyzstan. This broadband network has recorded numerous near-field effects for several reasons: the seismometers are all broadband and recorded with 144 db of range, the sites are exceptionally quiet (among the quietest in world) hard-rock sites, and the network is located in a seismically active area. In particular, station AML is located 8 km above the fault plane of a magnitude 7.4 earthquake (the 1992 Suusamyr earthquake) and has recorded hundreds of aftershocks within 20 km of the station. Dozens of these vents show clear near-field effects. Stations AAK and KBK are also located sufficiently close to active faults to record near-field phases.

Observations of near-field phenomena may give insight into the physics of the earthquake generating process. The abundance of examples allows comparison between events and with source parameters determined from far-field phases. The KNET data can be used to study other near-source phenomena such as the apparent "nucleation phase.'

Shown here are near-field phases recorded at station AML (records converted to displacement) for small (m_l~3) earthquakes. The bottom right figure shows the displacement recorded at AML in one particularly puzzling case. We believe that this offset represents a site effect possibly produced by high-amplitude shaking rather than the direct static offset produced by the earthquake, but this is still under investigation.

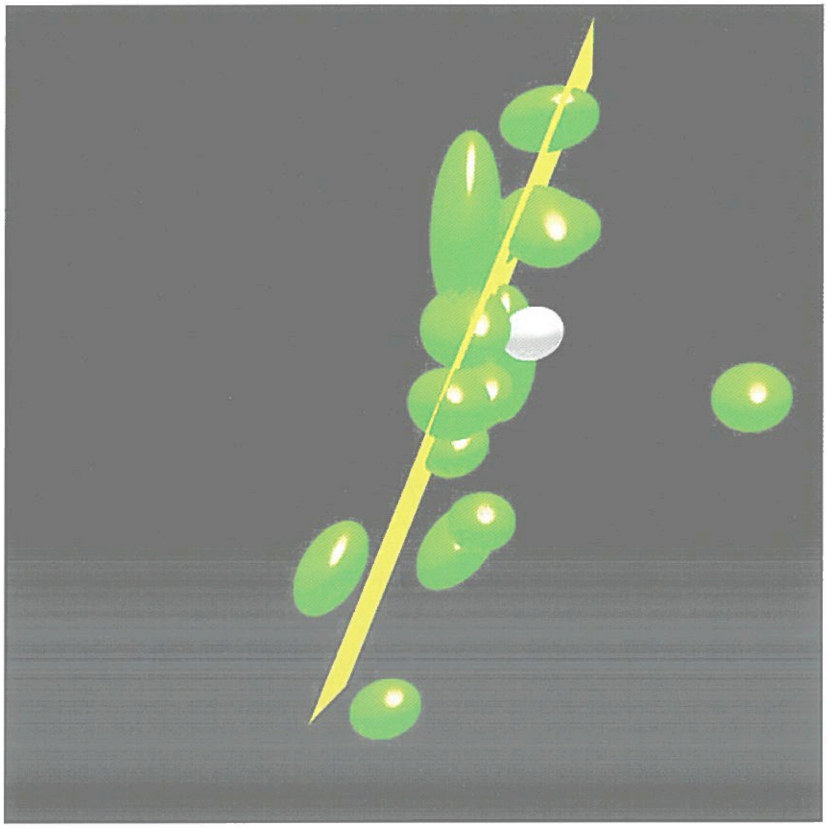
The Southwest Pacific Seismic Experiment

Doug Wiens
Washington University

Prior to 1994 little was known about the rupture details or aftershock characteristics of large deep earthquakes. It was generally thought that deep earthquakes lacked significant aftershock sequences, and that the few aftershocks which occurred did not delineate a fault plane. Fortunately, the March 9, 1994 large deep earthquake (Mw 7.6) occurred beneath a newly installed array of eight PASSCAL broadband seismographs in Fiji and Tonga, which allows the aftershock sequence to be mapped in detail. 83 aftershocks have been detected, and these events show a power law decay in time similar to aftershocks of shallow events.

Most of the well-located aftershocks locate along a steeply dipping plane (see figure), consistent with one of the main-shock nodal planes, and appear to delineate a 50 km x 65 km main shock rupture zone. The aftershock zone cuts entirely through the active seismic zone and extends 20 km into the surrounding a seismic region. Broadband regional waveforms, recorded on-scale by six of the PASSCAL stations, also suggest that this plane denotes the rupture plane, and that seismic rupture also propagated outside the previously active seismic zone.

These results have profound implications for understanding the mechanism of deep earthquakes. Large deep earthquakes and aftershocks must be able to occur outside the Benioff zone delineated by smaller earthquakes. The width of the rupture and aftershock zone is difficult to reconcile with the transformational faulting hypothesis for the occurrence of deep earthquakes, which suggests that deep earthquakes should be confined to a narrow zone of metastable olivine. This study also illustrates the type of unexpected, ground-breaking results which have been made possible by the availability of high quality portable instrumentation through the IRIS-PASSCAL program.



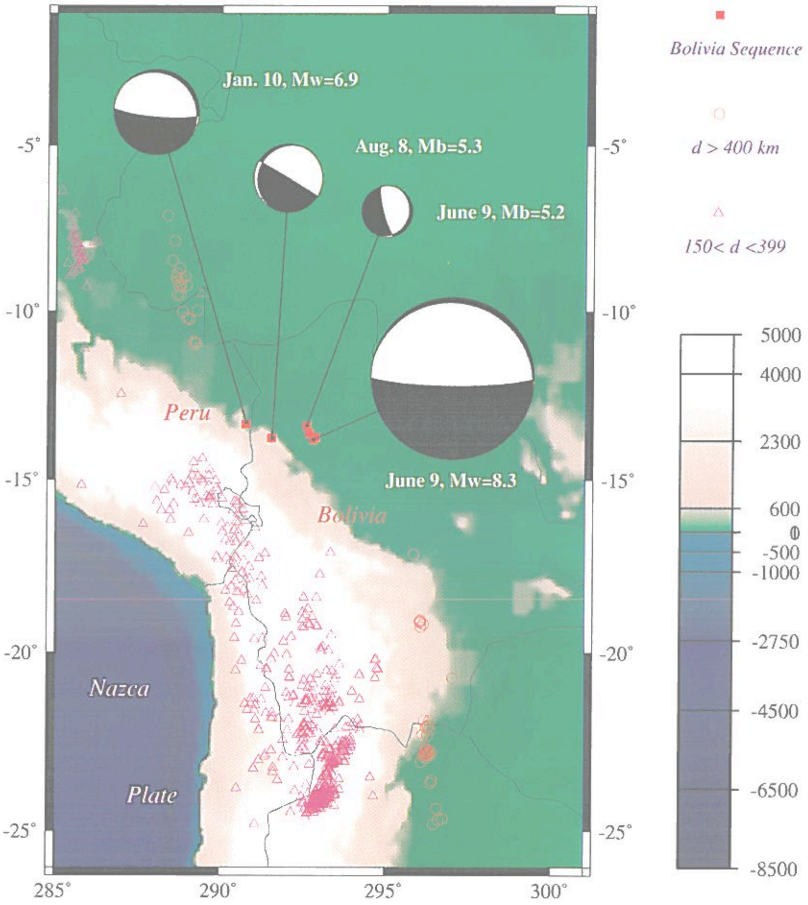
3-D visualization of locations of the mainshock hypocenter (white ellipsoid) and the best located aftrshocks (green ellipsoids) from the March 9, 1994 (M_w 7.6) deep earthquake. The ellipsoids denote the 95% confiendence regions for the realtive postion of each earthquake determined using a hypocentroidal decompostion inversion of arrival time data. The yellow plane (viewed nearly edge-on in this figure) represents the plane which best fits the aftershock locations, and is nearly coincident with one of the nodal planes of the main shock focal mechanism.

The June 9, 1994 Bolivia earthquake: Implications of the largest deep earthquake in recorded history

Terry C. Wallace, Susan L. Beck, George Zandt, Mark Tinker, Stephen Myers, Jun Wu, and Wenjie Jiao
University of Arizona, Tucson
Paul Silver
Carnegie Institution of Washington, Washington, D.C.

The Nazca subduction zone, which extends for more than 5000 km from Colombia to southern Chile, shows remarkable variability along its length. This is especially true between central Peru and southern Chile. North of 11°S the Wadati–Benioff zone (WBZ) dips at an angle of approximately 30° to a depth of 100 km; the slab then "flattens" until it reaches a depth of 200 km, where it resumes a normal dip. Similar slab flattening occurs south of 16°S. The deep seismicity ($h > 550$ km) north of 11°S and south of 16°S defines north–south trending lineations. These lineations are offset nearly 700 km beneath central Bolivia. For at least 60 years previous to 1994 there have been no earthquakes in this offset zone. The westernmost expression of this zone, beneath the Peru–Bolivia border, had earthquakes in 1958 and 1963.

Deep seismicity in the central, or offset, section of the WBZ began on January 10, 1994, with a moderate-sized event (M_w = 6.4) at a focal depth of 600 km. This event was located beneath the Peru–Bolivia border (see figure). Moment tensor inversion of the body waves from this event yield a double-couple source; we infer the faulting to have occurred on a nearly horizontal plane ($\delta = 11°$), striking along an azimuth of 309°. There were apparently no earthquakes larger than magnitude 2.5 between January 10 and June 9 in the offset zone. On June 9 the largest deep earthquake in recorded history ($M_w \approx 8.3$) occurred 200 km east of the January hypocenter. This earthquake is extremely well recorded globally; it was also recorded along a profile of portable broadband seismic stations in central Bolivia. The profile (known as the BANJO experiment) is a PASSCAL experiment operated jointly by the University of Arizona and the Carnegie Institution of Washington. The combination of BANJO and teleseismic data provides remarkable constraints on the mechanism of the June 9 event. Time-independent moment tensor inversions yielded a nearly horizontal fault plane ($\delta \approx 8°$), very similar to that of the January 10 event.



Focal Mechanisms of Bolivian Sequence, 1994

Detailed analysis of the time function indicates that there were at least four subevents; the rupture was initiated on the western margin of the fault plane as a magnitude 7 event, propagated to the east, and then continued bilaterally along a nearly north–south trend. The total fault area is approximately 30 x 50 km. The apparent rupture velocity (as indicated by the timing of the subevents) is very low, approximately 1–2 km/s. We performed a time-dependent moment tensor inversion to map the source complex (changes in fault orientation or slip direction). The total duration of the source is approximately 45 s, and there is almost *no* indication of mechanism change with time. This is extremely unusual for a magnitude 8 earthquake, and probably indicates that rather homogeneous stress conditions are controlling growth of the slip surface. We found no significant evidence for an isotropic component of the source.

The June 9 event was followed by a weak aftershock sequence. In the 20 days which followed the mainshock, 45 events with magnitudes between 2.4 and 5.7 occurred in the vicinity of the mainshock hypocenter. The aftershocks define a tabular volume, mostly below and east of the mainshock. The aftershocks define a plane which strikes west–northwest and dips at 55° to the northeast. We interpret this plane to represent the subducted Nazca plate. We were able to determine the focal mechanisms for 12 of these aftershocks using the P, S_V and S_H amplitude ratios for recordings from the BANJO array. Most of the aftershocks show near-vertical P axes. Although aftershock activity decayed rapidly, there was a large event ($m_b = 5.4$) on August 8. This event was located 100 km west of the June

9 hypocenter (approximately half way between the June 9 and January 10 locations) and had a focal depth of 590 km. The August 8 event had a nearly horizontal fault plane ($\delta = 12°$), but unlike the January 10 and June 9 events, the strike is rotated to be parallel with the inferred strike of the WBZ.

Approximately 10 minutes after the June 9 mainshock an apparently triggered event (m_b ~6) occurred 330 km east–southeast of the mainshock at a depth of 670 km. On March 14, 1995, a m_b = 4.9 event occurred at nearly the same location. The January 10, August 8, June 9, and March 14 events define a lineament nearly 550 km long which we infer to represent the seismogenic base of the Nazca plate. This interpretation allows us to fit a smoothly bent slab between the well-defined north–south lineations bracketing the offset zone beneath central Bolivia. This implies that the Nazca plate is continuous; further, this allows a geometry which is consistent with the extreme shortening of the Bolivian orocline.

The spatial extent of the June 9 rupture, the aftershock distribution, and the inferred geometry of the Nazca plate all provide constraints on the mechanics of deep earthquakes. Any proposed mechanism must account for (1) horizontal rupture, (2) likely rupture through the *entire* subducted plate, and (3) a stress system which allows for slip oblique to the convergence direction before and during the June 9 event, and parallel to the convergence after.

Geometry of the Subducted Nazca Plate Determined With Data from the PASSCAL Seismic Deployment BANJO

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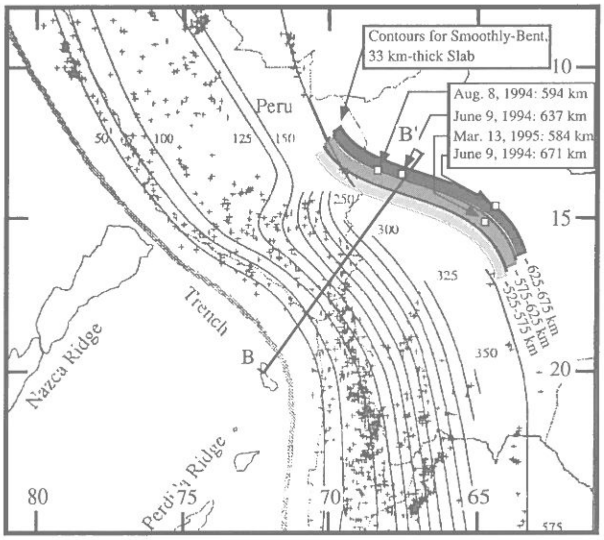
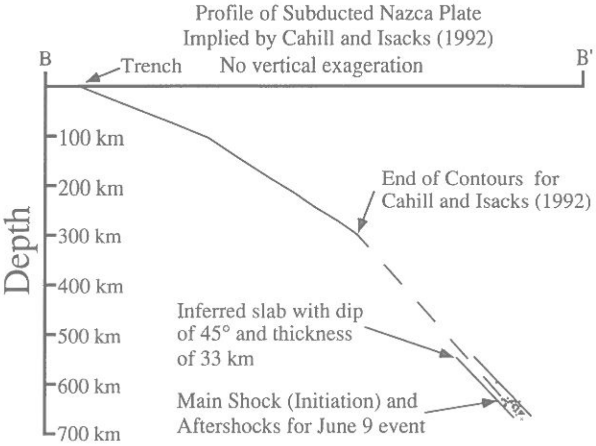
University of Arizona
P. Silver, J. VanDecar
DTM, Carnegie Institute of Washington
E. Minaya
San Calixto Observatory, Bolivia





The geometry of the subducted Nazca plate is closely correlated to tectonic features in the over-riding South American plate. The importance of the interplay between subduction and orogenic processes has become increasingly apparent only through seismic and geologic reconnaissance in South America. The latest of these efforts, a PASSCAL project (BANJO) operated by the University of Arizona and Carnegie Institution of Washington, is providing the best constraint to date on the geometry of the Nazca plate at depths between 575 km and 670 km. Before 1994 the deep portion of the Nazca plate was defined by two linear segments. One segment extends from southern Columbia into southern Peru. The other segment extends from central Bolivia into western Argentina. The two segments are laterally offset in northern Bolivia by an ~800-km jog that before 1994 was aseismic. Further, the deep seismicity is isolated from intermediate depth hypocenters by a gap in seismicity between ~300 km and ~575 km depth. These gaps in seismicity fostered speculation about the continuity of the subducted plate, from how stress transmits through the plate to the regional pattern of mantle circulation. In 1994, however, the region of the deep seismic jog was illuminated by the most powerful deep earthquake sequence ever recorded (mainshock on June 9). The 1994 earthquake sequence was well recorded on the BANJO network and provides the best earthquake locations available from which to determine the Nazca plate geometry in the newly-defined bend region.

The hypocenters of aftershocks and triggered seismicity associated with the June 9 deep Bolivian earthquake have confirmed the connectivity of the Nazca plate in the bend region. Hypocenters can be fit by a smoothly-bent, 30km-thick slab that bends between the two linear sections of deep seismicity. Additionally, the dip of the seismicity-defined deep slab is directly in line with the intermediate-depth (100km-300km) dip of the Nazca plate, suggesting continuity of the plate from the subduction zone to 670 km depth. Of the 45 earthquakes that have been located in the bend region, less than 10 were recorded at enough of the global-network seismic stations to determine locations. The event locations relied heavily on the very broadband recordings from BANJO. Detailed patterns of intra-slab seismicity, including the dip of the slab, would not have been possible without the BANJO data. The importance of determining patterns in seismicity that are defined by small earthquakes is clearly illustrated by the 1994 deep Bolivian earthquake sequence as recorded on the BANJO network.

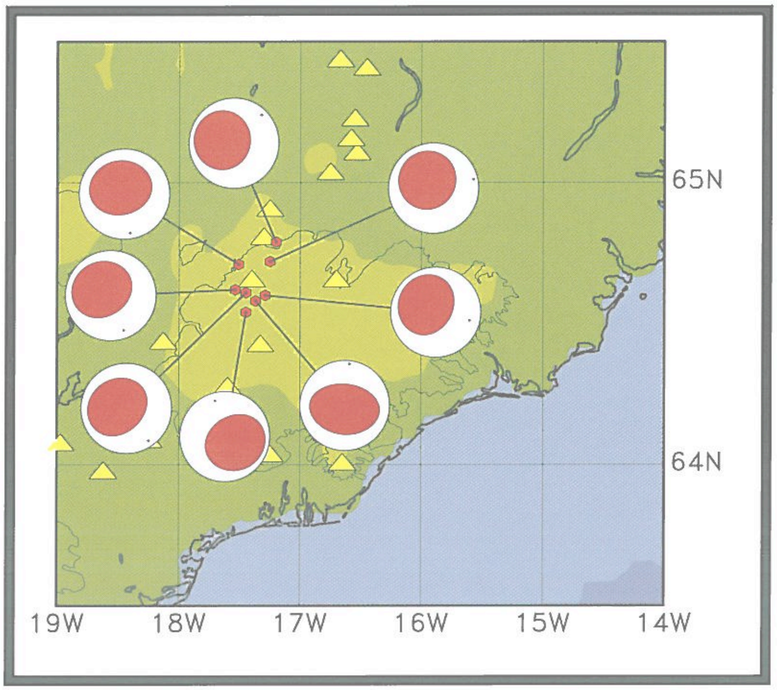
Rapid Earthquake Analysis Utilizes the Internet

G. Ekstrom, A.M. Dziewonski, M.P. Salganik, and S. Sianissian
Harvard University

Open access to many remote IRIS GSN stations via telephone modems and the Internet now makes it possible to retrieve seismograms and determine focal mechanisms and moment estimates for all moderate and large earthquakes within hours of their occurrence. The Harvard seismology group, as well as the Earthquake Research Institute in Japan and the USGS, take advantage of this possibility to routinely calculate and distribute source parameters for all moderate and large earthquakes around the world. In several recent severe earthquakes, including those in Landers, Northridge, and Kobe, the rapid availability of source parameters derived from the GSN has been of great value in the quick identification of active faults and rupture zones, as well as in the assessment of continuing earthquake hazards. The rapid earthquake analysis project at Harvard, and similar efforts elsewhere, rely on the rapid availability of seismic data. The SPYDER software, supported by the IRIS DMS, provides an efficient and cost-effective way of collecting and distributing these data to research groups and agencies in the U.S. and around the world. The Figure illustrates an important aspect of the rapid solutions, their overall quality. For the 43 earthquakes for which we provided a "Quick CMT" during September, October, and November of 1994, we compare our preliminary focal mechanism with the one obtained morerecently from the full GSN. In all cases, except for one, there is extremently close agreement. The "problem event" on September 12 was initially mislocated by 150 km by the USGS. We did not have sufficient azimuthal station coverage to refine the location, and the quality of the focal mechanism suffered as a consequence. Our experience from the Quick CMT project suggests that with future access to continuous data from a subset of well-distributed GSN stations around the world, a complete catalog of focal mechanisms for M>5.5 earthquakes could be determined with a delay of only few hours.

Anomalous Earthquakes on Volcano Ring-Fault Structures

Goran Ekstrom
Harvard University



From studies of global seismicity it is observed that some shallow earthquakes generate seismic waves which cannot be explained by the simple earthquake model of crustal block motion along a planar fault. Some well-known examples of such "anomalous" earthquakes are several M=6 earthquakes near Mammoth Lakes in 1980, the Tori Shima earthquake south of Honshu in 1984, and microearthquakes in geothermal areas. A systematic search for M > 5.0 earthquakes with unusual focal mechanisms shows that many of these events occur near volcanic centers. In particular, eight earthquakes in the last 15 years near the volcano Bardarbunga on Iceland show similar deviations from a double-couple source.

This figure shows the locations and focal mechanisms of the eight shallow earthquakes near Bardarbunga. The yellow triangles show the locations of active volcanos. The strain released in these events is consistent with vertical extension and nearly axisymmetric horizontal shortening. Previous explanations for this pattern of strain release is a rapid opening of a tensile crack, possibly associated with dike or sill injection. A new explanation for the source process in these unusual earthquakes is that the faulting occurs on steeply-dipping, curved, cone-shaped faults surrounding magmatic intrusions. Faults of this geometry and orientation, called ring faults, are frequently mapped in eroded extinct volcanos, and have recently been imaged by microearthquake activity beneath active volcanos.

IRIS and the Skin of Our Planet

Alan Levander and ILIAD Workshop participants*
Rice University
ILIAD : Investigations of Lithosphere Architecture & Development

The dynamics of Earth's surficial layers result from the response of the lithosphere to the driving forces which deform it. The theory of plate tectonics does a remarkable job of explaining the behavior of the oceanic lithosphere, none of which is older than 200 million years. The continental lithosphere typically records the cumulative geologic evolution of a billion years. Even for contemporary deformation, assessing the force balance in the continental lithosphere is difficult. In cases where the Earth's stress field can be measured directly, e.g., using breakouts in boreholes, lithospheric geometry and physical state are required to extrapolate these point measurements to meaningful volumes of the Earth. GPS measurements of real time deformation measure the instantaneous strain field, which can be related to the stress field only by using an appropriate constitutive law. Seismic data are necessary to survey the subsurface record of past and present motions within the skin of our planet.

"Imaging" the lithosphere is not easy. Strong variations occur laterally and vertically over scales similar to the seismic wavelengths used to interrogate the structure of the crust. These variations modify the passage of seismic waves, producing complicated patterns in the seismic wavefield recorded at the Earth's surface. The structure of the lithosphere can be described as a three dimensional heterogeneity spectrum, but one which extends across a broad wavenumber band, and one which is only locally stationary. A variety of seismic probes are required to reconstruct this complicated wavenumber spectrum, that is, to characterize lithospheric structure. Reflection seismology provides the highest resolution method for making detailed structural images of the continental crust, with resolution on the order of a few hundreds of meters in the deep crust, and a few meters in the shallow crust. Refraction seismology provides somewhat coarser measurements of seismic velocity variation in the crust and upper mantle, with resolution on the scale of a few to ten kilometers. Local earthquake measurements at regional seismograph arrays provides structural information on scale of 5-10 km, as well as providing highly detailed seismicity maps. Broadband measurements of teleseismic waves on linear and areal portable seismograph arrays provide information on the gross structure of the crust, and provide the highest resolution of mantle structure available, currently to scales of ~30km. Improving resolution provided by all three methods, and combining the results from different scale measurements is an important element of seismological research.

Brittle and Ductile Deformation: A Glimpse from Deep Seismic Reflection

Deformation processes differ greatly from the base of the tectonic plate to the Earth surface. So does our ability to resolve subsurface variations in seismic properties. This has led to diverse approaches to both seismic deployment and seismic data analysis. Some approaches are extensions of commercial exploration methods, some have been developed within the IRIS PASSCAL community. Both brittle and ductile rheology is present in the crust and its underlying plate, depending on location and time scale. How these mechanisms combine to form mountains, plateaus and basins is not understood very well. A combination of geological and geophysical investigations in key field laboratories is needed to answer the following questions in understanding lithospheric rheology:

- How do middle and lower crustal ductile flow balance with upper crustal brittle deformation during contractional, extensional, or transcurrent deformation? Implicit in this question is the nature and evolution of rheologic boundaries: the temporal and spatial scales of layers and their interactions, and the nature of coupling between layers.
- What is the coupling between crust and mantle lithosphere during deformation? When is the Moho a zone of decoupling and when is the deformation distributed in a weak lower crust? To what extent can lower crust be recycled by subduction or delamination into the mantle?

In order to characterize the general properties of rheologic layers and the degree of coupling between layers it is useful to identify key field laboratories. For example, 1) continued studies of the 3-D structure of extensional tectonism in the western US is needed to provide constraints on palinspastic restoration of the thermal-mechanical deformation of the lithosphere; 2) imaging of assembled, diverse continental lithospheric blocks into new lithosphere in Indonesia (active), the western US and Alaska (Phanerozoic—active), Arabian Shield (Proterozoic), cratonic North America (Proterozoic), and the Canadian Shield (Archean- Proterozoic). Only through the study of several examples will we obtain adequate constraints on lithospheric assembly processes through Earth history.

Continental deep seismic reflection profiles reveal a portfolio of characteristic patterns that can be linked with different tectonic regimes. For example, folded belts show long continuous packages of reflective rocks on scale lengths of tens of km laterally and 1 to 10 km vertically. These patterns document the mechanical transport of large packages of sedimentary, metasedimentary, and metamorphic rocks along detachment surfaces during formation of the mountain belts. Frequently the crust is reflective from top to bottom in series of these packages, suggesting that brittle deformation can occur through large parts of the crust. In contrast, continental reflection profiles from regions of Phanerozoic extension show a low to moderately reflective upper crust, a highly reflective lower crust and a seismically transparent upper mantle. Lower crustal reflectivity can be caused by a variety of factors, including fine-scale (100-meter) layering of lithologic and metamorphic grade, mafic igneous intrusions, shear zones, and layered seismic anisotropy due to ductile deformation. The diversity of lithologies in the lower crust contributes greatly to its seismic reflectivity. Fabrics of the reflective lower crust have scale lengths estimated to be from sub-kilometer to several kilometers. If deep crustal reflections in extensional regions represent lower crustal flow patterns, it may follow that the brittle failure and extension seen at the surface and in the upper crust are compensated by ductile flow in the lower crust.

The uppermost mantle is usually relatively non-reflective in deep seismic reflection profiles. In contrast to the crust, its composition is mostly restricted to ultramafic rocks, resulting in significantly fewer and weaker seismic reflections. Exceptions include the upper mantle beneath paleo-suture zones, where both bright flat and dipping reflections are sometimes observed over tens to hundreds of kilometers.

While the upper mantle is less reflective at near-vertical incidence than the lower crust, it appears to be highly heterogeneous on longer length scales (10-100km) than the lower crust. Long-range seismic profiles show that the upper mantle contains velocity fluctuations of a few percent, which produce a strong forward scattered wavefield due to the long horizontal paths traversed by mantle arrivals. Teleseismic observations suggest that the heterogeneity may be due to anisotropy variations in upper mantle fabric.

An exciting multi-disciplinary challenge in continental dynamics is the investigation of currently active regional metamorphism. Researchers have identified "conveyor belt" settings from structural geology, characterized by quasi-steady transport of material from the surface to the deep crust along shear zones. Mid- and lower-crustal imaging and remote-sensing using geophysical methods can be directly related to field studies of petrology, geochemistry, and tectonics. Obvious targets for such work include Taiwan, the Aleutian arc, and various portions of the Himalayan orogen, where old, cold, and/or wet crustal material could be followed into the thickened active orogenic welt. The geophysical investigations would comprise regional-scale tomography aimed not so much at structure but physical state parameters such as the temperature field and the recognition of zones of fluids and partial melt. Insofar as these parameters are first-order controls on rheological behavior, such studies would provide essential data constraining deformation during orogeny.

Descriptions of Heterogeneity

Most active source seismic investigations are designed to determine the seismic velocity or impedance structure of the crust and upper mantle. Crustal models derived from one-dimensional analysis of refraction travel-time data in the 1950's and 1960's were essentially two-layered models: a felsic upper crust overlay a mafic lower crust. Lateral variations in velocity were generally of a scale which reflected only regional differences in crustal and layer thicknesses. The development of 2-D ray-trace analysis, amplitude analysis, and the increase in the number of available seismic recorders during the late 1970's and early 1980's led to more complexly layered crustal models in which crustal layers varied in number, thickness, and velocity laterally over scales of 10's of kilometers. Refraction analysis generally led to models consisting of isovelocity layers (or near isovelocity layers) which were many wavelengths in thickness and lateral extent. The nearly simultaneous development of deep seismic reflection profiling in the late 1970's presented a somewhat paradoxical view: reflection images showed a highly heterogeneous crust containing bright reflectivity in distinct bands either localized or distributed throughout the entire crust. The traditional view of a grossly layered crust becomes a subset of a more modern view in which the individual layers of the crust can themselves contain highly heterogeneous structures. This is geologically more satisfying, as surface exposures of crystalline rocks show highly heterogeneous structures, and also opens a new and exciting area of research in wave propagation, referred to as the saturated regime, in which the seismic wavefield is multiply scattered by many wavelength scale fluctuations in velocity and density.

Seismic velocity structure can be divided into two types, "deterministic" and "stochastic." "Deterministic" structures are large enough to be isolated by seismic processing — a working definition is that scattered waves from a "deterministic" reflector must correlate across the recordings of several sensors and/or several shots. "Stochastic" structure resembles what a field geologist sees in an outcrop, a pattern of prominent compositional contrasts that is too fine-scale to be resolved interface-by-interface with seismic waves, but that exerts a significant influence on the detailed waveform. The wavelength of a 30-Hz P-wave in crystalline rock is 150-200 meters, so the deterministic paradigm fails miserably on structures that one can bang a hammer on.

If the mean velocity structure of the Earth's outer layers is well-constrained and the seismic signals scattered from deteministic-scale heterogeneities are recorded by a spatial array of seismometers, it is possible to "depropagate" and image the points at which the energy was scattered. There are a number of classic imaging techniques available to "depropagate" scattered energy. Surface integration or Kirchoff techniques are widely used in oil exploration to process seismic reflection data. The velocity model is used to predict when, at a given station, a scattered wave arrives from a particular location in the Earth. This processing methodology has been applied to crustal seismic reflection data with great success. The method has been adapted to migrate densely-sampled wide-angle data, a problem of greater complexity than the vertical incidence case, since travel paths are considerably longer and imperfections in the velocity model can cause greater biases. Nonetheless, this is a promising technology which can be used successfully in surveys in which shots and receivers are both sampled relatively densely.

Seismologists have often ignored the fact that the rocks that their waves probe have pervasive small scale variations in elastic properties. In a typical crustal reflection seismic experiment, approximately 10-30% of the seismic energy can be modeled deterministically as resulting from large-scale impedance contrasts. The additional 70-90% of the wavefield can be modeled as a scattered, field. By using appropriate statistical models one can calculate a seismic wavefield that compares favorably with that observed. Statistical characterization of geologic maps of archetype terranes has been used to develop statistical models of the crust which reproduce the gross seismic response and account for a good fraction of the observed seismic wavefield. Further studies of crustal exposures and well-log data are needed to construct realistic models of small-scale crustal heterogeneity. Outcrops and exposures contain much information over a large range of scales (from hand samples to continental scale geological provinces) which has not yet been exploited by seismologists.

How small can we go? Seismic imaging needs to be refined to allow deterministic description at the smallest possible scale. In active-source experiments, it is possible to increase resolution through variable frequency analyses and careful control of source and station geometry. For passive source experiments, station spacing can be reduced, and analyses can be tuned to exploit the bandwidth of modern broadband sensors. Data processing techniques that systematically bootstrap our analyses from low to high frequencies and wavenumbers will allow us to push our understanding of heterogeneity to increasingly smaller scales. Without the continued technical innovation provided by IRIS and similar organizations, we will not be able to develop our interpretation tools appropriately.

Structural Geology of the Upper Mantle: The Revolution in Portable Broadband Recording

Over the last decade, lateral variations in upper mantle seismic properties have been imaged with increasing resolution and sophistication using the permanent stations of the Global Seismographic Network and temporary arrays of portable seismographs, including the PASSCAL Refteks, which can record ground motion from both broadband and high frequency sensors. Seismologists now map both lateral and vertical variations in lithospheric and asthenospheric structure in P- and S-wave velocity and anisotropy, finding clear spatial relations to known crustal provinces on a variety of scales.

Teleseismic imaging provides the best resolution of lithospheric-scale structures. P-wave images are the best-resolved among the teleseismic images, both due to the relative abundance of P-wave data and due to the high frequency content of P-waves. Upper mantle P-wave images of unprecedented resolution have become available in the last decade, providing heretofore unavailable glimpses of lithospheric and asthenospheric structure. Observed structure, often unanticipated, has proven crucial in constructing regional syntheses of ongoing tectonic activity, and has enabled a broader understanding of tectonic and magmatic processes in general. However, exciting as these new images have been, their information content is frustratingly limited in several regards. The location of the early studies usually were restricted to pre-existing regional seismic networks. Since regional networks are sited for purposes unrelated to lithospheric imaging, these regions were often not ideal. Furthermore, P-wave velocity provides but a single parameter for interpretation, and its relation to upper mantle physical state is not known very well. Crustal structure (which is better explored with S waves) often is poorly known, degrading resolution beneath the Moho.

The IRIS PASSCAL portable array of broadband seismometers has begun to overcome these problems. Instruments are deployed temporarily in locations of interest, with a station density and geometry that maximizes resolution. The broadband three-component data admit consideration of P, S, Qp, Qs, and anisotropy structure, thereby permitting a more thorough investigation of the physical state of the upper mantle. Receiver-function studies allow for direct (station by station) estimates of local crustal structure.

Results from these experiments are just beginning to emerge, and are exciting. In the western US, for instance, the lithospheric boundary between the craton and the western US lies beneath western Kansas, not the Rocky Mountain Front, suggesting that uplift of the Great Plains is maintained by buoyant mantle emplaced after the Laramide orogeny. The Laramide orogeny apparently removed much of the Great Plain's lithosphere without deforming it. Magma-associated asthenospheric processes dominate upper mantle activity beneath the high-standing interior of western US, as compared to lithospheric processes dominating the 200-300 km-wide margin of the western US. The upper mantle, in a narrow slot beneath the Snake River Plain, appears to be partially molten to depths of about 200 km. Beneath the Snake River Plain's "tectonic parabola," much wider than the plain itself, there is a strong and uniform anisotropy (~1.5 sec split S-wave anomaly) that is inconsistent with the plume-flattening models commonly used to explain the parabola. In contrast, the upper mantle beneath Colorado is strongly anisotropic only in a small fraction of its volume, suggesting that Laramide shear structures penetrate the whole lithosphere. Variations in Cascade arc magmatism, which is very active in the south and nearly inactive in the north, correspond to variations in backarc temperature, and presumably partial melt content.

Geophysical Imaging in the Top Kilometer

Most of our direct geologic observations, as well as the interactions of modern industrial society with the Earth, occur in the upper kilometer of the crust. Yet this is an area traditionally overlooked by academic seismologists. High-resolution geophysical methods, in particular high-resolution seismic reflection profiling, provides a unique opportunity to image the near-surface directly, allowing us to address a host of geologic questions with both scientific and societal relevance. Shallow seismic profiling commonly records frequencies in the 100-500 Hz range, yielding subsurface resolution of a meter in imaging structure and stratigraphy. This technology provides the link between surface geology and the seismic methods which measure the properties of the deeper crust and mantle. Moreover, because shallow seismic profiles are inexpensive to collect, the acquisition of 3-D data volumes is feasible. Due to cost, 3-D technology is now almost unavailable to the academic community, despite its importance for examining the complex structure of active fault systems. The shallow subsurface is an extremely heterogeneous region, providing a natural laboratory to look at theoretical problems in wave propagation in highly heterogeneous media. Results from shallow surveys can be verified by shallow drilling and by direct comparison to outcrops.

High-resolution images of the upper kilometer of the subsurface will lead to a broader understanding of the processes shaping the Earth's crust. They are among the best means for directly imaging subsurface faults and understanding the genesis of fault plane reflections. Specific reflection events or patterns of reflectivity can be unequivocally tied to fault zone properties, zones of cataclasis, mylonitization, mineralization, or pore fluids, at least in low-pressure metamorphic environments. In active tectonic areas, high-resolution images can be used to map fault networks in two and three dimensions, relating surface geodetic measurements to the tectonic processes causing uplift and subsidence, and mapping both discrete and broad zones of deformation. In addition these techniques can be used to directly image seismically active fault zones, providing the geometry and physical properties of faults which have recently ruptured, or which have high seismic potential. Since high resolution profiles map meter-scale structure in two and three dimensions at depths to several kilometers, they provide a natural link between surface geology and crustal scale reflection profiles.

An understanding of the upper 1 km of the earth has direct impact on societal issues such as evaluation of groundwater and mineral resources, mitigation of environmental hazards, earthquake hazard assessment, and education. Currently the most common technique used to characterize near-surface materials in both groundwater and environmental hazards studies is shallow well boring. This can be expensive and provides only point measurements of the subsurface. One knows little about the lateral extent of key horizons, structures, and material properties, such as porosity and permeability. The near surface environment can be incredibly heterogeneous. Shallow seismic methods are non-invasive techniques capable of defining the continuity of stratigraphic layers, pinch-outs, fault geometry and distribution, and depth to bedrock, all of which are important parameters in geotechnical investigations. They are also an inexpensive and efficient means of developing cost-effective strategies for well-bore sampling. Lastly, high- resolution seismic profiling is extremely useful for delineating potential earthquake hazards in seismically active areas, particularly when active faults do not break the surface. Seismicity patterns established from local and regional seismic networks can be further investigated using shallow profiling techniques.

*** ILIAD Workshop Report**

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The Mendocino Triple Junction Seismic Experiment

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The Mendocino Triple Junction experiment was a combined marine-land seismic investigation of the lithospheric architecture in the San Andreas transform, Mendocino fracture zone, and Cascadia subduction regimes that compromise the triple junction. The seismic experiment consisted of three land refraction profiles totaling 700 km, 3 high resolution reflection/refraction profiles, 1900 km of marine reflection data along 14 profiles, 6 ocean bottom seismograph profiles, 5 onshore-offshore profiles, and an onshore-offshore areal array. The primary objectives of the experiment are to image the structures forming: the fault bounded crustal blocks and the upper mantle "slab-free" gap beneath the transform region, the fracture zone offshore and its buried extension onshore, and the Gorda plate subduction zone north of the transform. Principal results to date include: 1) Detection of anomalously bright reflections which we believe to be from thin layers of melt in the lower crust and at the Moho in the onshore transform environment. 2) Recognition of Moho-depth offsets in the San Andreas, Maacama, and Bartlett Springs transform faults. 3) Clear indication that the seismicity associated with the Cascadia subduction zone is not due to imbrication of the Gorda Plate. 4) Remarkably clear offshore reflection images of the top of the down-going slab in the Cascadia subduction zone.

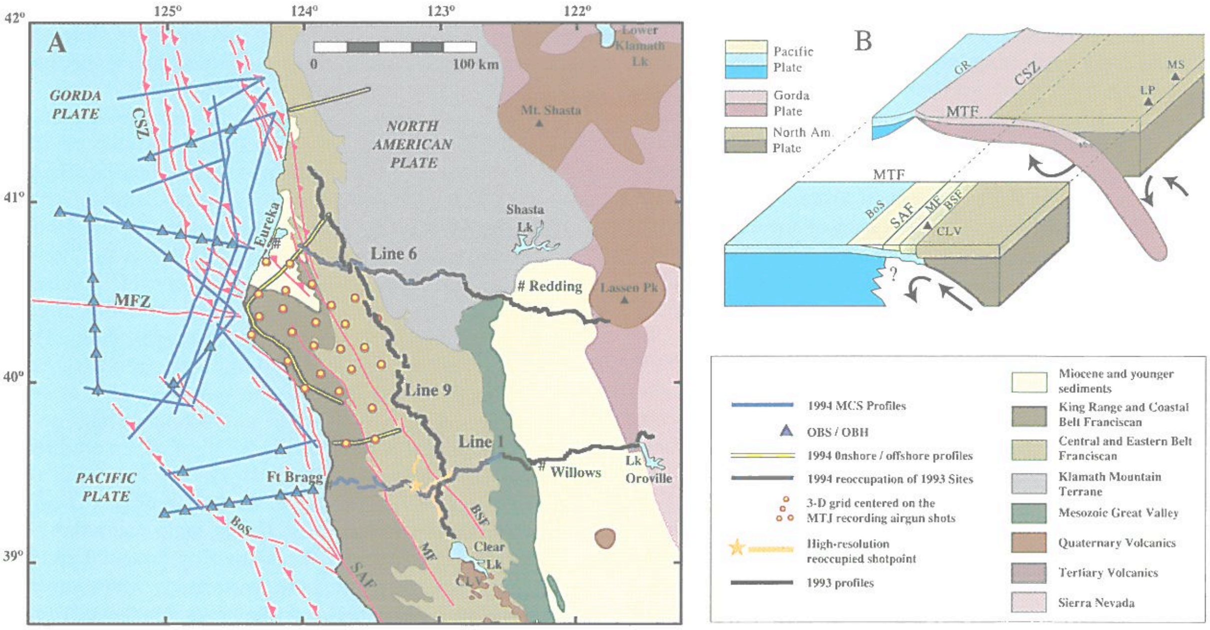

Figure A. Locations of the 1993 and 1994 seismic experiments overlain on a simplified geological map of northern California. BoS - Base of Slope; BSF - Barlett Springs Fault; CLV - Clear Lake Volcanics; CSZ - deformation front of the Cascadia Subduction Zone; MF - Maacama Fault; SAF - San Andreas Fault.
B. Schematic three-dimensional diagram of plate interactions in the region of the Mendocino triple junction showing development of a slab window as the Gorda plate migrates north (not to scale). GR - Gorda Ridge; LP - Lassen Peak; MS - Mount Shasta; other abbreviations are the same as in 1A. Pale shades represent crust; darker shades represent lithospheric mantle. Pale yellow "Pacific plate" indicates crustal material that has been transferred from the North American to the Pacific plate; gradual shading from yellow to green indicates crust within the San Andreas fault zone that has a motion intermediate between that of the North American and Pacific plates. Arrows represent directions of asthenospheric flow.

The Brooks Range Seismic Reflection/Refraction Experiment

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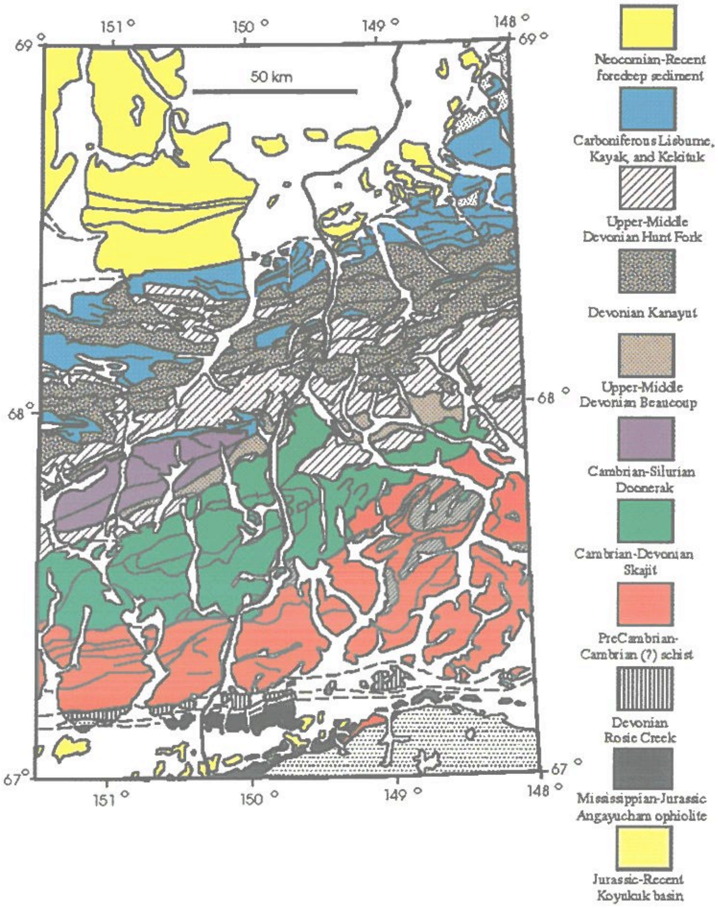
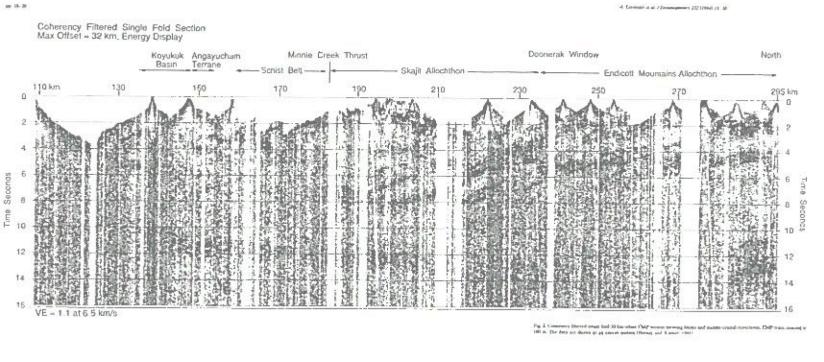
U.S. Geological Survey

The Brooks Range seismic experiment was an integrated reflection/refraction investigation of the Brooks Range fold and thrust belt, the northernmost mountain range in the North American Cordillera. The experiment was the final segment of the Trans-Alaska Crustal Transect, an integrated geophysical and geologic investigation of the Alaskan crust extending along the Trans-Alaska Pipeline corridor from the convergent margin in the Gulf of Alaska to the rifted margin along the Arctic Ocean. The Brooks Range seismic experiment took place entirely north of the Arctic Circle. A 1988 pilot survey was followed by the 1990 main experiment which provided a 300 km long refraction profile extending from the Arctic Circle to the Arctic Ocean within which was embedded a 190 km crustal reflection profile.

The primary objectives of the experiment were to image the large scale structural elements of the fold and thrust belt, and to relate the seismic images to detailed geologic studies along the pipeline corridor. The seismic reflection images show clear indications of crustal scale (~30km depth) duplexing during Cenozoic development of the range. The basal detachment in the range extends to more than 30km depth, and documents the fault structures which permitted the rapid exhumation of high grade metamorphic rocks which equilibrated at 10 Kbar (~30km depth). The reflection images also constrain balanced cross-sections which suggest that shortening of approximately 500km took place during the development of the range.

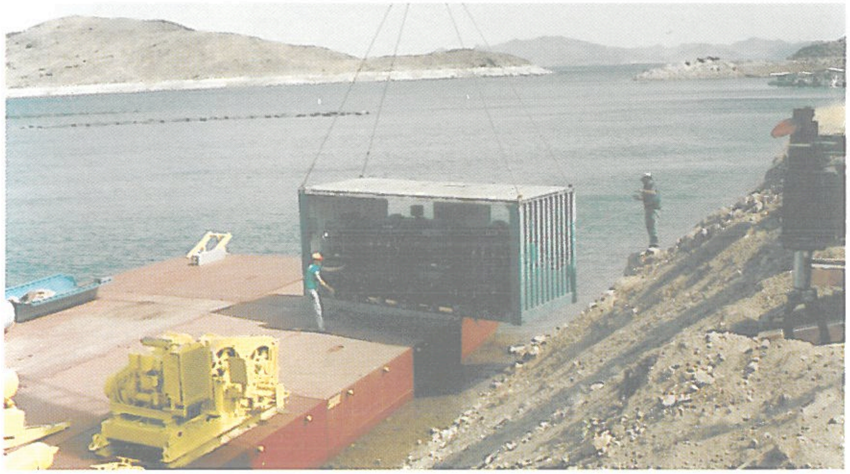




The Basin and Range Geoscientific Experiment (BARGE): Intracontinental Lacustrine Seismology

Arthur Lerner-Lam
Columbia University

Why should marine seismology stop at the coastline? Why should a small impediment such as lack of navigable access prevent the application of marine seismological tools and techniques to problems of continental dynamics? Is it useful to merge marine multichannel seismics with onshore recording at greater offset in complex geological settings? The advantage of using marine acoustic systems, such as the R/V Ewing multi-channel seismic system, coupled with onshore recording with PASSCAL equipment has been demonstrated convincingly along the western margin of North America. Marine air gun systems provide simple, inexpensive, repeatable and nondestructive sources and the hydrophone streamers provide good acoustic coupling and, with stacking, decent signal-to-noise ratios. Onshore recording provides large offset for velocity control and refraction analysis. Used together, they provide extraordinary images of the stratigraphy and make structural seismology in the crust possible. The breakaway zone along the eastern margin of the Basin and Range presents a tempting target for high-resolution crustal imaging. How is extension partitioned between the upper and lower crust and between the crust and the upper mantle? Is there an explanation for the anomalous relationship between crustal thickness and total extension intuited for the eastern Basin and Range? Is there flow in the crust as well as in the mantle? The use of onshore recording with marine MCS tools would be of obvious utility in answering these questions. Unfortunately, the only navigable body of water crossing this zone is Lake Mead, on the Colorado River near Las Vegas, a scenic but landlocked experimental venue. With funding from NSF's Continental Dynamics Program, eight portable barges were trucked from Salt Lake City to Lake Mead and assembled in situ. The streamer, compressors, air guns and control systems from the Ewing were bolted on deck. A complete air and hydraulics system was built, and R/V BARGE was able to sail after seven days of assembly. Meanwhile, 50 PASSCAL instruments with three-component seismometers were deployed around Lake Mead. Scientists from Cal Tech, MIT, and LDEO with the additional assistance of student interns from Colorado College all participated. BARGE sailed and shot for about ten days up into the mouth of the Grand Canyon (just past the breakaway boundary) before its ceremonious decommissioning and unceremonious disassembly. Preliminary analysis of the data indicates excellent propagation characteristics and many secondary arrivals. A simple travel time analysis has shown varying crustal velocities across the breakaway region, in partial support of models of lateral crustal transport. A definitive picture awaits further analysis. We now know, however, that lacustrine seismology with short-term vessels is technically feasible.



Crustal Reworking During Orogeny: An Active-system Himalayan Perspective

*Anne Meltzer, Peter Zeitler, and the Nanga Parbat Working Group**
Lehigh University

In the NW Himalaya of Pakistan, the peak of Nanga Parbat sits at 8126 meters and, with the Indus River at its base, defines the world's greatest continental relief ~ 7000 meters in 21 horizontal km. Nanga Parbat, together with the peak at Haramosh (7884 m) forms the Nanga Parbat-Haramosh Massif, a mass of Indian crust that has popped up from beneath Asia in the midst of the Himalayan mountain chain. Nanga Parbat reveals not only excellent exposures of rocks but also a wide variety of active geologic processes, including ferocious denudation, very high strain rates, and very young, perhaps contemporary melting and high-grade metamorphism. We have initiated a multi-disciplinary study to make and integrate a wide variety of measurements using techniques of geochronology, petrology, stable-isotope geochemistry, radiogenic tracer-isotope geochemistry, seismology, magnetotelluric sounding, structural geology, and geomorphology, to understand the mesoscale interaction between petrological and mechanical processes during collisional orogenesis. Our ultimate goal is to exploit the excellent exposures and access to active tectonic processes offered by Nanga Parbat to assess which specific processes are most important in reworking the crustal lithosphere, and whether these processes are in fact those traditionally associated with continental collision.

Extremely rapid exhumation, the presence of hot springs, young intrusive rocks, and young metamorphism all suggest an anomalous thermal structure lies beneath Nanga Parbat. As part of our study, we will deploy an array of short period and broadband IRIS PASSCAL instruments to record local, regional, and teleseismic events and use tomographic techniques, receiver function analysis and first motion studies to help characterize the state of the crust beneath the Nanga Parbat-Haramosh Massif and to determine the subsurface geometry and kinematics of faults bounding the massif. The crustal structure beneath Nanga Parbat is unknown. Determining the thickness and structure of the crust and the character of the crust-mantle transition will provide key constraints for our metamorphic, structural, and magnetotelluric studies, constraints required for an understanding of the active tectonics of the region and for developing geodynamic models for uplift of the massif. In addition, establishing the presence or absence of magma or zones of partial melt in the crust beneath Nanga Parbat is of first-order importance in distinguishing between alternative models for the recent melting and metamorphism observed at Nanga Parbat. Himalayan granite generation is typically viewed as a relatively deep-seated phenomenon, divorced in time and process from the relief-cutting phase in which the high peaks grew, and it would constitute a fundamental shift in our view of the Himalayan chain if it turns out that at least some of the high peaks sit astride melts.

Recent and still-active metamorphic processes at Nanga Parbat are etching an indelible overprint on the Proterozoic crust of the massif that is far more intense than the early Himalayan metamorphism seen elsewhere in the northwestern Himalaya. We hope to determine whether this region represents a singular accident contingent upon local details of the India-Asia collision, or whether it might in fact provide us with important lessons about how continental crust can be reworked during orogeny.

View of Nanga Parbat (center) from the Astor Road.

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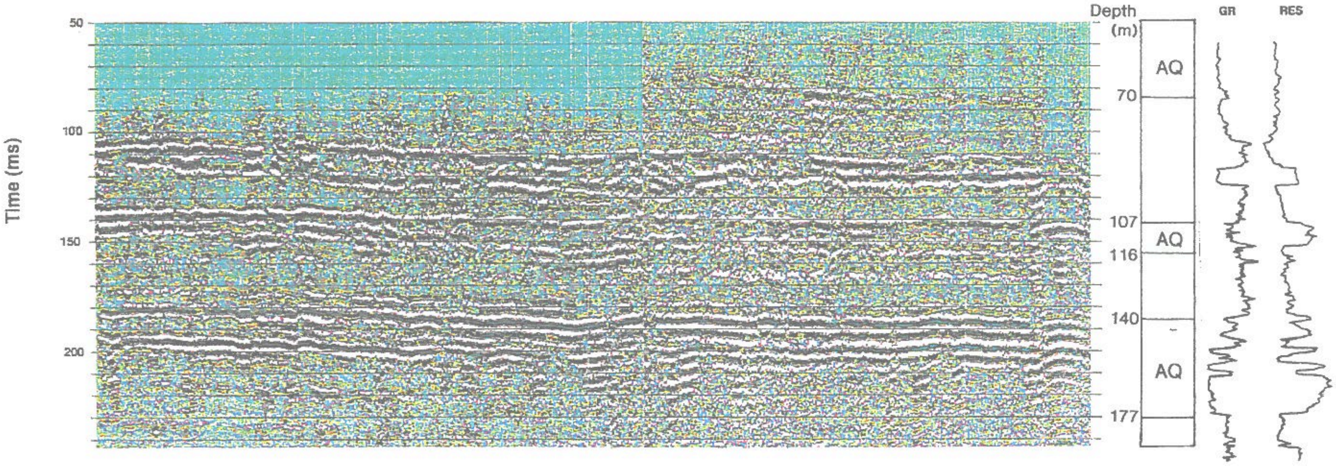
Shallow Imaging

Susan McGeary
University of Delaware

The recent development of very high-resolution seismographs and digital ground penetrating radar (GPR) systems now provides IRIS members with the opportunity to image the uppermost portions of the Earth's crust with a high level of spatial resolution. Such knowledge of the shallow subsurface is required by a diverse set of studies including neotectonics, sedimentary processes, Quaternary stratigraphy, resource exploration (water, coal, hydrocarbons), hazardous waste mitigation, and geotechnical engineering. In addition, fundamental questions related to wave propagation in heterogenous media can be addressed in geophysical studies of the relatively easily characterized shallow crust. IRIS is in the position to take advantage of these developing technologies to provide instrumentation and support to the growing number of IRIS members involved in shallow subsurface research.

As an example, this figure shows part of a high-resolution multichannel seismic reflection profile collected along the barrier island system in New Jersey. This experiment was designed to study the hydrostratigraphy and physical properties of four regionally important aquifers. This profile segment is 3.1 km long, with depth penetration to about 200 m (using a 10 lb sledge hammer source). The figure also shows the depths to three aquifers mapped in the area and the gamma-ray and resistivity logs from a nearby well. Four features can be clearly identified in the profile. The base of the most shallow aquifer is weakly imaged at the top of the section (80-90 ms). The sand deposits of the two deeper aquifers (140 ms and 180 ms) are well imaged, with individual reflections in the deepest aquifer roughly correlatable to the boundaries between individual lithologic layers identified in the geophysical logs. In addition, a prominent sand body within the upper confining unit is imaged in detail (105-130 ms). The unit thins and eventually pinches out in both directions; the basal reflector cuts into the underlying unit as an erosional unconformity. This sand unit is interpreted to be a buried paleochannel deposit, with prograding clinoformal internal reflections. Signal frequencies recorded on the profiles in this experiment averaged 225 Hz, with a few regions up to 350-450 Hz. Average vertical resolution is estimated to be 1-2 meters using the 1/4 wavelength criterion, with resolution in a few areas close to 0.6 meters.



Exotic Terranes in Southeast Alaska

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University of Wyoming
John Diebold
Lamont-Doherty Earth Observatory
Anne Trehu
Oregon State University
Bob Ellis and Ron Clowes
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The Pacific Geoscience Centre
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Maria Luisa Crawford
Bryn Mawr College

ACCRETE is a combined geological-geophysical project in Alaska to study continental assemblage by accretion of exotic terranes and generation of new crust in an island arc along the coast of SE Alaska. Geophysical studies are primarily based on marine-land recording using the RV Maurice Ewing airguns and streamer to simultaneously obtain MCS profiles and REFTEKs on land to obtain wide-angle seismic profiles. The ship traverse crossed the Queen Charlotte fault at sea and went up the Portland Canal to reach 134 km inland.

The ACCRETE "pilot study" was carried out in August and September 1994 with 10 days of ship time and relatively few delays, so that more than the original pilot study was completed. 1700 kms of MCS profiling data were obtained and common receiver gathers were recorded by 60 REFTEKs on land from EWING's 28,000 airgun shots.

In general, the seismic data quality can be described as good to excellent—surprisingly so for the MCS reflection data recorded in narrow waterways. The MCS profiling has been successful at mapping the Moho and has also imaged a series of deep crustal reflections in preliminary cross-sections. The MCS data are being analyzed to determine static corrections (for bottom depth and sediment thickness) prior to the next stage of both MCS and wide-angle data processing. The Moho is at about 10s, and a continuous event at about 16s has been demonstrated (substantial recent effort went in to establish this important result from the analysis of wide-angle data) to be the SmS phase with surprisingly large amplitudes even at near - vertical incidence, which is attributed to the bottom roughness and large impedance contrast.

For land-based wide-angle recording of energy from the 8400 cu. in., 20 airgun source array, 60 REFTEKs were deployed by teams from Bryn Mawr College, and the Universities of Wyoming (UWy) and British Columbia (UBC). The stations to be processed by UWy were cemented to bare rock along the shores of Dundas Island and of Portland Canal. UBC located stations

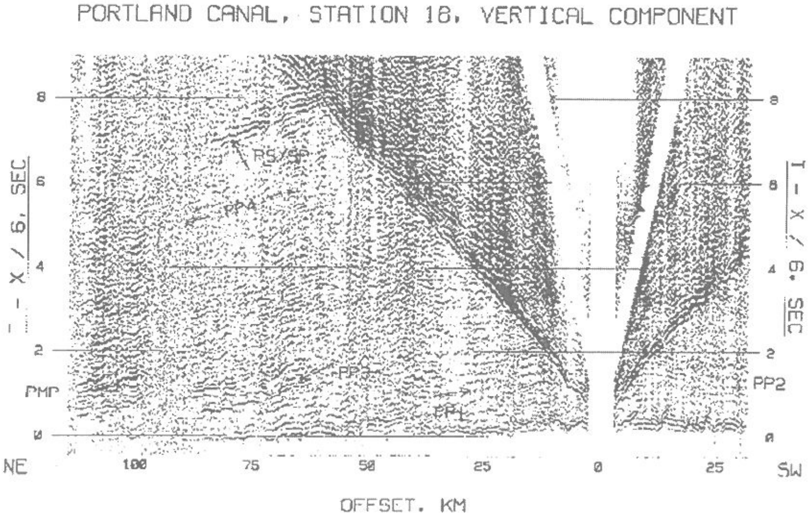

Figure 1. Reduced trace-normalized vertical component record section from station 18, Portland Canal. The reduction velocity is 6 km/s. MCS statics have been applied. Water wave has been muted out. PmP reflection, several crustal reflections (PP1-PP4) and a strong converted phase are marked on the plots. Note that: 1) S waves have remarkably high amplitudes; 2) the apparent velocity of both P- and S- refracted waves is higher in NE then in SW direction. This suggests a lateral upper- and/or mid-crustal velocity inhomogeneity across the Coast Shear.

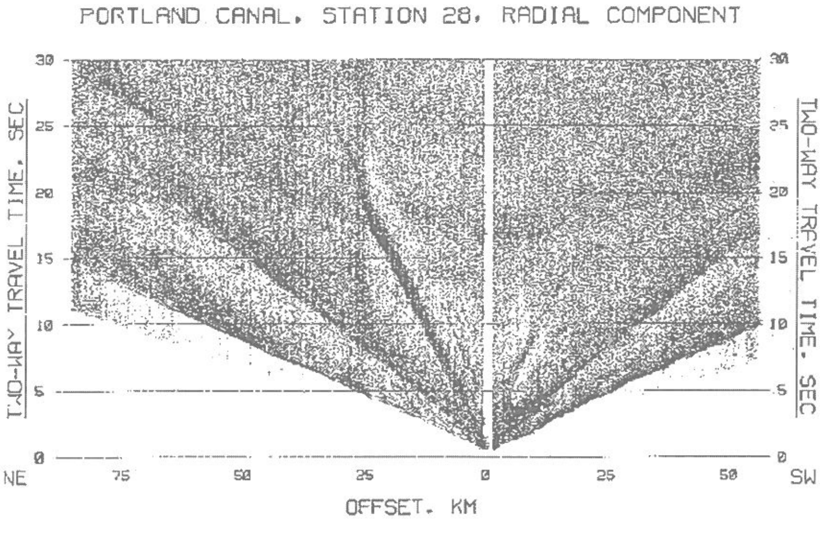

Figure 2. Radial component receiver gather from station 28, 60-sec Portland Canal line. Note prominent P- and S-wave reflections and converted phases which can be traced to zero offsets. Clear crustal reflections are seen in secondary arrivals.

(some by helicopter) NE of Stewart and on Graham Island. The UBC team is processing the data collected on the 17 REFTEKS placed north of Stewart following which an integrated UWy - UBC interpretation will be produced. Continuous coverage and dense trace spacing were achieved because the airgun shots were spaced at 50 m (20s) and 100 m (60s) intervals (both shooting intervals were done along the same ship tracks, taking advantage of the fact that the ship had to retrace its path entering and exiting the fjords). The common receiver gathers thus generated are characterized by strong S-wave as well as P-wave arrivals (Figures 1 and 2). These almost all show PmP and SmS together with crustal phases, which are abundant on some receiver gathers (Figures 1 and 2). Pn is observed both on NE and SW sides of the Coast Shear for offsets up to 230-240 km and at various azimuths (Figure 3). S-P and P-S conversions are also found. Preliminary ray-trace modeling of the Portland Canal wide-angle data shows that the Moho deepens across the Coast Shear zone from 28 on the west to 32 km on the east. A close (about 140 km, Fig. 3) Pn crossover observed in preliminary analysis of the Clarence Strait line corroborates this conclusion. Portland Canal data are sorted into common midpoint gathers (CMP) showing good continuity of events. With the use of CMP gathers, a bright shear-wave reflective spot was found. Vp/Vs can be determined for a number of layers, although shear wave splitting is also observed. Data from NE of Stewart indicate a NE-wards deepening Moho to 35 km and laterally heterogeneous crust. Coherent energy is also present at times consistent with either a mantle reflector or a converted phase. Preliminary velocity measurements have been made by Nik Christensen on typical rocks from the area. The results show high velocities (>7km/s) for restites that project to beneath plutons along the east side of the Paleogene arc and strong shear wave splitting for some gneisses and migmatites.

The MCS sections allow us to determine structural detail; the wide-angle data allows us to determine broader structure (in general without high dips) and to determine velocities for larger scale rock units. These velocities, including S-wave velocity, are the bridge to geology (rock types). Poisson's ratio and/or anisotropy from analyses of S-wave data furnish further constraints on geology. The vertical incidence seismic data can indicate the presence of small-scale layering (30-200 m). The wide-angle together with vertical incidence data will reveal the continuity and detail of crustal-scale layering (or velocity discontinuities), if it exists. Variations in Pn velocity may indicate different upper mantle beneath different terrains; likewise the seismic Moho response may reveal differences in nature of the Moho in different terranes — or that the Moho has been reconstituted after accretion.

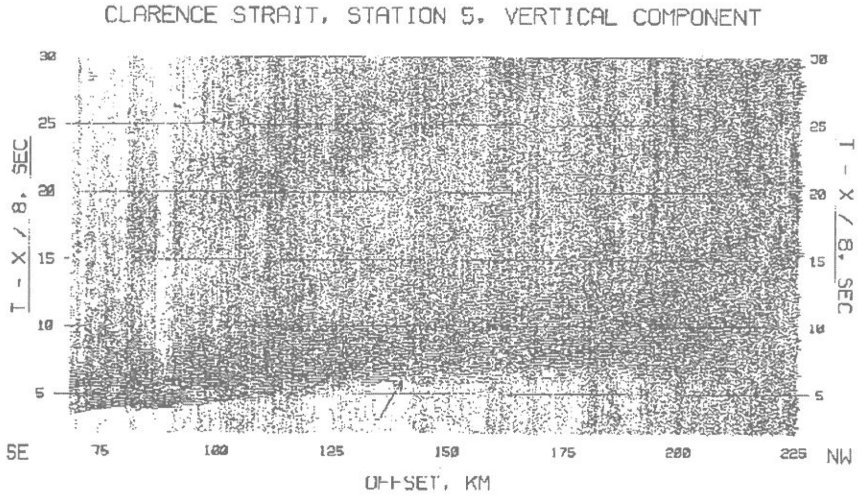

Figure 3. An example of observed Pn phase propagating approximately parallel to the Coast Shear. The reduction velocity is 8 km/sec. Pn has apparent velocity about 8.0 km/sec and is seen within the 140-225 km offset range. The arrow indicates the crossover point.

Wide-angle refraction/reflection recordings from the Aleutian Arc

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Woods Hole Oceanographic Institution
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N. Bangs
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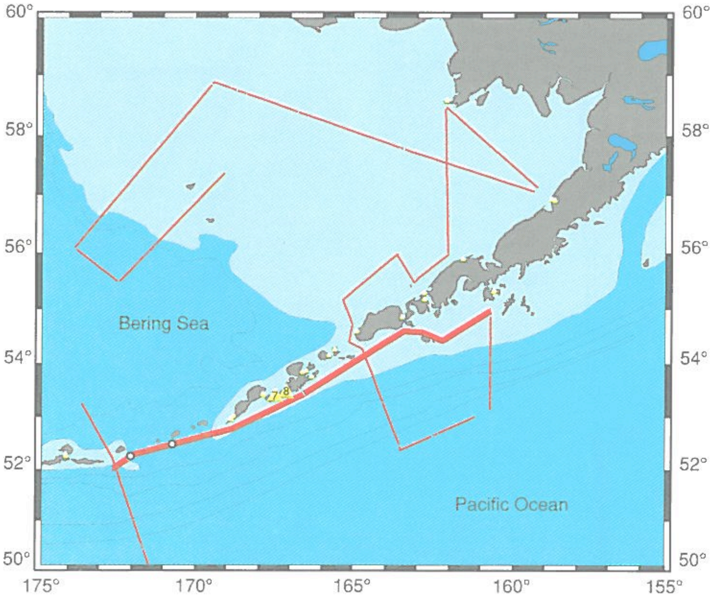
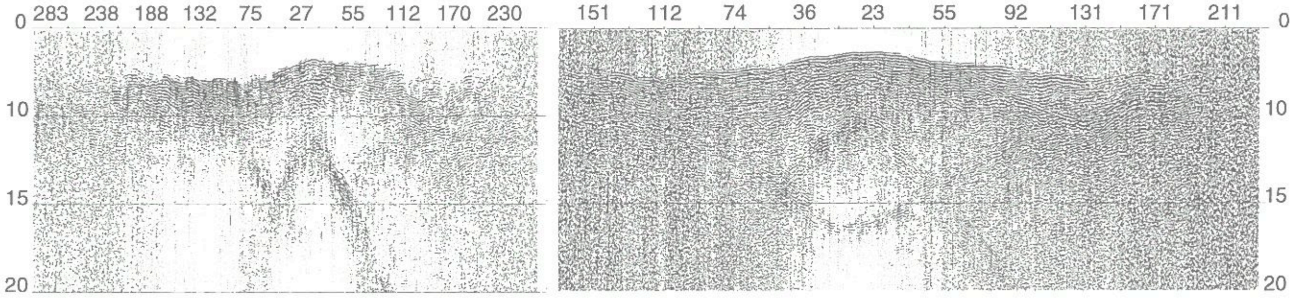
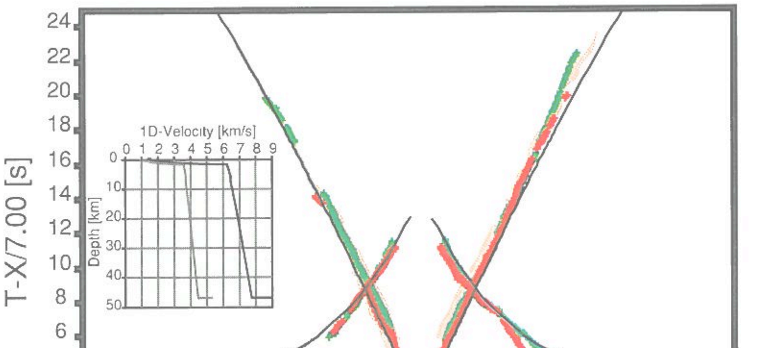
Multi-channel seismic data (red shiptrack) were recorded at wide angles on 3-component Reftek portable seismographs (yellow triangles) and OBSs (two of them shown as white circles) to determine the velocity structure of the magmatic arc and its evolution from an oceanic (Aleutian Islands west of 165°W) to a continental arc (Alaska Peninsula; shelf indicated by bathymetry and light blue). Receiver gathers and traveltime picks are shown below for line A2 (thick red), which samples the arc along strike from oceanic crust in the west to continental in the east.





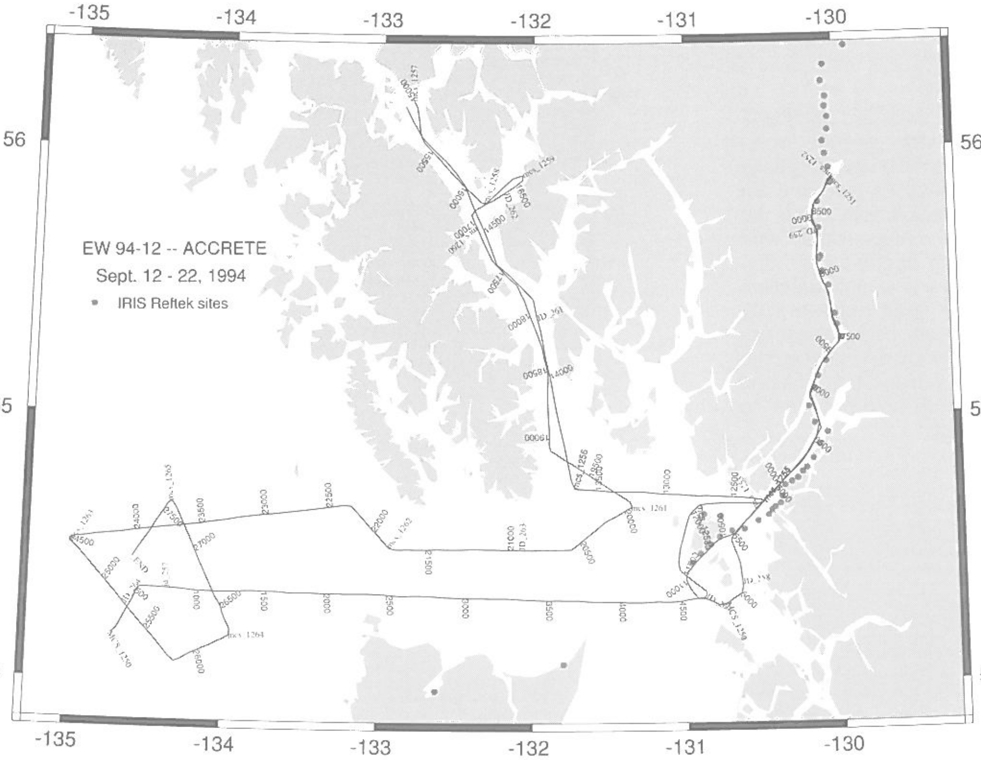
Gathers for receivers 7 (left) and 8 (right) with constant trace spacing (traveltime in seconds reduced at 7 km/s; distance annotations in km). Station 7 shows the maximum distance, at which a first arrival can be distinguished in the unstacked data. Station 8 shows a major reflection, which is particularly strong at small offsets; applying a NMO correction of 7 km/s moves this event out to 15 s. The same reflector is slightly weaker on station 7. Both stations show fairly strong shear waves.



Traveltime picks of first arrival, main reflection, and S-wave arrival for stations 7 (green) and 8 (red). Blue shading indicates range of first arrivals from all stations west of 165°W; red shading for all S arrivals. Overlain is the traveltime curve calculated from the 1-D velocity model shown in the inset (P-velocity black, S-velocity gray, Poisson's ratio is 0.25).

ACCRETE

Lincoln Hollister
Princeton University



Ship tracks for the EWING cruise EW 9412. CDPs 22000 - 28000, and 0 - 2500 cover the Queen Charlotte transform fault. The line labelled with CDPs 13500 - 20000 along two directions of Clarence Straight were primarily for fan shots to Reftek locations.

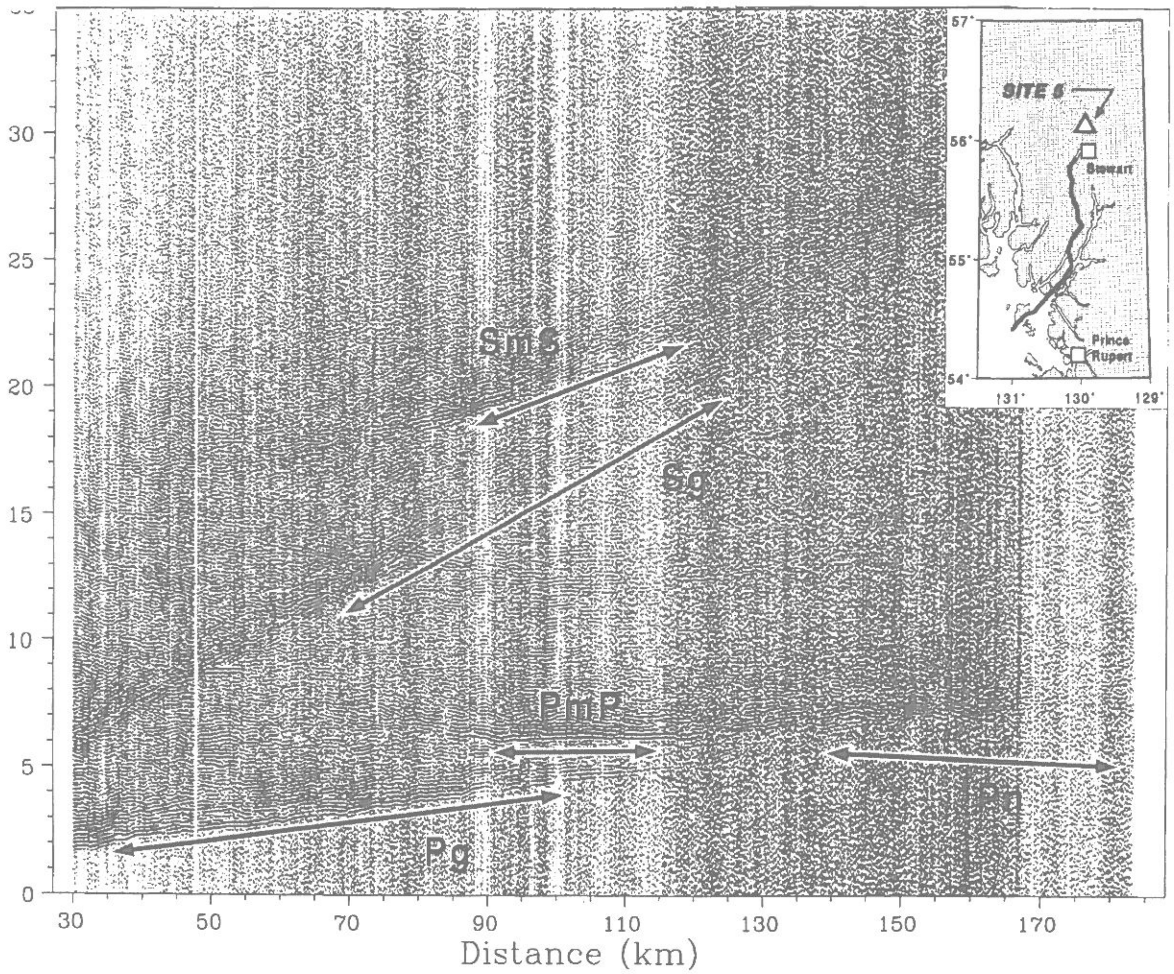
The ACCRETE program is a collaborative endeavor to determine how continents grow by magmatic and terrane accretion, and to investigate the relative roles of these processes. The central segment of the Coast Mountains orogen is an ideal laboratory because (1) we have already acquired geophysical data across it that are exceptional in quality and quantity, (2) rocks presently exposed at the surface were formed at mid-crustal levels, and (3) we can project mid-crustal geological features from the surface down-dip into the seismic section. Using these geophysical and geological data we will be able to construct a section across the orogen from the surface to the upper mantle. Besides providing answers to fundamental questions regarding continental growth at convergent to transpressive plate margins, we also address major questions regarding the overall tectonic history of western North America.

The ACCRETE project involves the study of the British Columbia - Alaska border, between 54° 15' and 57° N. A geophysical project along this transect in the summer of 1994 resulted in 1700 km of MCS, gravity and magnetic data, and common receiver gathers from 60 REFTEKS, and a profile. The data gathered in this experiment will help us define:

1. The history and architecture of thrust belts resulting from convergence accompanying the mid-Cretaceous episodes of accretion.
2. The history and significance of the Coast shear zone, a zone of intense deformation with unknown displacement, that extends 800 km along the orogen. This fundamental boundary marks the western edge of a high temperature orogen dominated by a Paleogene batholithic complex.
3. The magmatic record. The plutons date events in the accretionary history and provide information on the subsurface distribution of geochemically distinct terranes; the geophysical properties of the crust below the Paleogene plutons provide information on the mechanism(s) of pluton generation (crustal growth by magmatic accretion).
4. The history of deformation and mechanism(s) of uplift culminating in rapid exhumation of the metamorphic core.

Offshore-Onshore Seismic Surveys

John Diebold
Lamont-Doherty Earth Observatory of Columbia University



During 1994, three offshore-onshore projects were shot by R/V EWING, operated by Lamont's marine office on behalf of the ship's owners, NSF. These included the second phase of the Mendocino Triple Junction survey, the Aleutian arc, and ACCRETE, a transect of accreted terranes in SE Alaska. Another large scale survey, forming two transects off New Zealand's southern island, is funded and scheduled for early 1996. A look at some of the data from the ACCRETE project shows why this mode of acquisition is becoming increasingly popular. EWING's 8400 cubic inch 20-airgun array can be fired every twenty seconds, or more slowly if desired. Its peak-to-peak output (13.5 Mega Pascals) is equivalent in the exploration seismic band (5 - 50 Hz) to many hundreds of pounds of TNT. During the ACCRETE project, clear coherent arrivals are observed at the largest offsets recorded (ca. 250 km). The dense shot spacing and the repeatablity of the shots makes it easy to correlate arrivals in shot gathers. Since the same GPS clock times are used for both Refteks and EWING shot logging, record sections can be extracted with little difficulty. During each of the three 1994 experiments, shot times and locations were transmitted from the ship to the land parties daily by email. The gun towing system was designed to allow repair of any faulty gun while the others continue firing, with only an average 5% reduction in output while the bad gun is out of action. Gun depth can be controlled between 6 and 12 meters by varying the ship speed. Increasing tow depth enhances lower frequencies (5 -10 Hz) significantly. When MCS data are collected coincidentally with large aperture PASSCAL profiles, the results can be used to provide shot-by-shot source statics, and to constrain the upper parts of final velocity models. We anticipate that participation of EWING in performance of similar collaborative experiments will become increasingly common in coming years.

Imaging Active Processes Of The Yellowstone Caldera By Earthquakes, Active Seismic Experiments, And GPS

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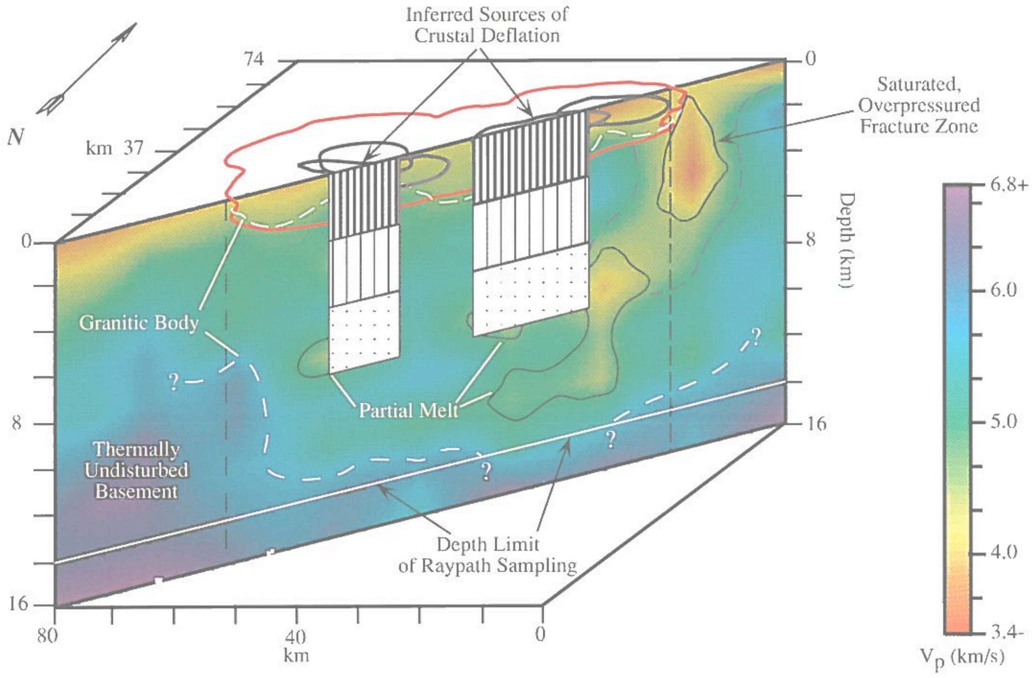
University of Utah

An integrated seismic-GPS approach was employed to investigate active tectonic processes associated with the Yellowstone volcanic system. Yellowstone lies within a major zone of intraplate lithospheric extension, i.e., the Intermountain Seismic Belt, and has experienced the largest historic earthquake of the Rocky Mountains, the 1959 Hebgen Lake, Montana, Ms = 7.5 earthquake. Within Yellowstone's youthful, 70 km x 45 km, 0.6 Ma caldera, seismicity is characterized by extensive earthquake swarms and a notable shallowing of hypocenters from ~ 15 km outside the caldera to ~ 5km beneath the caldera indicating the influence of an intense crustal heat source. The caldera is also the focus of unprecedented deformation marked by uplift as large as 1 m from 1923 to 1984 followed by a rapid reversal to subsidence which began in ~1985. Bi-annual GPS surveys from 1987 to 1993 reveal up to 21 mm of horizontal caldera contraction and 70 mm of caldera-wide subsidence. The crustal velocity structure and relocated hypocenters of Yellowstone were studied by tomographic inversion of P-wave data acquired by the Yellowstone seismic network, the 1978 and 1980 Yellowstone-Snake River Plain seismic refraction experiments, and augmented by a special study using up to 6 IRIS-PASSCAL Ref Tek dataloggers with Guralp CMG-ESP broadband seismometers for three 6 month winter periods to acquire S-wave data . Data from 7942 local earthquakes and 16 controlled shots (recorded on multiple caldera crossing profiles in the active experiments) were recorded at a total of 254 stations. Our results revealed a 15 % P-wave decrease to depths of 14 km beneath the caldera and an additional 15% reduction beneath Yellowstone's two resurgent domes (Figure 1).

S-wave data from 512 earthquakes were analyzed independently and reveal a 20% S-wave velocity reduction beneath the caldera to depths of 14 km and an additional 30% reduction for the NE caldera. Relocated hypocenters show linear NW trends within the caldera parallel to NW alignments of young volcanic vents. Stress field inversion of earthquake focal mechanisms shows a dominant N-NE direction of regional extension consistent with the strain field implied by the GPS measurements, relocated epicenters, and geologic stress indicators. Models of the GPS derived deformation are consistent with a NE-elongate, sill-like magmatic-hydrothermal fluid body, at 3-6 km depth beneath the caldera. This body occupies a volume similar to the anomalous P- and S-wave anomalies suggesting that these methods image the same source. The data clearly complement each other—the relocated earthquakes provide information on seismotectonic structures while the velocity and elastic strain models provide information on the geometry and composition of anomalous crustal magmatic bodies. Our results suggest that high quality three-component active and passive seismic data can be integrated readily with ancillary information on long term strain such as acquired with GPS observations. This provides a valuable integrative tool to elucidate active tectonic processes.



Interpretive SW-NE geologic cross-section parallel to the axis of the Yellowstone caldera. The Interpretation of peripheral high velocities in poorly resolved parts of the model as thermally undisturbed basement rocks is based in part on the results of previous seismic studies of Yellowstone. Inferred sources of crustal deformation are from Meertens et al. [1992, 1994]; density of fill indicates relative importance of deformation cell.

Mantle Anisotropy: the Crucial Role of Portable Broadband Deployments

P.G. Silver
Carnegie Inst. of Washington
R. M. Russo
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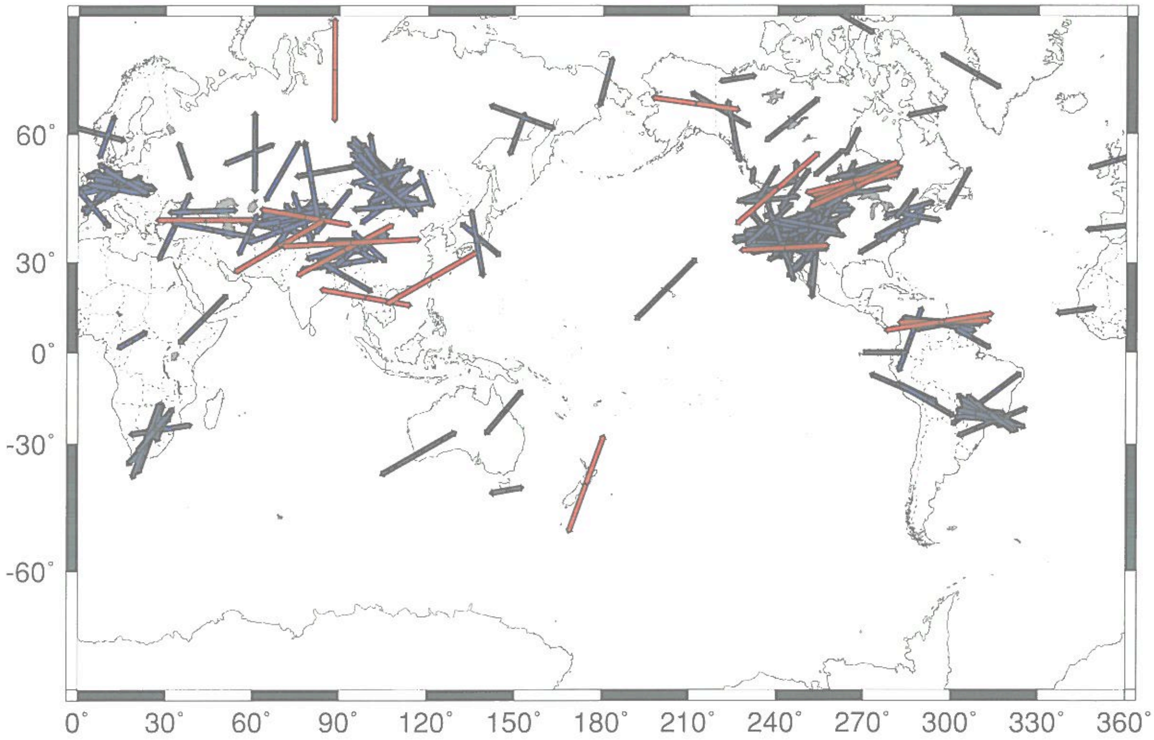
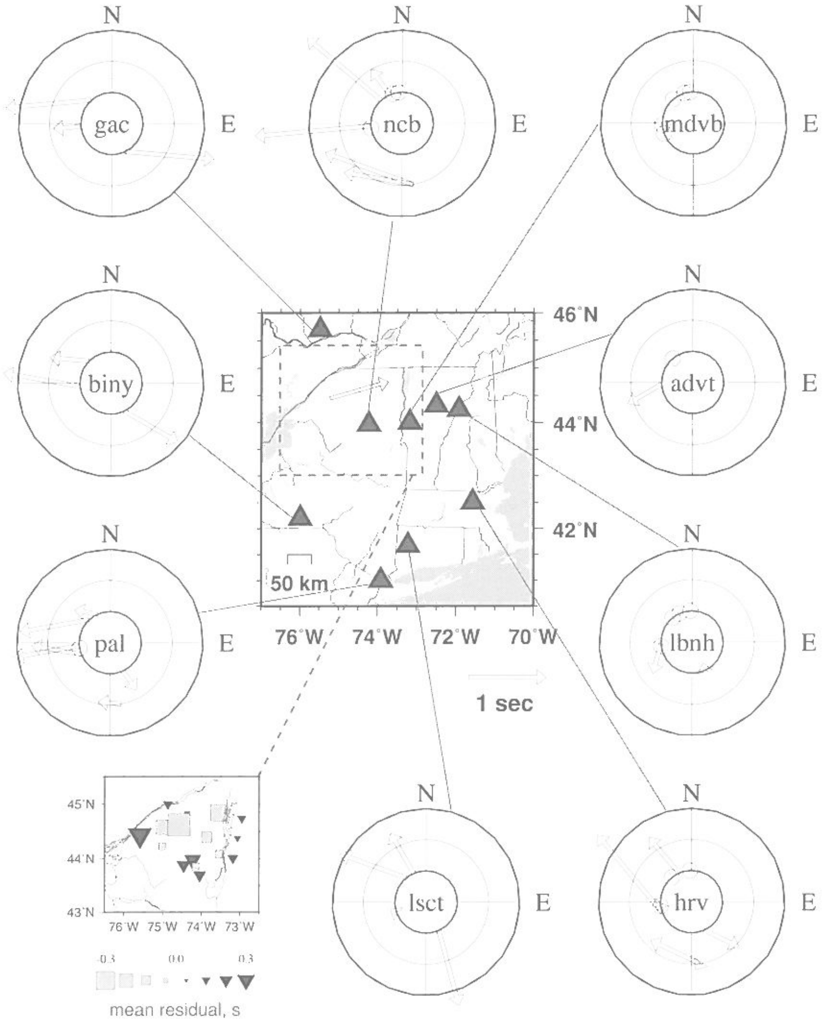


The study of mantle anisotropy can address questions of the mantle's contribution to continental geology, and the convective flow regime associated with plate tectonics. Mantle anisotropy beneath the continents is best revealed by shear-wave splitting. The fast polarization direction ϕ and delay time δt can be used to constrain orientation and spatial extent of deformed regions. The recent proliferation of portable, broadband experiments, particularly those associated with the PASSCAL program, are crucial in understanding anisotropy in the subcontinental mantle, since it allows sampling of the mantle on intermediate spatial scales appropriate for examining geological variations. A survey of all the available splitting data for the continents, both from permanent stations and portable deployments, reveals the following: the very largest delay times, those above 1.5s, are in two geologically distinct groups. The larger group is associated with zones of current large-scale transpressional deformation such as the Alpine-Himalayan chain (including the Caucasus, Tien Shan, Tibetan Plateau), the Alaskan Cordillera, and northern Venezuela. The second group comprise shields and platforms (Canadian Shield, Siberian Platform) that have been subjected to intense deformation in the Precambrian. For both groups, the fast polarization direction is parallel to transpressional features as would be expected if the mantle deformed coherently with the surface. We draw two fundamental conclusions from these results: 1) geology can be deep, penetrating some 200 km into the mantle; and 2) this mantle geology is often preserved in the form of fossil anisotropy. Another area that can be explored is the mantle flow associated with plate tectonics. Indeed, a variety of surface wave studies in the ocean basins over the last 20 years have obtained results consistent with simple shear occurring in the oceanic asthenosphere, with the shear orientation being controlled by the absolute motion of the surface plates. Recent shear-wave splitting results from both portable and permanent deployments, however, suggest that this simple picture breaks down near subduction zones. The data reveal a more complicated three-dimensional sub-slab flow field. Beneath the Nazca plate, this flow field appears to be predominantly trench-parallel. A survey of other subduction zones suggests that trench parallel flow is probably not limited to this particular region, but may be a general feature of Pacific-rim subduction.

Seismic Anisotropy in Northeastern US

Vadim Levin, William Menke and Arthur Lerner-Lam
Columbia University



Short -term deployments of broadband seismometers allow us to address, in detail, of the structure of the earth's mantle. Our work in the Northeastern US illustrates the advantage of such an approach. From our previous work (Levin et al., GRL, 1995) we knew that a large gradient in teleseismic P wave delays occurred across the Champlain Valley, near a mid-Paleozoic suture. Existing data were insufficient to address the cause of this gradient, but by deploying two broadband stations (MDVB and ADVT) to fill in the gap in the permanent array, we were able to show that the effect is due to lateral heterogeneities in mantle anisotropy.

Presented on the figure is a summary of our seismic anisotropy measurements. Shear wave splitting measurements are plotted as arrows on polar diagrams, one diagram per station. The position of the arrow's tail indicates the back azimuth to the earthquake, the arrow's direction indicates the direction of the fast axis, and arrow's size corresponds to the splitting time between the components. Observations of SKS without a clear transverse component are designated null measurements and are plotted as circles.

Symbols on the inner circle of the diagram represent observations of SKS and other core phases, and on the outer circle represent observations of direct S phases. The arrow on the basemap shows the Silver and Chan (JGR, 1991) estimate of the anisotropy at RSNY (fast direction 74°, splitting time 0.9s). An inset shows mean teleseismic P delays from a study by Levin, Lerner-Lam and Menke (GRL, 1995).

Our observations show that seismic anisotropy is present throughout the Northeastern US, and that anisotropic parameters vary from site to site and, at some sites, azimuthally. They may be used to define three anisotropic domains in the region. Large (>1s) values of S splitting time and a westerly (260° - 280°) fast direction define one domain, while similarly large splitting times and the north-western (300° - 320°) fast direction define another. The third domain may be described as having no anisotropy in the mantle, as splitting values observed on both ADVT and LBNH are small enough to be accounted for by features within the crust. The first domain corresponds to cratonic North America. The second domain corresponds to the accreted Appalachian terranes, and the third may represent a suture zone between the first and the second.

RISC Experiment : The Basin and Range-Salton Trough Transition from Deep Crustal Seismic Reflection Data

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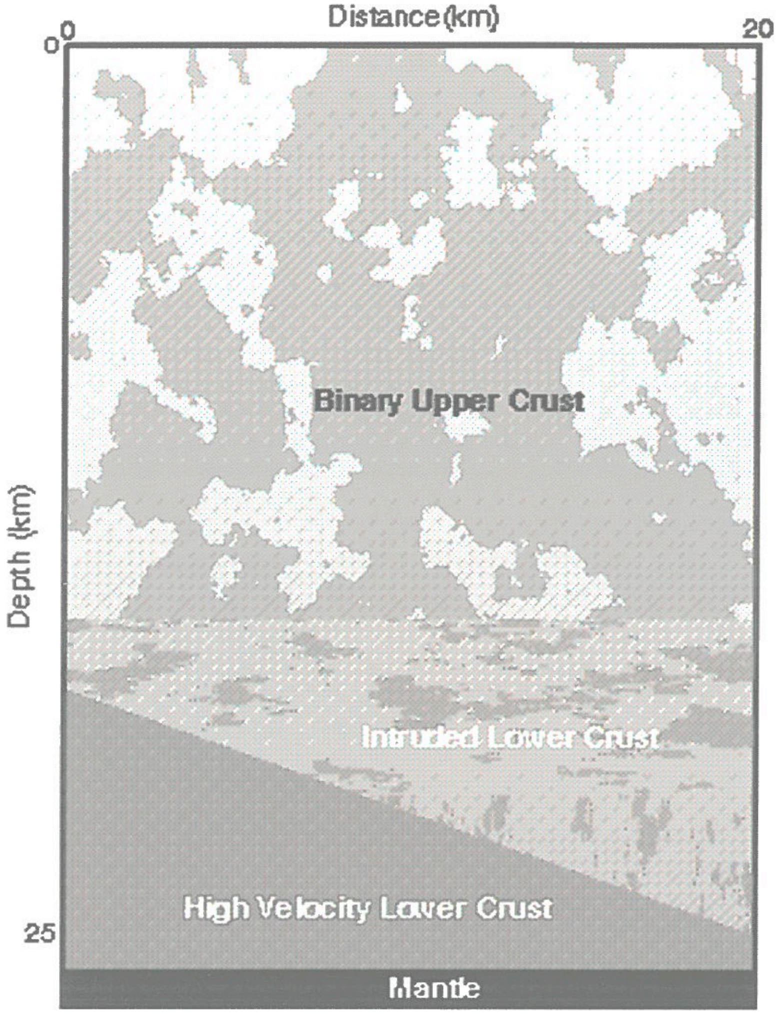
David Okaya
University of Southern California

We conducted a crustal imaging/ scattering experiment in the complex Salton Trough/Basin and Range transition zone in southeastern CA. We acquired an extensive three-component deep crustal seismic reflection profile across the Chocolate Mountains using 27 explosive shots recorded at 870 receiver locations spaced 50m apart. More than 25% of the instruments deployed were PASSCAL REFTEKS, the rest were industrial offsets ranging instruments. The resulting 45 km long profile had offsets ranging from 0 km to greater than 180 km. The dense receiver array yielded a low-fold CMP stacked image, which, when combined with wide-angle traveltime modeling, produced a detailed structural image of the crust and upper mantle. This image shows the northeastern lateral extent of high velocity mafic lower crust centered beneath the Salton Trough. The first-order velocity structure was determined from conventional refraction traveltime analysis. The fine-scale structure, inferred from reflectivity patterns, can be matched with a stochastic velocity model superimposed on the deterministic structure. Figure 1 displays the combined deterministic/stochastic velocity model. This complex model reproduces the observed full wavefield reflection/wide-angle response. The deterministic components are the mean crustal velocity and velocity gradient, and the high velocity mafic lower crustal layer. Two different stochastic models can account for crustal scattering: 1) the effect of weak upper crustal scattering is included by developing a stochastic model from mapped surface geology and laboratory measurements of exposed rocks within the Chocolate Mountains. The model consists of a binary velocity pdf and an isotropic self-affine spatial fabric; 2) moderate amplitude reflections from mid-crustal levels display the offset dependent coherency and frequency characteristics produced by a highly heterogeneous, velocity field. We model the middle and lower crust as horizontal and vertical mafic intrusions with a binary velocity pdf and an anisotropic self-affine fabric. Visco-elastic finite-difference simulations from models of this type indicate that as little as 5% mafic rocks intruded into the more felsic background are sufficient to produce the observed reflectivity.



Tectonic and Magmatic Processes Active in the Western U.S.

Gene Humphreys
University of Oregon
Ken Dueker
University of Colorado

This figure is a composite of recently produced seismic images of the structure beneath North America. Relationships on many scales are recognized between the upper mantle structure and patterns of present and past magmatic and tectonic activity. Several examples are discussed below that are attributed to the region's current setting, its pre-existing structure,and to a dynamic self organization within the asthenosphere. Such information provides important clues to the processes of continental deformation and differentiation:on asthenospheric convection and the resulting active supply of melt, heat, and buoyancy; on compositional segregation of continental lithosphere;on modifications to potential energy and lithospheric strength, and their relations to "plate" and locally created forces;and on how these tectonic and magmatic processes interact. Seismic imaging resolves structural information within the upper several hundred kilometers of the Earth. By using scaling relations to aid in understanding the physical state of the upper mantle, and including observations of isostasy, tectonism, magmatism, and geologic history, hypotheses of the processes underlying continental activity may be proposed.

At the longest wavelengths considered here, the 100 km depth shown in Figure 1 includes cratonic "tectosphere" east of the Great Plains, and asthenosphere beneath the elevated western U.S. This basic structure is attributed to Laramide orogenic penetration into and disruption of a Precambrian lithosphere by a flat-subducting slab, which presumably thinned the lithosphere that presently is elevated. Slab removal at the end of the Laramide and the consequent influx of east Pacific asthenosphere to shallow depths beneath the western U.S. is associated with profound magmatism, extension, and a maintenance of high elevations. This post-Laramide activity, then, appears to have resulted from processes originating beneath the lithosphere. The tectonic and magmatic activity that was vigorous in the mid-Tertiary currently is waning, though elevations remain high. This small-scale structures of seismic magnitude as great as that found on the continental scale. It seems apparent that the asthenosphere over this broad region has indeed been very active since the Laramide.

At a regional scale, structures are organized into two geographic domains: a marginal domain, about as wide as California, where high-velocity structures

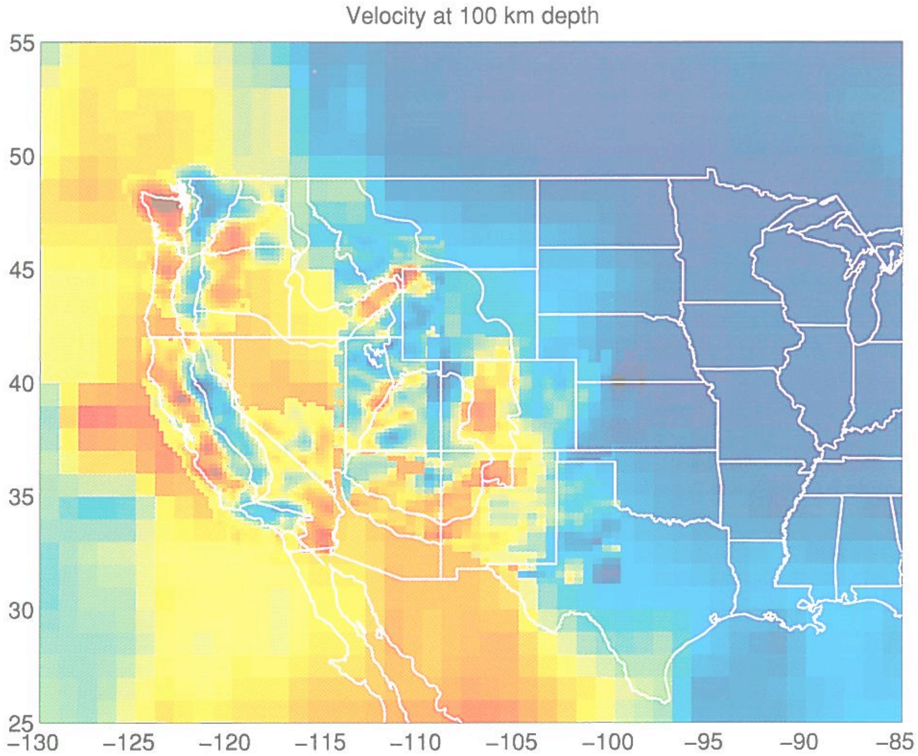


Figure 1. Composite image of upper mantle seismic structure at 100 km depth beneath North America region. Blue is high velocity mantle and red is low velocity mantle. The image is from the multi-bounce S-wave modeling of Grand (1994). With block size interpolated from 120 by 120 km to 60 by 60 km. Resolution of this image is variable, but is approximately 300 km. Overprinting Grand's image are regional array inversions from five separate inversions in the western U.S.: the Washington-Oregon, California-southern Nevada, and Idaho-Utah-western Wyoming P-wave images of Humphreys and Dueker (1994), the northern Arizona-New Mexico P-wave image of Slack et al. and Colorado S-wave image of Lee and Grand. Several problems were addressed to superimpose these images: P and S images are of differing amplitudes; (neither are well constrained) and the average velocity of each regional image is essentially unknown. To handle these problems, we rescale the inversions and shift each image into concordance with Grand's image. More specifically, the range of each regional images and the Grand image has been normalized. Because most of the western U.S. upper mantle is slow, most of the regional images have been made slower with the California-Oregon-Washington region being slowed down the most, and the Colorado inversion left unshifted. Actual total range in resolved P-wave velocity is about 8%. Using standard scaling relations, red regions are partially molten and blue regions are subsolidus.

are elongate and correspond to tectonic patterns; and an interior domain, where low-velocity structures are NE-elongate and correspond to patterns of young magmatism. A separation of western U.S. deformation into toroidal and poloidal fields defines the same two domains. Because poloidal and toroidal deformation originate from fundamentally different tectonic processes, correspondence between tectonic style and asthenospheric character suggests a fundamental interaction between the lithosphere and asthenosphere. Pacific-North America transform accommodation occurs across a broad continental shear zone (that has been, and in the Pacific Northwest continues to be, an oblique convergent margin). In contrast, the broad interior region, including the Basin and Range and most of Rocky Mountains, is dilating by moving away from stable North America in a direction that is nearly normal to Pacific-North America relative motion. The toroidal deformation of the marginal domain is indicative of forces created remotely and guided to western North America through the plates, whereas the elevated interior, deforming poloidally, signifies locally created forces. Thus, we conclude that the general conditions for tectonic and magmatic activity resulted from early Cenozoic thinning of the lithosphere, and the regionalized organization of upper mantle structure results from ongoing plate interaction near the continental margin and local, non-plate tectonic processes beneath the interior..

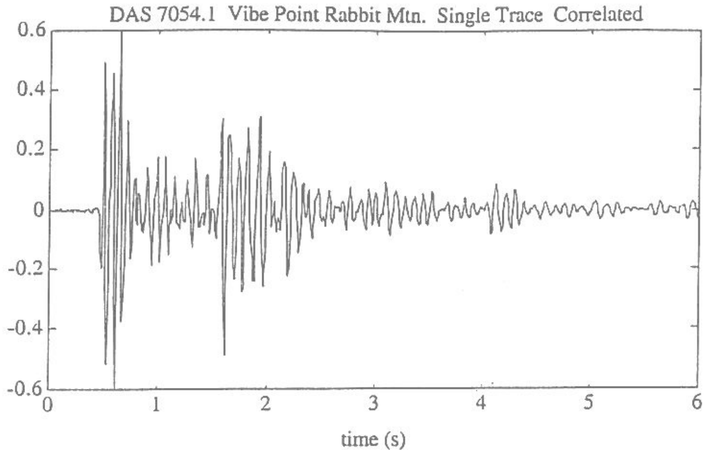
Local magmatic and tectonic activity correlates with individual upper mantle features. Transform accommodation shows the influence of both strength variations and the action of locally-created forces. Shear in central California, being concentrated on the San Andreas fault and eastern California shear zone (near the California-Nevada border), avoids the high-velocity (and presumably higher strength) upper mantle of the Sierra Nevada. In southern California, the high-velocity Transverse Ranges anomaly is interpreted as descending lithosphere whose flow maintains convergence in the Transverse Ranges and the "big bend" orientation of the the San Andreas fault. High-velocity structure beneath the Cascades is attributed to the sinking Juan de Fuca slab. Beneath the broad continental interior, low-velocity structures correspond with the Jemez, St. George and Yellowstone magmatic lineations. The association of magmatism with zones of inferred asthenospheric partial melt indicates convective activity driven by melt buoyancy. The tendency for NE alignment suggests an orientation control provided by absolute plate motion, such as asthenospheric simple shear. And the 300-400 km wavelength indicates an asthenospheric thickness of roughly 150-200 km.

In summary, we conclude that the structures imaged at 100 km depth beneath the western U.S. map patterns of small-scaleconvection (and subduction of the Juan de Fuca plate) occurring beneath the thin lithosphere of the western U.S. In the cases of Juan de Fuca subduction and lithospheric descent beneath the Transverse Ranges, the sinking of thermal boundary layer is consistent with standard notions of convection. Melt buoyancy within the asthenosphere drives convection beneath the magmatic trends of the western U.S. interior. Melt segregation differentiates the continent through crustal growth and mantle depletion. Depletion of the upper mantle creates a relatively buoyant and viscous (and therefore stable) chemical boundary layer. The organization of convective patterns into regional domains represents processes that influence orientation: plate interaction near the margin and plate motion over the deeper mantle for the continental interior.

The Jemez Tomography Experiment (JTEX): Active Source Seismic Program

Lawrence W. Braile
Purdue University

The Jemez Tomography Experiment (JTEX) is an interdisciplinary and multi-institutional program to study Earth structure and the geological evolution of the Jemez volcanic system, New Mexico. The seismic study consists of both active and passive programs and is dependent on the availability of large numbers of modern digital IRIS/PASSCAL seismographs. In the Fall of 1993, the first phase of the active source experiment was undertaken in the Jemez Mountains. These mountains sit astride the western boundary of the Rio Grande rift and represent a major volcanic edifice, the Jemez Mountains volcanic field, which contains the Valles Caldera whose most recent major eruption was at 1.1 Ma. This complex, but primarily silicic, volcanic field, has produced approximately 2000 km^3 of exposed volcanic rocks. The modification of the crust due to this igneous activity and the evolution of the field through time are questions which the JTEX project is addressing through the integration of a variety of geophysical and geological data, including both active and passive seismic observations. The first phase of the active source seismic study consisted of recording a NNW-trending, refraction and wide-angle reflection profile centered on the Valles Caldera. Over 300 vertical- and three-component instruments were deployed along the 180 km long profile. Four explosive sources (1000 to 2000 kg) were fired and Vibroseis (three trucks, 5-30 Hz, 30s sweeps) were employed as sources at three locations. An example of 3-component seismograms (showing strong P- and S-wave arrivals) recorded from the vibroseis sources (after summation and cross-correlation with the pilot sweep) is illustrated. Additional seismic recording will be performed in September and October, 1995 utilizing 250 3-component IRIS/PASSCAL instruments, 180 vertical component SGR seismographs (IRIS/USGS/Stanford facility) and 16 sources providing linear profiling (along approximately E-W and SW-NE lines) and 2-D coverage to allow 3-D velocity models of the caldera and sub-caldera crust to be derived.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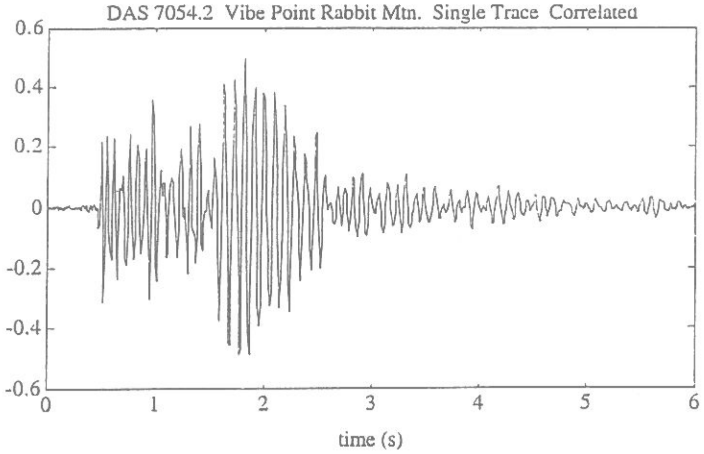
Time scale is origin time minus approximately 0.8 s.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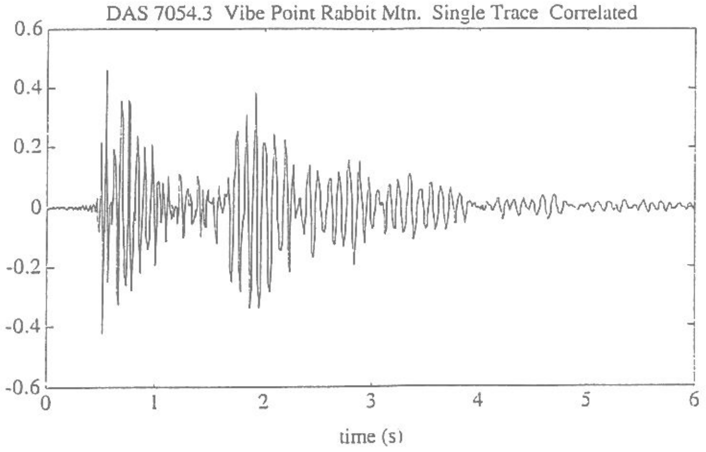
DAS 7054.3 Vibe Point Rabbit Mtn. Single Trace Correlated

Colorado Plateau - Great Basin PASSCAL Seismic Deployment 1994-1995

Anne Sheehan, Craig Jones, Ken Dueker
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Martha Savage, Serdar Ozalaybey
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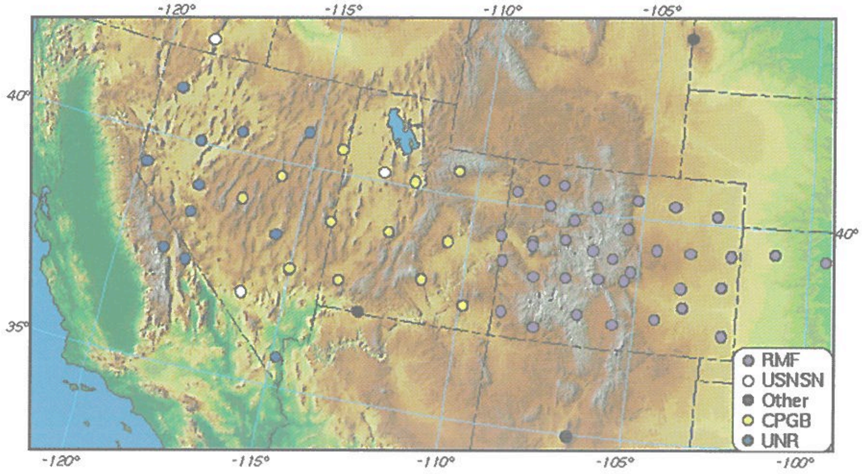
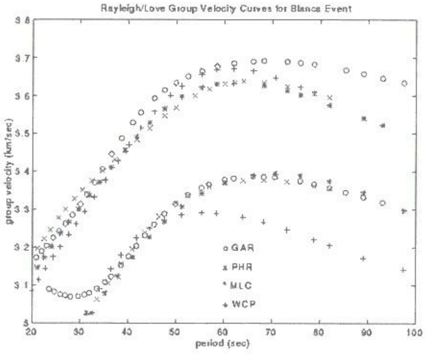
The Colorado Plateau - Great Basin (CPGB) PASSCAL experiment is a nine month deployment of twelve portable broadband seismographs throughout the Colorado Plateau and eastern Basin and Range area of Nevada and Utah. The instruments were installed in November of 1994 and will remain in place through July 1995. These data are supplemented by existing National Network stations in the region and other cooperating regional stations in order to give a total of seventeen broadband sensors and ten short period stations. The average spacing between the broadband stations is approximately 150 kilometers. This deployment of portable seismometers fills in a 150,000 square kilometer gap in broadband station coverage between the 1992 Rocky Mountain Front portable array to the east, and the University of Nevada permanent broadband network to the west. The planned work will build on knowledge gained from analysis of data from the Rocky Mountain Front PASSCAL deployment and the University of Nevada permanent broadband network in the regions immediately to the east and west borders of our experiment. Instrumentation for this deployment consists of 11 Guralp CMG3-ESP broadband seismometers from the PASSCAL equipment pool supplemented by one CMG4 intermediate period seismometer from the University of Nevada, Reno. Data are recorded on a single continuous data stream at 25 sps, with compression. Recording is on Reftek 24 bit data loggers with 550 mb external disks, and data pickups are at 40-70 day intervals. Our data recovery rate over the winter months, despite adverse weather, was greater than 85%.



Station geometry for CPGB experiment

The main goals of the deployment are to image the structure of the crust and upper mantle in the Colorado Plateau and eastern Basin and Range primarily through the use of body wave converted phases and shear-wave splitting of teleseismic body waves. The crust and upper mantle structure results will be combined with gravity and topography data in order to investigate the dynamics and buoyancy of the region. Our analysis of converted body wave phases will be extended to include not only the Moho but will also deeper discontinuities such as the 220, 440, and 660 km discontinuities. This data will be combined with existing data from the Rocky Mountain Front experiment and Nevada broadband array in order to provide a high resolution image of mantle discontinuity structure spanning the Basin and Range, Colorado Plateau, Rocky Mountains, and Great Plains physiographic provinces.

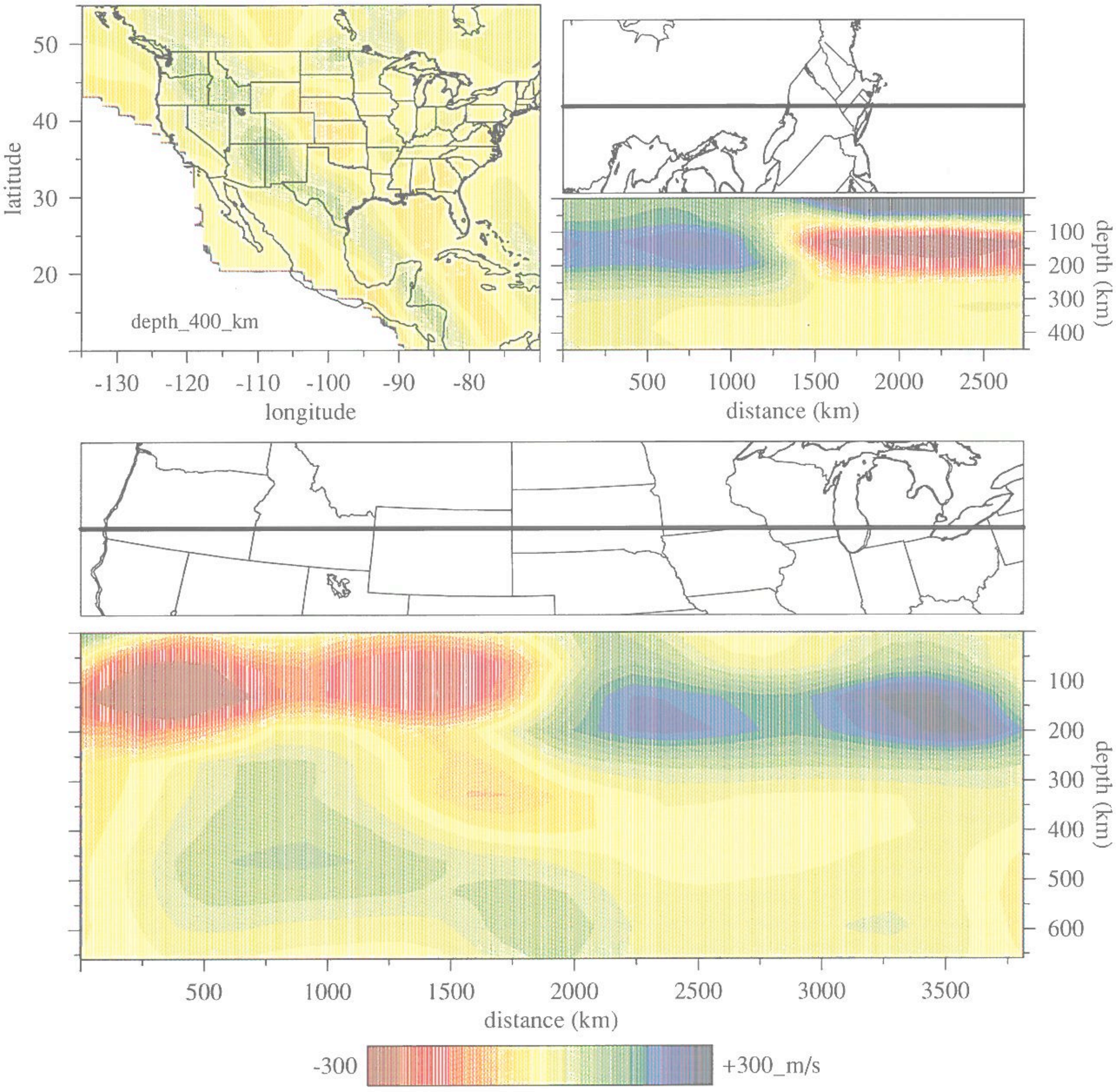
Resolution of the variations in the sharpness and depth of these discontinuities across a large continental transect as proposed here is fundamental to determining the thermal and chemical structure of the upper mantle and to understanding the nature of continental evolution. The experiment is well suited for surface wave analysis and will contribute to the existing data base of arrival times for P and S wave tomography. Although the deployment was designed with structure objectives in mind, data from the array are quite useful for regional source studies. In particular, the 2/3/95 southwest Wyoming event, suspected to be a mine collapse, was recorded on scale by all sensors, and includes the closest broadband recording available of this event. The analysis of data from this deployment in combination with data from complementary experiments will help answer some of the outstanding problems of the tectonics and evolution of the western United States, such as the nature of the mantle flow and extension, the mechanism of compensation for the observed elevation changes, and the nature of transitions between the various physiographic provinces.



Group velocity curves for both the Rayleigh waves (lower curves) and Love waves (upper curves) for 10/27/94 Ms 6.4 Blanca Transform event (offshore Oregon) as recorded on four stations of the CPGB deployment. The velocity is slow compared to global averages and a significant discrepancy between Love and Rayleigh wave exists. We intend to study whether this discrepancy is due to isotropic and/or anisotropic structure.

Images of the Upper Mantle Beneath North America

Suzan van der Lee and Guust Nolet
Princeton University



A powerful method to interpret broadband digital seismograms consists of fitting the higher- and fundamental mode wavetrain in a single seismogram to retrieve 1-D path-averaged models. The 3-D Earth is then constructed in a linear inversion such that it is consistent with the well resolved features of these 1-D models. We have applied Partitioned Waveform Inversion to invert for the upper mantle beneath North America. This figure shows a preliminary result. Top **left:** map view at a depth of 400 km. Striking is the roughly coast-parallel trend of high velocities, possibly related to the subducted Farallon plate, accompanied by low velocity zones east of this anomaly. Top **right:** cross section through the Canadian shield and the Atlantic. Apparently the high velocity root reaches to a depth of no more than 250 km. **Bottom:** cross section running west-east. Here the dip of the high velocity anomaly from the upper left is clearly visible, as well as the low velocity zone normal to the dipping high velocity layer, which seems to connect with low velocity anomalies under Yellowstone. The high velocity root of the stable shield is visible at depth in the eastern part of the cross section.

Inversion of Teleseismic Delay Times Across the South American Continent for Upper-Mantle Structure

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Carnegie Institution of Washington,
Susan Beck, Terry Wallace,
University of Arizona
Marcelo Assumpcao
Universidade de Sao Paulo

We have made a preliminary analysis of P-wave delay times recorded on portable and permanent broadband seismograph stations across South America. In Figure 1, the portable station sites are shown as open squares and permanent GTSN stations as filled squares. The portable data in Brazil were gathered from October 1992 to April 1995 as part of the Brazilian Lithosphere Seismic Project (BLSP). Data collection in Bolivia/Chile began in March 1994 and will continue through Fall 1995 (projects BANJO and SEDA). The P-wave delay times are obtained through a multi-channel cross correlation of band-passed waveforms for each teleseismic event. Inversion results beneath southeast Brazil indicate that a high velocity root of the 3.2 Ga Sao Francisco Craton extends to 200-300 km in depth and that a residual signature of the Tristan da Cunha plume head - which is thought to have produced the Parana flood basalts at 130 Ma - remains in the upper mantle beneath the region. Continuing westward through the sub-Andean, Eastern Cordillera, Altiplano and Western Cordillera provinces our preliminary results reveal the high velocity root of the Brazilian shield beneath eastern Brazil and Western Bolivia and the subducting Nazca plate beneath central Bolivia (Figure 2).

To complement the broadband data, we hope to soon bring together additional researchers from throughout South America to combine data from their regional short-period networks. This will help to further refine the region's upper-mantle structure as well as supply an improved velocity model for the more accurate location of hypocenters. This effort is being pursued through the Scientific Alliance for South America (SALSA) and the new SALSA data center in Santiago, Chile. For more information see: http://loki.ciw.edu/salsa.html

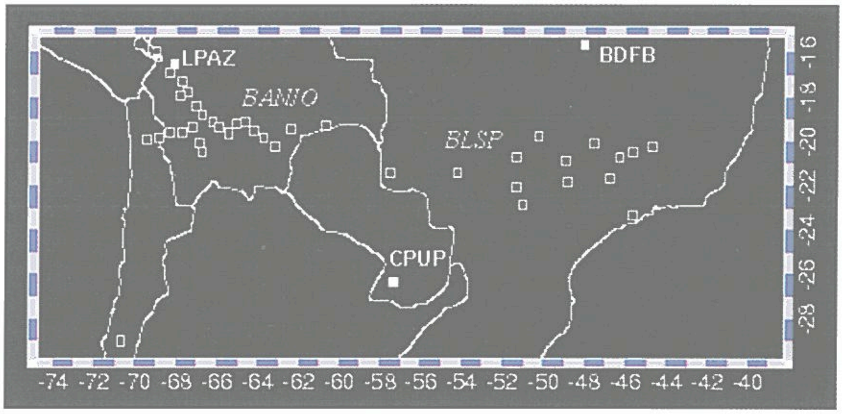

Figure 1

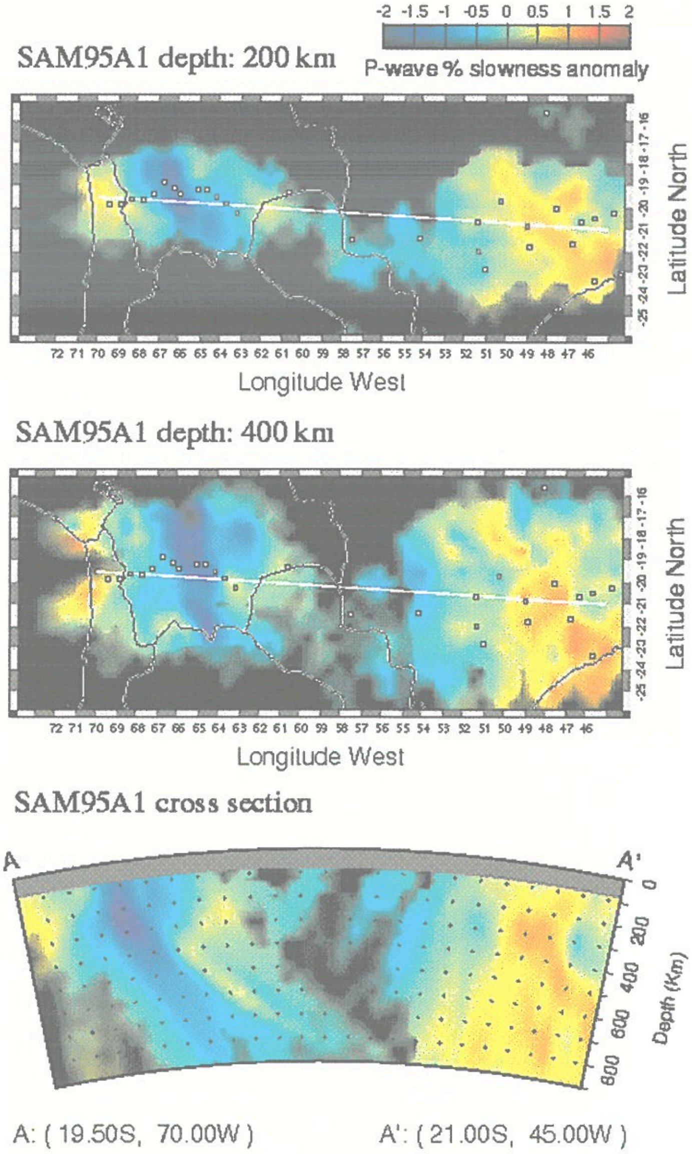

Figure 2

Results from the SECaSA92 Array

R. M. Russo, J. C. VanDecar, D. E. James
DTM, Carnegie Institution of Washington

With support from IRIS, we deployed a six seismometer broad-band array in the Caribbean-SouthAmerica plate boundary zone in northeastern Venezuela and Trinidad to studycrustal and upper mantle structure and deformation. The six stations operated at seven sites (six in Venezuela, one in Trinidad) for various intervals between May 1992 and November 1993. We recorded 4209 seismograms at the array, many of them high quality, of 1367 teleseismic and regional earthquakes during this period; we also recorded 1623 local earthquakes, many of them previously undetected. The goals of our research were to test two widely contradictory models of the southern termination of the Lesser Antilles subduction zone, and to establish constraints on the tectonic history of the eastern Caribbean-South America plate boundary zone. The regional crustal and lithospheric structure has important implications for the tectonic history and current displacement regime in the plate boundary zone: different histories and displacements may result in radically different crustal and lithospheric architecture. In the classic hinge faulting model of the southern Lesser Antilles, the subduction zone is presumed to terminate at a lithospheric scale tear fault along which the subducting slab is torn from buoyant South American continental lithosphere. The more recent tectonic wedging model of subduction termination involves overriding of the Lesser Antilles subducting slab (to which it was once attached) by the midcrust of continental South America. In this model, the subducting slab does not terminate at the Caribbean-South America plate boundary, but, detached, continues far to the southwest below the continent. The two models imply significantly different tectonic histories and displacement regimes for the plate boundary zone. Thus, the predicted structure of the crust and upper mantle will differ in several crucial aspects which we tested seismologically. We find that travel time inversion of P and S waves recorded at the array show clearly that the Lesser Antilles slab indeed is present beneath continental South America. Thus the tectonic wedging model is validated in its large-scale predictions. Work continues to examine shallow (crustal) structure to determine how shallow architecture might fit in to scenarios for the development of the Caribbean-South American plate. In Figure 1 we show the P-wave (left) and S-wave (right) velocity structure beneath NE Venezuela at 100, 200, and 300 km depth (top three images) and the cross section shown by white lines on the depth sections. In Figure 2 one can see the P-wave velocity field with all material greater than 1% fast enclosed by the light blue volumes. The earthquakes are represented as green spheres from 80 to 100 km depth and as red spheres from 60 to 80 km. The top of the region shown is at 100 km depth and the bottom 500 km. boundary zone.

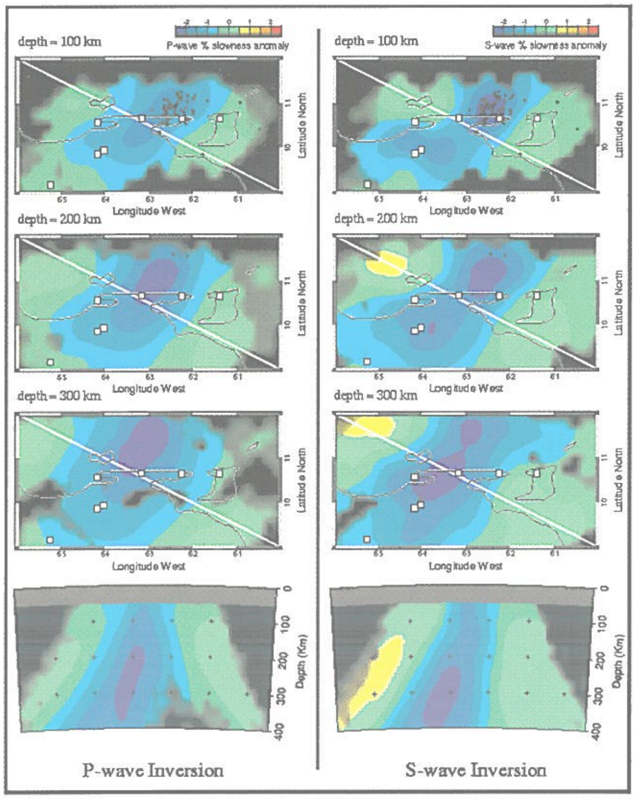

Figure 1

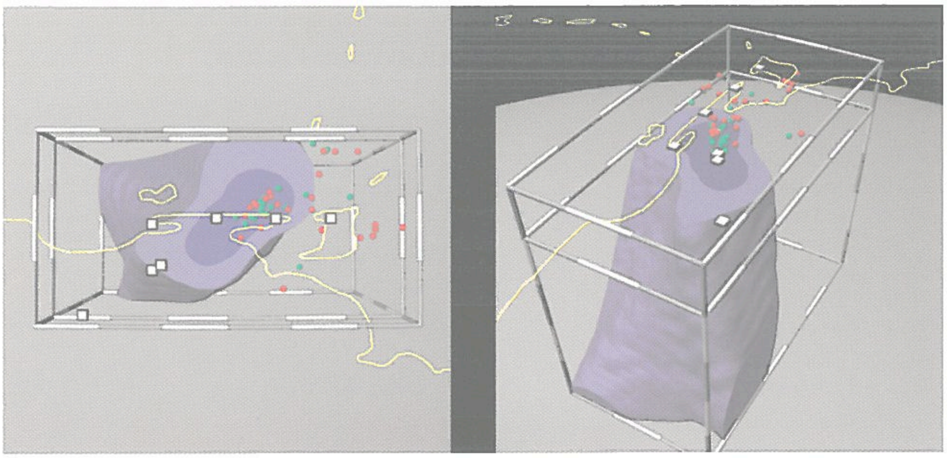

Figure 2

Exploring Tibet with Broadband Portable Seismometers

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University of South Carolina
F.T. Wu
SUNY Binghamton

The 1991-92 Tibetan Plateau Broadband Seismic Experiment has produced the most extensive set of seismograms ever recorded in this unique region. The deployment, a cooperative effort between the University of South Carolina, SUNY-Binghamton, and the Institute of Geophysics, State Seismological Bureau, People's Republic of China, consisted of 11 broadband PASSCAL stations spanning the east-central plateau with and average station spacing of 150km. It operated for 1 year and produced an extensive data set that is now available through the IRIS DMC. Analysis of data from this experiment has significantly improved our resolution and understanding of the lateral variations in the lithospheric structure of the plateau. Major studies have included:

Shear-wave Splitting Analysis demonstrating major differences in seismic velocity anisotropy between the northern and southern plateau. Increased thickness or magnitude of anisotropic parameters in the northern plateau argue strongly for a correlation between deformation at depth in the lithosphere and/or asthenosphere that correlates with observed surface deformation patterns. Regional shear wave propagation characteristics confirm and expand a region of inefficient high-frequency shear wave propagation in the northern plateau. However, using broadband observations, it is possible to demonstrate significant frequency-dependence in the observed regional shear waves.

Analysis of Pn propagation demonstrates that Pn velocities are 4% lower in the northern plateau relative to the south and that the crustal thickness is up to 15km thinner in the north. A tomographic image produced by combining this experiment's data with ISC data is the highest resolution picture of Pn velocity measures yet within the plateau.

Differential attenuation measurements of teleseismic P and S-waves shows a region on increased attenuation in the northern plateau that is coincident with the anomalous shear wave propagation zone, the anomalous SKS anisotropy zone, and the low Pn velocity zone.

Comparison of propagation characteristics of Lg waves for paths entirely within the plateau and paths crossing the plateau boundary has allowed the resolution of a long-standing question of how Lg is blocked by the Tibetan Plateau.

Analysis of source characteristics of moderate-sized earthquakes within the plateau has important implications for the utility of PASSCAL experiments in regional characterization for nuclear nonproliferation monitoring. These events also provide a basis for ongoing broadband regional waveform studies of the structure in this region. Taken as a whole, results from this experiment strongly support the existence of a region of elevated temperatures and possible partial melting in the uppermost mantle of the northern plateau. The constraints provided by the use of multiple methods should allow the production of maps of temperature and/or compositional variations across the plateau.

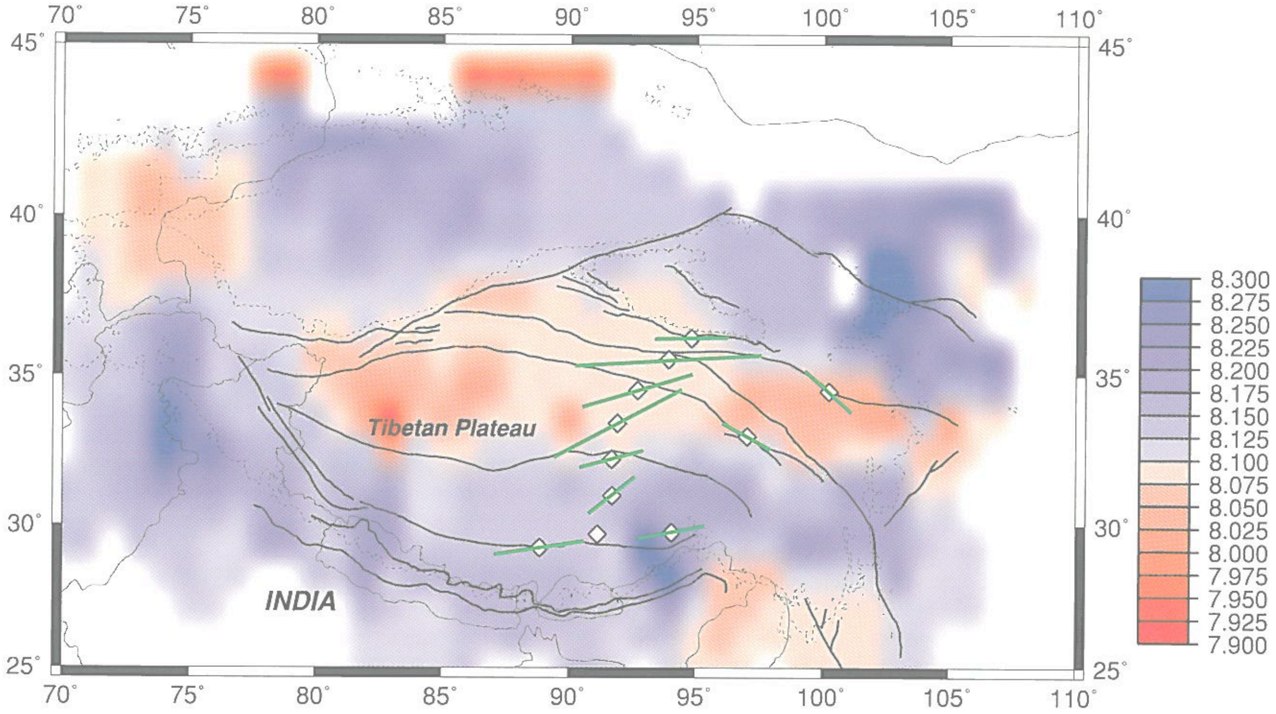

Figure: Summary results from the Tibetan Plateau Broadband Experiment. Color image shows Pn velocities from tomographic inversion of paths from both PASSCAL and ISC stations. White diamonds are the PASSCAL broadband sites. Green lines at each site show the orientation and magnitude of shear wave anisotropy beneath each site. For reference, the magnitude of the vector at the northernmost site is 0.9sec. Light dashed lines show the 4000m contour and solid black lines show large scale geologic features.

Surface Wave Tomography of Asia

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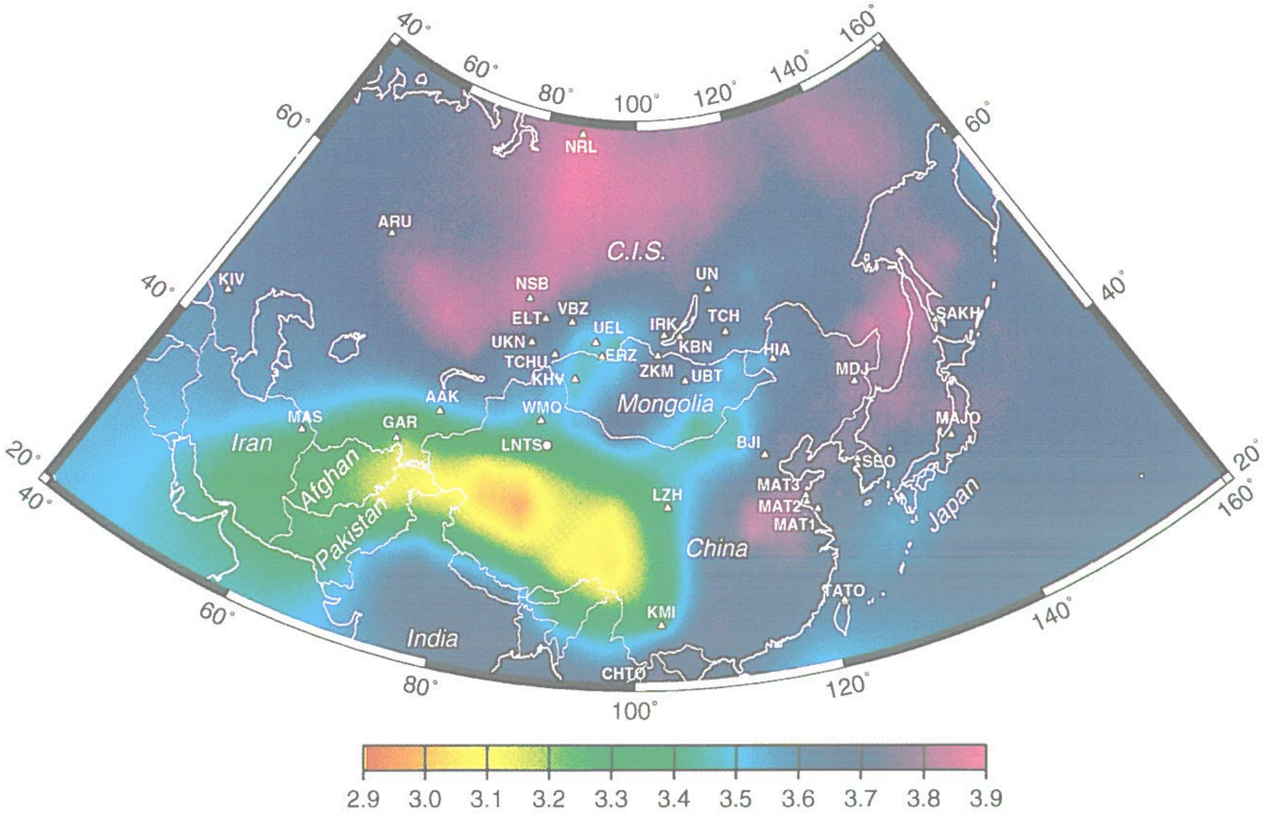
Anatoli Levshin
University of Colorado, Boulder.

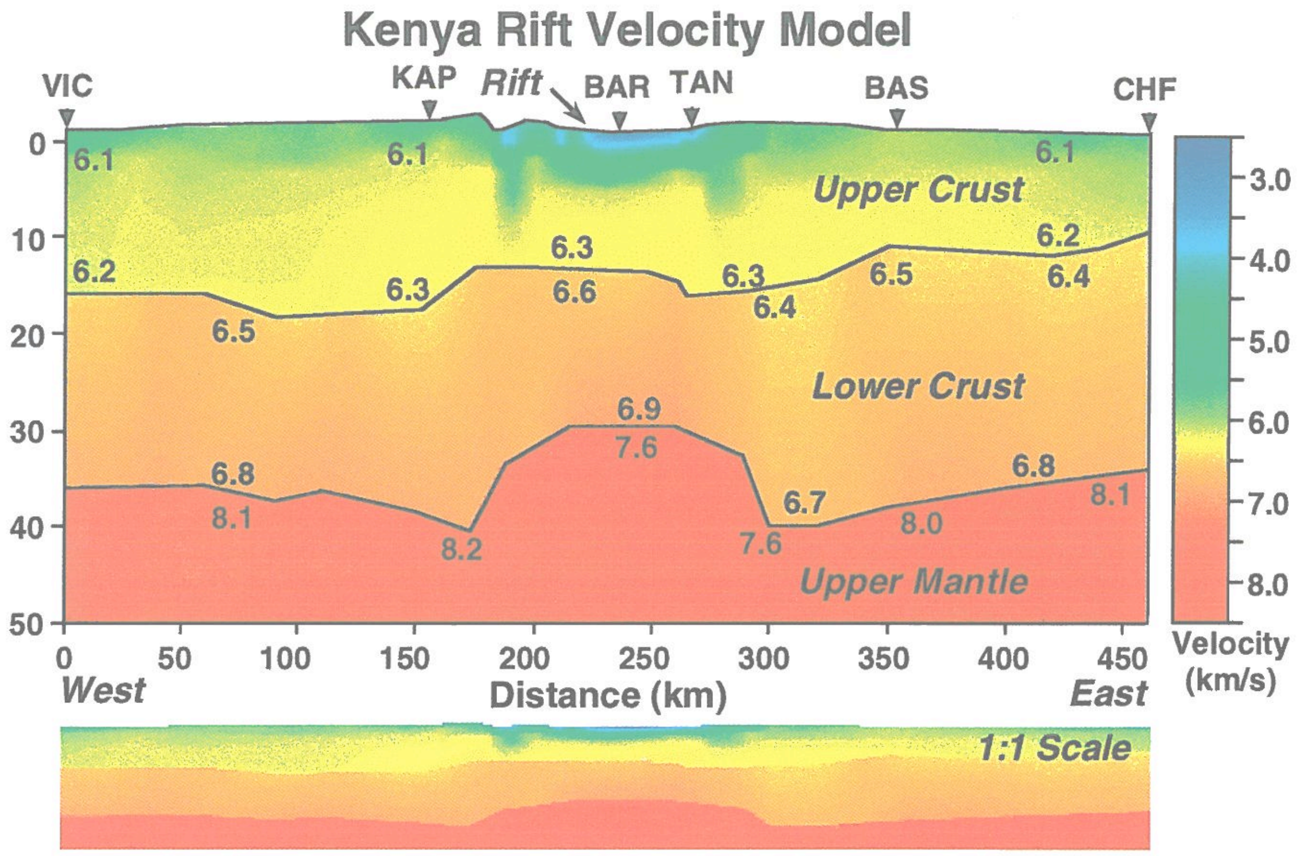


One of the seismologically unexplored area of the world is the great expanse of Eurasia. With data from the GSN/USGS/Chinese Digital Seismic Network in the IRIS DMS archive since 1987, from IRIS stations in Russia beginning in early 1990's, as well as the 1991-1992 IRIS/PASSCAL experiment in Tibet, we can now start to image the crust and upper mantle of this area in some detail. Surface waves are ideal for tomography with a global network because the path formed by a epicenter-station pair will traverse along a particular path and sample the section of the Earth down to the upper mantle. In Eurasia, with epicenters of moderate to large earthquakes populated around and within the area of interest, more than 1200 paths were available in early 1994 for our study. We chose to use Rayleigh wave group velocity first, because of the ease to get high path-density, and therefore better spatial resolution. This figure is a Rayleigh wave group velocity image of Eurasia (40°-160°E and 20°N - 70° N) at a period of 50 second. At this period, the lower crust and upper mantle characteristics affect the wave propagation the most. Although in case of Tibetan plateau, which appears as a very prominent low velocity feature in the image, the lower part of the thick crust and the low velocity uppermost mantle control this part of the dispersion curve. For the central part of this map, the resolution length of the image is about 300-1000 km, fine enough for us to compare this image to the large scale geological structures observed on the surface. With the addition of the 1991-1992 IRIS/PASSCAL data in our analysis, we were able to see some details within the plateau, reflecting most probably the changes in crustal thickness in response to the collision of India with Eurasia. The interior of Tibet is very difficult to access; tomography is a very effective tool for imaging the variations of crustal and mantle structures for the entire plateau. The first figure, we can also see the high velocity feature associated with the geologically ancient, and probably relatvely cold, Siberian platform in the north where the group velocities are high. One of the interesting features found by our tomography is the contination of the Lake Baikal rift southward across Mongolia. As seen in the figure, the Baikal high velocity ridge continues southward to the Chinese-Mogolian border. Although there is no surface rifting in this area, ample evidence of Late Cenozoic volcanism exists.

Modeling the 2-D Seismic Velocity Structure Across the Kenya Rift

Lawrence W. Braile
Purdue University

The Kenya Rift International Seismic Project (KRISP) included recording a seismic line across the Kenya Rift utilizing the 200 IRIS/ USGS/Stanford SGR digital seismographs. A 460-km-long seismic refraction/wide-angle reflection profile across the East African rift in Kenya has been interpreted using a travel-time inversion method to calculate a two-dimensional crustal and uppermost mantle seismic velocity model. The derived model is consistent with the crustal structure determined by independent interpretation of axial (along the rift) and flank (near the eastern end of the cross profile) data sets. The velocity model indicates that the Kenya rift at this location (near the Equator) is a relatively narrow (about 100 km wide) feature from surface expression (fault-bounded basins) to upper-mantle depths. A 5-km-deep, sediment- and volcanic-filled basin is present beneath the rift valley. Seismic velocities in the underlying crust are slightly higher directly beneath the rift valley than in the adjacent terranes. Additionally, the crust thins by about 8 km (to a thickness of about 30 km) in a 100-km-wide zone beneath the rift valley and anomalously low upper-mantle seismic velocity (Pn 7.6 km/s) is present only beneath the thinned crust and extends to depths of greater than 120 km.

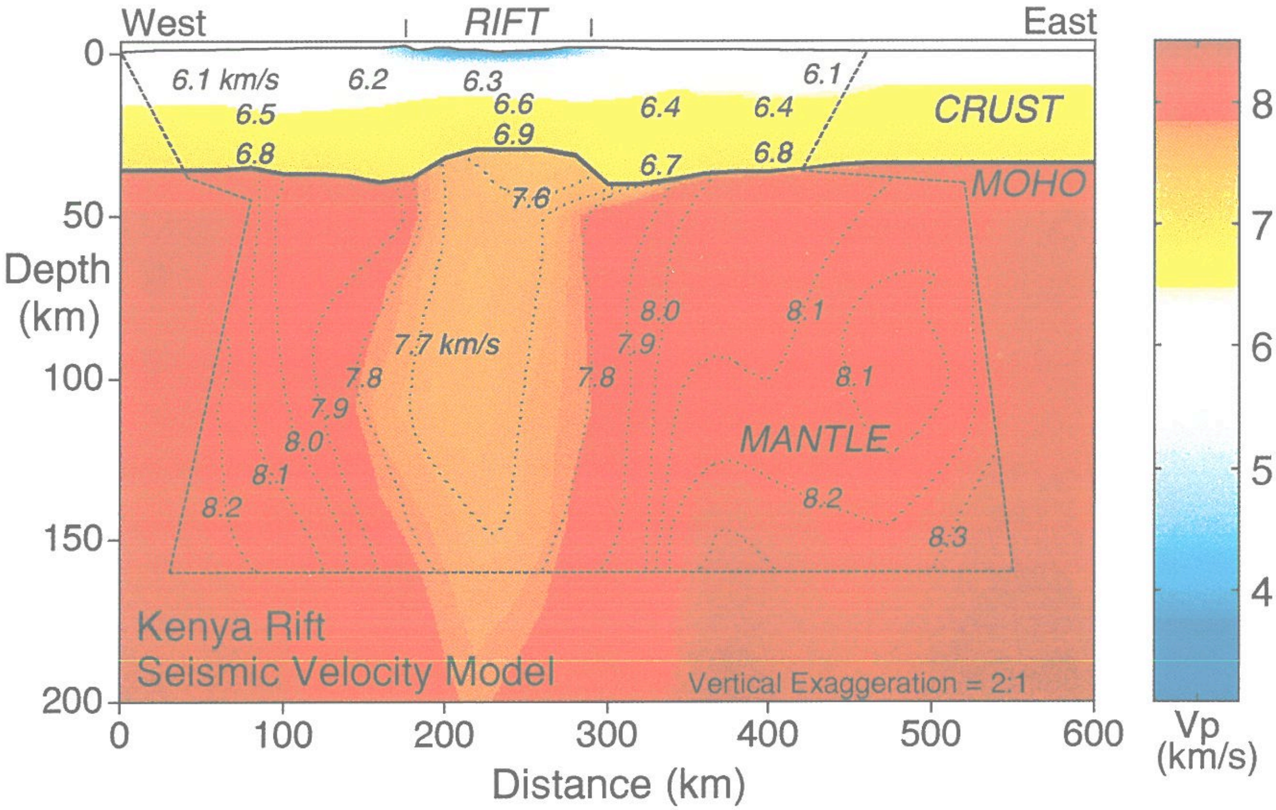


KRISP 90 velocity model derived by travel-time inversion (Braile et al., Tectonophysics 1994 KRISP Volume)

Kenya Rift Seismic Velocity Structure: Surface to 160 km Depth

Lawrence W. Braile
Purdue University

The Kenya Rift International Seismic Project (KRISP) conducted both passive (teleseismic) and active (explosion seismology) seismic studies of the East African Rift System in Kenya during 1990. KRISP 90 was a large, international and multi-institutional program. Seismograph recordings in linear and areal arrays using matched, digital seismographs (many provided by IRIS) were critical to the success of the study. The KRISP 90 refraction and teleseismic data provide an opportunity to examine the velocity structure of the Kenya rift from the surface to about 160 km depth. To simultaneously view the shallow (crustal) and deep (uppermost mantle) structure, we have combined the KRISP 90 cross line interpretation (Braile et al., 1994) for the upper 40 km depth range, with the teleseismic upper mantle velocity model (40 to 160 km depth range) of Slack et al. (1994). The crustal model consists of compressional wave velocity structure derived by travel-time modeling of refraction and wide-angle reflection arrivals from surface explosive sources along an approximately west-east profile. The crustal and mantle velocity values were gridded, smoothed and contoured to provide a consistent P-wave velocity model of the crust and uppermost mantle across the Kenya rift. The most striking features of the model are the relatively narrow (100-200 km) anomalous region and the vertical alignment of the rift valley (defined by topography and boundary faults, and the sedimentary and volcanic fill which extends to depths of greater than 5 km), the mantle upwarp (crustal thinning of about 10 km), and the underlying anomalously low velocity upper mantle. This alignment suggest that the rifting processes at the surface and within the crust (uplift, extensional faulting, graben formation, volcanism, igneous intrusion in the lower crust, and shallowing of the Moho) are the response to the hot (and therefore anomalously low-velocity) upper mantle beneath the rift. The interpreted crustal and uppermost mantle velocity structure also displays a high degree of symmetry. The crustal thinning across the rift is abrupt, and the narrow and steep-sided nature of the mantle anomaly provide evidence that it is young.

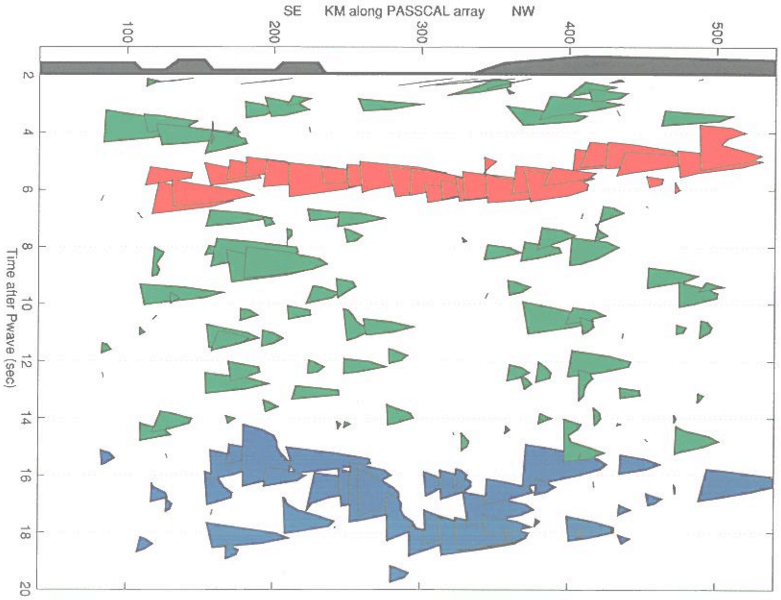


Imaging Large Crustal Thickness Variations Across the Yellowstone Volcanic Track

Ken Dueker and Anne Sheehan
University of Colorado at Boulder
Gene Humphreys
University of Oregon at Eugene

Fundamental to understanding the evolution of the Earth's continental lithosphere is accurate imaging of continental crustal structure. In the past, crustal structure was almost exclusively imaged with active source refraction and reflection profiling. With the advent of large pools of portable broadband recording - such as provided by PASSCAL - accurate imaging of crustal structure may now be done using natural earthquake sources. This figure shows results from a natural source crustal imaging technique called receiver function analysis.

The data shown are from the 1993 PASSCAL Snake River Plain experiment in which 52 portable stations were occupied over the course of seven months. The horizontal axis is the distance along our NW-SE trending line of sensors (our line is 250 km southwest of the Yellowstone Caldera). The vertical axis is the arrival time of converted P to S energy relative to the direct P-wave arrival. The generalized topography along our line is shown at the top in black. The crust at the southeastern end of the array is the unextended crust of Wyoming. At 110 km (on the horizontal axis), the Bear Lake fault manifests the eastern-most extent of crustal deformation associated with Basin and Range and/or Yellowstone Hotspot induced extension. From the Bear Lake fault to the SE edge of the Snake River Plain (220 km) is a sequence of fault blocks which have accommodated significant extension in the last 10 ma. In the middle of the array (from 220-330 km), lies the structural down warp associated with the Snake River Plain which has been in filled with a thick sequence of volcanic rocks associated with the passage of the Yellowstone Hotspot. To the northwest of the Snake River Plain are the uplifted and actively extending mountains of central Idaho.



In this figure, over 600 radial receiver functions have been processed and stacked with normal move out corrections to form an image of significant crustal velocity contrasts across the Snake River Plain. To accentuate the significant features of this record section, only upswings in the receiver functions are shown and any energy which fall below 30% of the maximum amplitude for each trace is not plotted. The arrivals shown in red shading between 4.5 and 6.2 seconds are almost certainly the direct P to S converted wave formed at the continental Moho. The second most significant arrival shown in purple shading arrives between 14.5 and 19 seconds and is consistent with being the first P to S converted wave reverberation. Surrounding these arrivals in green shading are less coherent arrivals due to near-surface and lithospheric "scattering".

The 1.7 sec variation in the timing of the direct Moho phase require \(~ 20% variations in the depth to Moho (Detailed P-wave travel-time inversion images a maximum 8% variations in the crust's average compressional velocity which could explain only 0.5 secs of the timing variation).The thickest crust resides beneath the unextended Wyoming crust and just northwest of the Snake River Plain. Previous to this experiment, it had been largely assumed that the thickest crust was directly below the Snake River Plain due to 6-8 km of magmatic addition associated with the passage of the Yellowstone Hotspot. The thinner crust is distributed symmetrically about the Snake River Plain about 50-70 km beyond the margins of the Snake River Plain with the surprising result that the thinnest crust resides beneath the highest elevations (Borah Peak at 420 km). Therefore, the source of support for these high elevations must derive from below the Moho. Another interesting results is the near absence of scattered energy generated beneath the Snake River Plain (i.e., absence of green arrivals). This "quiet region" correlates well with the anomalous 1-2 sec. delay in the reverberation timing beneath the NW half of the Snake River Plain (280-330 km). Because the reverberation's delay is larger than what the corresponding <0.5 sec delay of the Moho arrival from 289-330 km would predict and the NW dip of the Moho is too small we suggest that Poisson's ratio is being perturbed. To assess this possibility, Poisson's Ratio has been calculated using the timing between Moho and the first reverberation (Zandt et al., 1995). This shows that the delayed reverberation is consistent with a jump in Poisson's ratio from 0.27 to 0.30 between the southeast margin of the Snake River Plain and the center of the Plains. Since a chain of active Rhyolitic domes and Basaltic flows extends down the center of the Snake River Plains,we suggest that the high Poisson's Ratio is consistent with a zone of increased heat flow associated with magma intrusion.

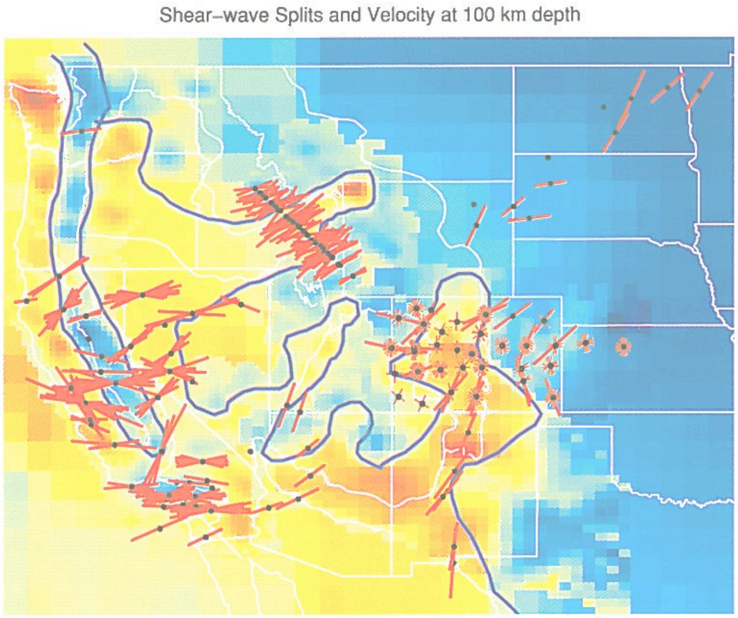
Shear wave splitting in the Western U.S.

Ken Dueker and Anne Sheehan
University of Colorado at Boulder
Martha Savage
University of Nevada at Reno

Understanding continental dynamics requires testable models of how the potential energy and strength of the lithosphere evolves and responds to both global plate forces transmitted laterally through the rigid lithosphere and the more locally derived forces from both thermal and melt buoyancy driven asthenospheric convection. Fundamental to this task is the accurate imaging of the the Earth's velocity structure. Both complicating this task and adding important new constraints is the knowledge that significant velocity anisotropy - comparable in some cases to the isotropic velocity heterogeneity - exists throughout the upper mantle. In the past, inadequate broadband coverage has limited our ability to accurately constrain the full measure of anisotropic velocity variations. The high density IRIS/PASSCAL deployments in the western U.S. (and worldwide) are now remedying this situation and proving to be an invaluable tool with which to probe the Earth's depths.

Better imaging of the Earth's anisotropic structure is important for several reasons. First, the anisotropy itself provides complementary information regarding the state and evolution of the upper mantle. In particular, in the asthenosphere and lower lithosphere (where dislocation creep is thought to predominate), velocity anisotropy is predicted to correlate with the finite strain tensor. Hence, anisotropic velocity images can provide constraints on the integrated strain within the asthenosphere and hence its flow patterns. Second, existing isotropic inversions suffer in quality due to parameterizing an anisotropic system as an isotropic system; thus, accurate interpretation of the isotropic velocity variation in terms of thermal, compositional, and phase (both solid-liquid and solid-solid) variations is hampered.

Largely as a result of PASSCAL deployments, shear wave splitting studies within the western United States are now providing our first local to continental scale images of upper mantle anisotropy. As shown in the figure, the shear wave splitting observations image significant variations in both the magnitude and orientation of the upper mantle fabric. Assuming a 5% average shear wave birefringence, the average 1.2 sec split time of vertically incident shear waves requires a 120 km thick anisotropic layer. Given the observations of a thin (<80 km) lithosphere beneath most of the western United States, the lithosphere is only capable of producing about 1/3 of the observed anisotropic travel-time signal. Thus, about 2/3 of the anisotropic velocity variations are presumed to exist in the underlying asthenosphere. This may imply that the dominant strain in the asthenosphere is not simply the plate shear induced by the southwest drift of the North America plate, but that vigorous asthenospheric flow is occurring.



Compilation of shear wave splitting measurements in the western United States and western U.S. velocity structure.Orientation of red lines corresponds to fast polarization axis, and length of lines represents magnitude of anisotropy. Null measurements are shown in lighter red as short lines (e.g., Colorado has many nulls). All good splitting observations for each station are shown except for the Wyoming to Minesota line, Arizona, and the New Mexico results, where an average is presented. Data sources: Dueker and Humphreys [1994], Ozalaybey and Savage [1994, 1995], Ruppert [1992], Sandvol et al. [1992], Savage and Silver [1993], Savage and Sheehan [1994, 1995], Savage et al. [1990], Silver and Kaneshima [1993].The underlying continental scale image is the multi-bounce shear wave image of Grand [1994] with five different regional array images plotted on top of the Grand image: The Washington/Oregon, California/southern Nevada, and Idaho/Utah/ western Wyoming P-wave images [Dueker et al., 1994]; northern Arizona/New Mexico P-wave images [Slack et al., in review]; and the Colorado S-wave image [Lee and Grand, 1994]. Blue is high velocity mantle; Red is low velocity mantle. We have used an empirical approach to mesh the results together.This is because the absolute velocity structure beneath these regional arrays is not well enough constrained to quantitatively shift each of the zero mean regional array P- and S-wave images into concordance with the Grand image. Note that by normalizing the P and S wave images, a constant yet unknown Vp/Vs scaling has been implicitly applied .The total range in the regional array P-wave images has been estimated to be about 8%.

Southern Sierra Nevada Crustal Thickness From Converted Phases

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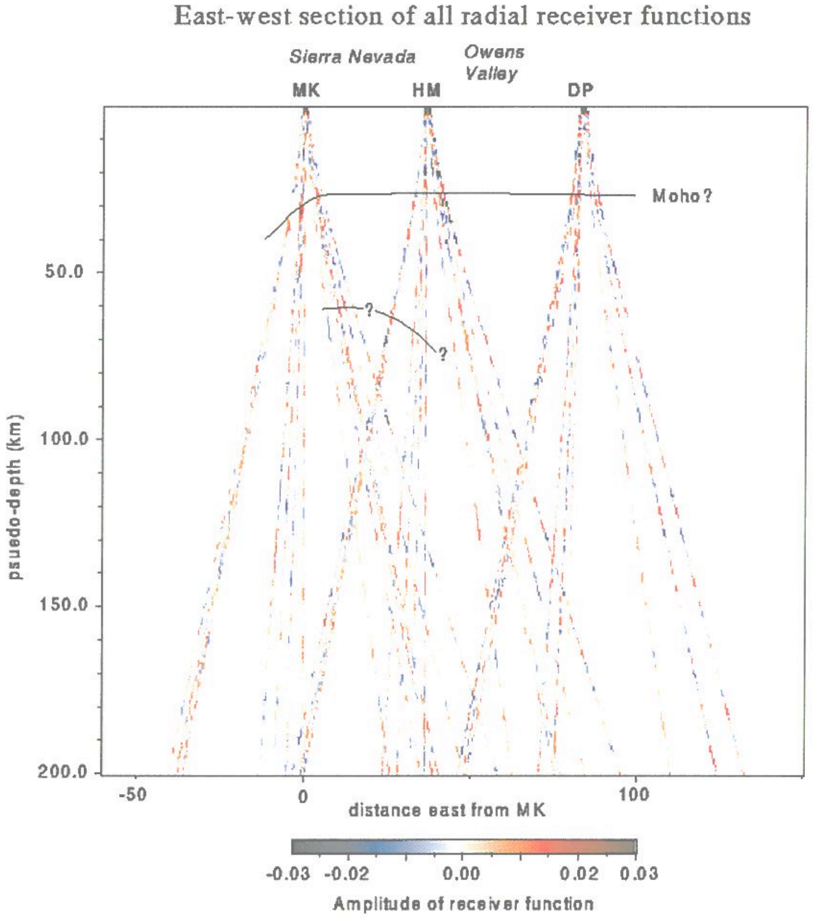
Department of Geology, Princeton University
Christian B. Parker
Southern Sierra Continental Dynamics Working Group


East-west section of all radial receiver functions

From July to October, 1993 over 100 teleseisms 30 to 100° distant were recorded by seismic arrays at Mineral King (MK) and Horseshoe Meadows (HM) in the southern Sierra Nevada and at Darwin Plateau (DP) between the Inyo and Argus ranges. HM and MK combined 3 broadband (CMG-3 or -4) with 8 short-period (L4-3D) sensors in an L-shaped geometry with interstation spacing of ~500 m; the DP array had 3 CMG-4s and 6 3-component HS-10s in an east-west line with 500 m spacing. We found that these array geometries permit separation of direct P and S arrivals, reflections from topography, scattered energy, and arrivals from different backazimuths (multipath arrivals). P-to-S conversions can be identified from beamed broadband or short-period seismograms even in the presence of substantial scattering from local topography.

Using a least-squares time-domain deconvolution, we recovered single-event receiver functions by deconvolving the beamed vertical from the beamed radial component. The receiver functions are displayed as colored amplitude projected back along the Ps raypath through a simple 1-d structure in the cross section in Figure 1. Converted phases attributable to the Moho are generally clear and uncomplicated at DP and east from HM; Ps-P times range from 3.8-4.2 s. Rays traveling under the High Sierra to either MK or HM have more energy on transverse components and a less distinct conversion from the Moho. Probable Moho conversions are at about 4.2 s; another conversion, prominent at MK, is ~7.3 s (MK) - 9 s (HM) after the P. Arrivals from the west to MK have a Ps 4.9 s after the P. Assuming crustal vp of 6.3 km/s and vp/vs of 1.70, the depth below sea level of the Moho would be 32.5 ± 1 km east from the Sierran crest, between 33 and 37 km under the High Sierra, and about 40.5 km west of MK.

Shear-wave splitting beneath the Cascadia subduction zone

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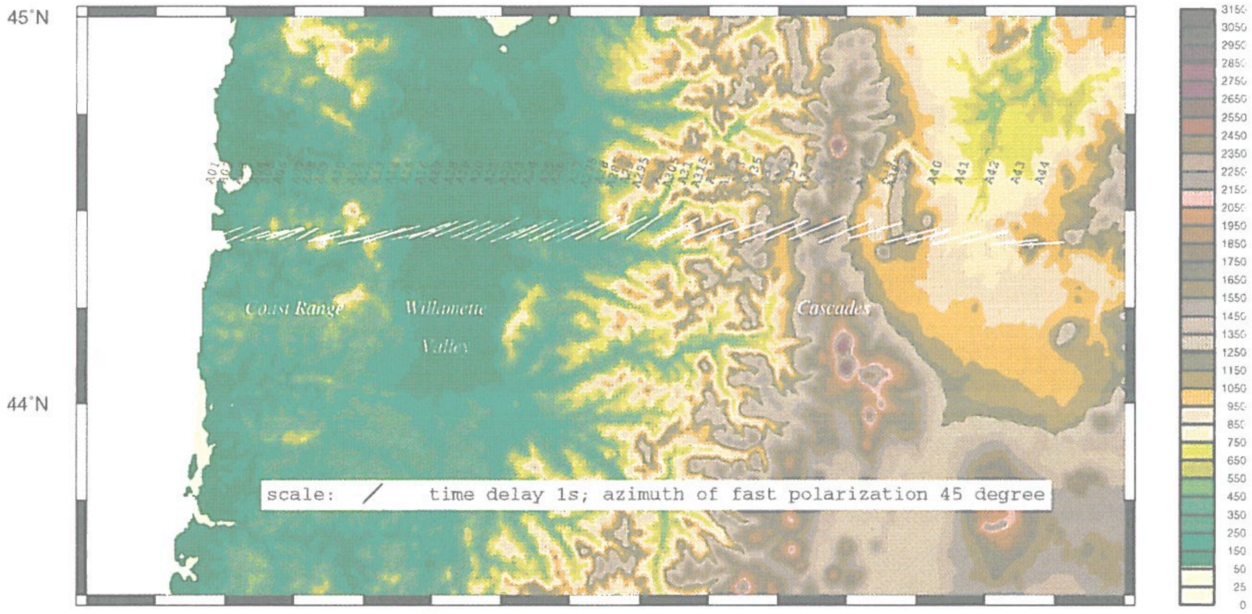
A 1993-1994 PASSCAL broadband array experiment provided an opportunity to study in detail the shear-wave anisotropy across the Cascadia subduction zone using SKS splitting. Fig.1 shows vectors describing the average split-time (δt) and fast polarization direction (ϕ) for each station of the array determined from measurements of ten suitable earthquakes. While the measurements are remarkably consistent between neighboring stations, they show a well-defined variation across the subduction zone. The average splitting parameters for the entire array are [1.61 s, 72°]. The split-times range from a minimum of about 1.0 s in the Coast Range to a maximum of about 2.2 s in the High Cascades, which are among the largest split-times recorded worldwide. The array can be divided into five regions according to their gross anisotropic characteristics: the western Coast Range [average δt, ϕ: 1.20 s, 71°], characterized by relatively small split-times; the eastern Coast Range [1.60 s, 75°], with abruptly increased split-times; the Willamette Valley [1.61 s, 66°], characterized by very stable measurements; the Cascades [1.95 s, 69°], showing the largest split-times; and the back arc [1.69 s, 81°], with lower split-times and rapid change in fast-polarization direction.

The direction of fast polarization beneath the fore-arc and the arc is consistent with the direction of motion of the Juan de Fuca plate (absolute: 68°; relative to North America: 65°), suggesting that much of the anisotropy is caused by the alignment of olivine in the upper mantle imparted by the motion of the Juan de Fuca plate. Performing the analysis in different frequency bands indicates that the signal responsible for the observed anisotropy variations is confined to 0.2-1.0 Hz band. Fresnell-zone estimates indicate that the long-wavelength variations require the source of anisotropy to be shallower that 130 km. The abrupt variations, e.g., the rapid change in split-times between western and eastern Coast Range, or the rapid rotation of fast-polarization direction in the back arc, require a substantial contribution from crustal sources shallower than 30 km. The five regions defined by anisotropy, presumably reflecting crustal and upper-mantle processes, correspond well to surface geology. On the crustal scale, they probably reflect shear structures and cracking developed during formation of these units. It is interesting that these large-scale units appear to be less well defined in the receiver-function and reflection/refraction data. The presence of the largest anisotropy under the Cascades suggests ductile flow related to the thermal anomaly.



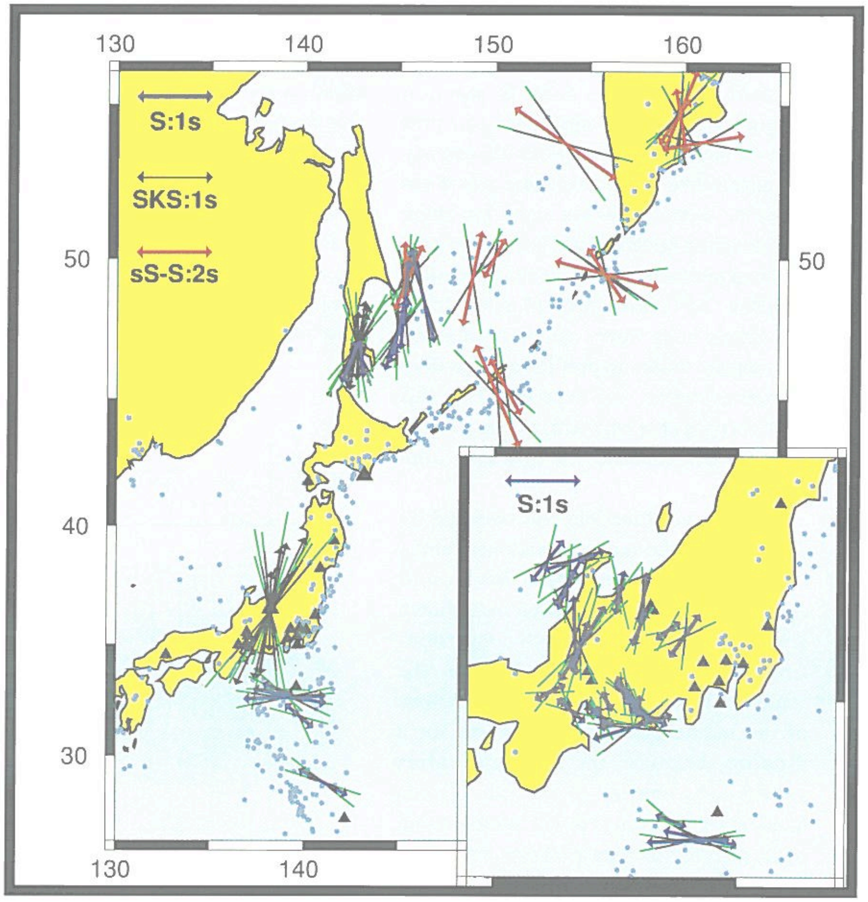
Subduction Zone Anisotropy from Shear Wave Splitting

Karen Fischer
Brown University

To assess the location, strength, orientation, and source of subduction zone elastic anisotropy in the Kuril-Kamchatka, Japan, Izu-Bonin subduction zones, we have analyzed shear-wave splitting in local and teleseismic phases recorded by stations of the IRIS GSN, the Japanese pre-POSEIDON network, and GEOSCOPE. (Locations of some of these stations are shown by the triangles in the figures). The dataset includes *S* phases for subduction zone sources and stations, *SKS*, *SKKS*, and *PKS* phases for teleseismic souces recorded at subduction zone stations, and *sS* and *S* phase pairs from subduction zone sources recorded at teleseismic stations. *SKS*, *SKKS*, and *PKS* phases are sensitive to anisotropy from the core-mantle boundary to the station. After correction for splitting apparent in the *S* phase, residual splitting in the *sS* phases may be attributed to anisotropy in the source region.

Fast directions obtained from local *S* and teleseismic phases that sample similar regions are consistent at 95% confidence and show a strong correlation with subduction zone tectonics. In the figure, splitting parameters and error bars are plotted as vectors at source-station mid-points, stations, and *sS* bounce-points for local *S*, *SKS*, and *sS* phases, respectively. Vector azimuths indicate fast directions and vector lengths scale to splitting times. Fast direction orientation smoothly rotates across the Pacific-Philippine-Eurasia triple junction, from roughly convergence-parallel for phases that sample the Izu-Bonin subduction zone to roughly arc-parallel for phases that sample the Japan subduction zone in central Honshu. The ~NNE fast direction trend continues northward into the Kuril back-arc near Sakhalin Island and also occurs in phases that sample the Kamchatka Peninsula. Elsewhere in Kuril-Kamchatka, fast directions are more convergence-parallel. Local *S* phase splitting times increase with source depth down to at least 400 km, indicating that a significant component of the apparent anisotropy occurs at sub-lithospheric depths.

The sum of these results with similar studies in Tonga and the eastern Aleutians suggests that the orientation of back-arc anisotropy is dominated by the overriding plate, probably through its effect on strain and thermal structure in the underlying asthenosphere. In Tonga and Izu-Bonin where the upper plate is oceanic and back-arc spreading is active, fast directions are roughly convergence-parallel. In north-central Japan, the Kamchatka peninsula, and the eastern Aleutians where the upper plate is quasi-continental with a complex history of accretion and deformation, fast directions are roughly arc-parallel. Other possible influences on anisotropy include oriented lenses of partial melt or volatile-induced variations in olivine slip systems.



Shear wave splitting for Japan-Kurile region.

Imaging of the Cascadia subduction zone with teleseismic converted phases

John Nabelek, Xiao-Qing Li, Anne Trehu, Steve Azevedo, Jochen Braunmiller, Axel Fabritius, and Beate Leitner
College of Oceanic and Atmospheric Sciences, Oregon State University

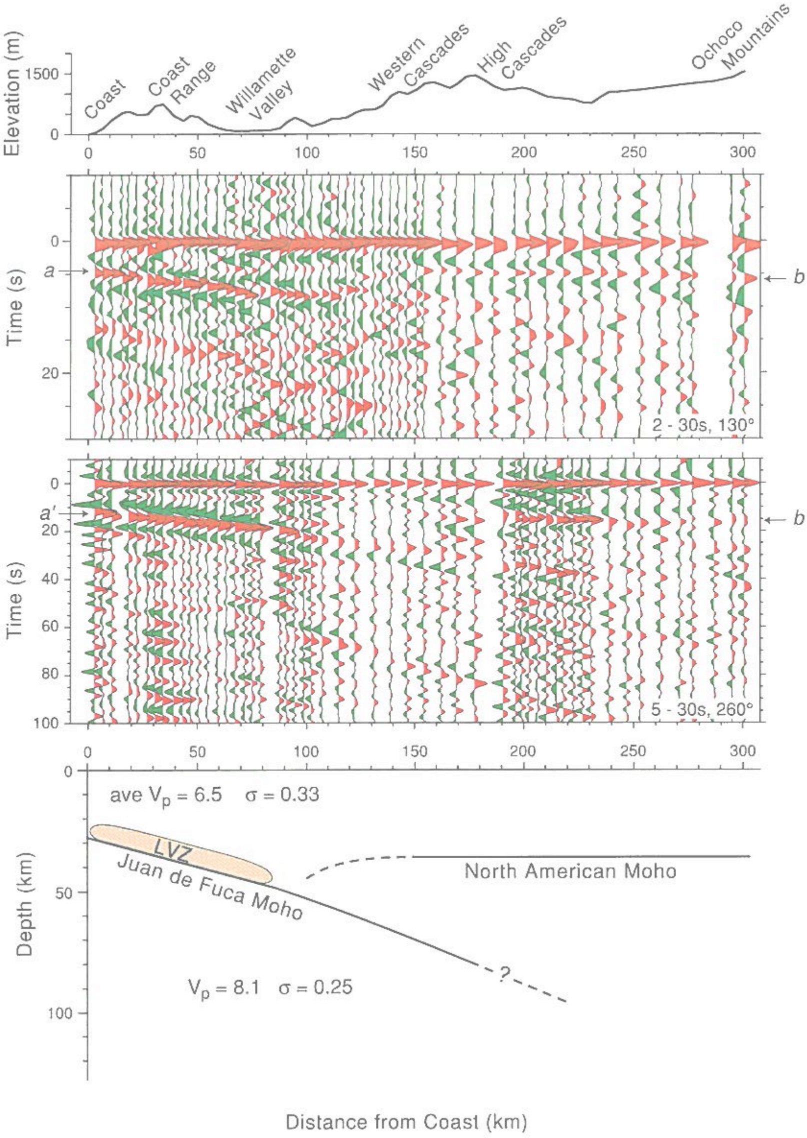
From April 1993 until April 1994 we operated a large, dense linear array of broadband seismometers across the Cascadia subduction zone in western Oregon. Altogether 69 sites were occupied with 44 stations operating simultaneously at a given time. Station spacing was 4 km along the western 240 km and 8 km along the remaining eastern part. The primary goal of the experiment was to demonstrate that profiles of converted phases from teleseismic body waves can be approached in a manner similar to profiles in reflection/refraction studies. An experiment on this scale was possible only with a large number of portable broadband seismographs from PASSCAL.

The receiver functions are obtained by deconvolving the vertical component of the P wave from the radial horizontal component. This procedure removes source effects and emphasizes P-to-S conversions from structural interfaces beneath the stations. The converted phases are functions of the incidence angle; therefore, for a dipping structure, the response varies strongly as a function of azimuth. On one hand, this complicates direct interpretation of the receiver function profiles; on the other hand, predictable azimuthal behavior enables identification of the individual phases.

The receiver functions for the Mexico earthquakes (Fig. 1B), back azimuth 130°, were band-pass filtered between 0.03-0.5 Hz. Direct Ps conversions dominate. The main coherent features are conversions from the Moho of the east-dipping Juan de Fuca plate (JDFP) in the west and from the nearly horizontal Moho of the North American plate (NAP) in the east. The prominent Ps conversion from the JDFP Moho can be traced from the coast to the eastern edge of the Willamette Valley; further east, Ps decreases in amplitude and becomes obscured by multiples from the shallower structure. The JDFP Moho is at a depth of 27 km at the coast, with depth increasing eastward at a 15° angle. The NAP Moho is at a depth of 37 km and shows little or no crustal root beneath the Cascades. Its depth appears to increase as it approaches the JDFP Moho beneath the Willamette Valley.

The receiver functions for the New Ireland earthquakes (260° back azimuth, 0.03-0.2 Hz band, Fig. 1C) are dominated by PpPms multiples, which are better at revealing the deeper structure. The PpPms multiple from the JDFP Moho can be clearly traced to stations 240 km from the coast. This confirms the presence of the JDFP as far east as the High Cascades.

Fig. 1D summarizes the principal findings thus far. Modeling the amplitudes and timing of Ps and PpPms indicate high (0.33) Poisson's ratio and an average compressional velocity of 6.5 km/s for the crust beneath the coastal range. The derived Poisson's ratio supports earlier inferences that the Coast Ranges are underlain by an anomalously thick mafic terrane. The Poisson's ratio of the NAP crust beneath and east of the Cascades is lower (0.27-0.29). A large negative arrival preceding PpPms beneath the Coast Range indicates the presence of a low-velocity zone just above the JDFP Moho, possibly due to fluids derived from dehydration of subducted oceanic crust.



A) Topography and main physiographic units along the profile. **B)** Receiver-function profile derived from five earthquakes from the coast of Mexico. "a" indicates Ps conversion from the JDFP Moho and "b" indicates Ps from the NAP Moho. **C)** Receiver-function profile derived from two earthquakes in New Ireland and Vanuatu Islands. "a'" and "b'" indicate PpPms phase from the JDFP and NAP Moho, respectively. Note the change in time scale between figures B and C. **D)** A preliminary model of the Cascadia subduction zone consistent with the receiver-function data.

The Snake River Plain Experiment

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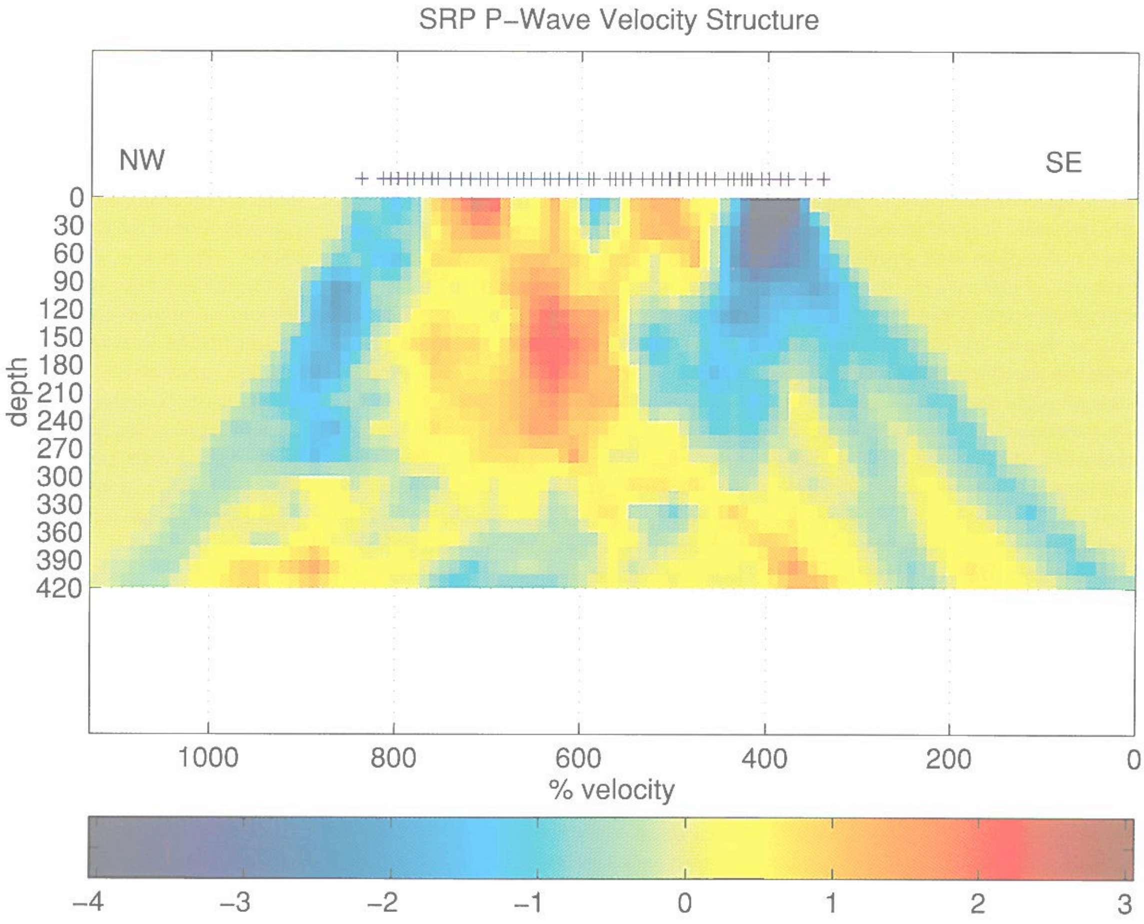
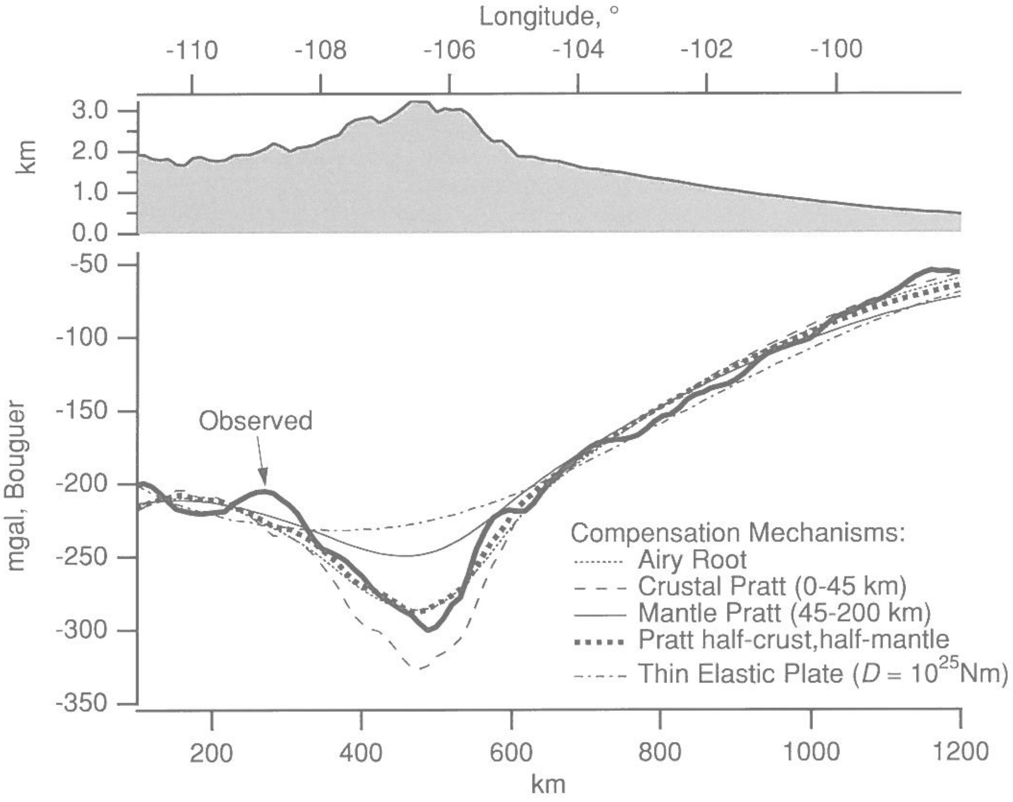
For six months in 1993, we operated a 550 km array of broadband seismometers with a 10 km average spacing in a line perpendicular to the track of the Yellowstone hotspot. The array of seismometers spanned the entire width of the "tectonic parabola" which definesthe active region of faulting and seismicity around Yellowstone.The array geometry allows resolution of the upper mantle velocity structure on the cross-section of the Snake River Plain region through which the Yellowstone hotspot passed 6 to 8 million years ago.A total of 375 earthquakes (Mb > 4.4) were recorded, from which 5000 usable P-wave residuals can be derived. (The image shown is produced with 3500 residuals.) Travel times are reduced with the Iasp91 radial earth model. Residuals are then demeaned as a first order correction for differences between source events, as well as to minimize the effects of mantle differences outside the region of interest.Crustal corrections, as determined from receiver function analysis, are applied.The traveltime residuals (difference between actual and predicted travel times) were inverted for velocity structure using a SIRT algorithm. Block dimensions are 20 km wide by 30 km deep. Model smoothness was increased by imposing 40% nearest neighbor covariance during inversion. We attribute the imaged structure primarily to variations in partial melt content that are modulated by variations in mantle composition.Our reasoning hinges on the fact that the relatively high-velocity (blue) regions in the figure lie beneath relatively thin crust that stands at great elevation, implying that this higher velocity uppermantle is buoyant. Such upper mantle would be created by depletion of basaltic component; it cannot be relatively cool. If the above reasoning is true, then the only reasonable cause for the great depression of velocity beneath the Plain is the presence of partial melt. This inferred partial melt zone extends to depths of over 150 km. Mantle plume models predict that the plume ponds at the base of the lithosphere in a layer about 100 km thick. Movement of the lithosphere over the asthenosphere then will drag this flattening plume material away from its source, producing a widening parabola downstream that has been modeled to be about 500 km wide at the location of our experiment.However, our image shows a low-velocity anomaly that is far narrower (at most 200 km wide) and far deeper (up to 300 km deep) than is predicted by mantle plume models. We are therefore considering an alternative explanation for the observed structure, in which melt buoyancy convectively overturns an elongated roll within the asthenosphere (similar to the "gravity rolls" inferred near mid-ocean ridges). Melt is released above the ascending arm, and the depleted residuum is pushed aside. In this scenario, the motion of the North American plate is important in two ways: (1) orientation of the convective rolls and (2) propagation of the magma. Shearing of the mantle below the plate causes the roll to be oriented in a direction parallel to the direction of plate motion. This same shearing causes a void at the tip of the roll that is filled by the upward flow of fertile mantle material, which propagates the magmatic release forward.



Support of Rocky Mountain Topography: Crust or Mantle?

Arthur Lerner-Lam and the Rocky Mountain Front Team



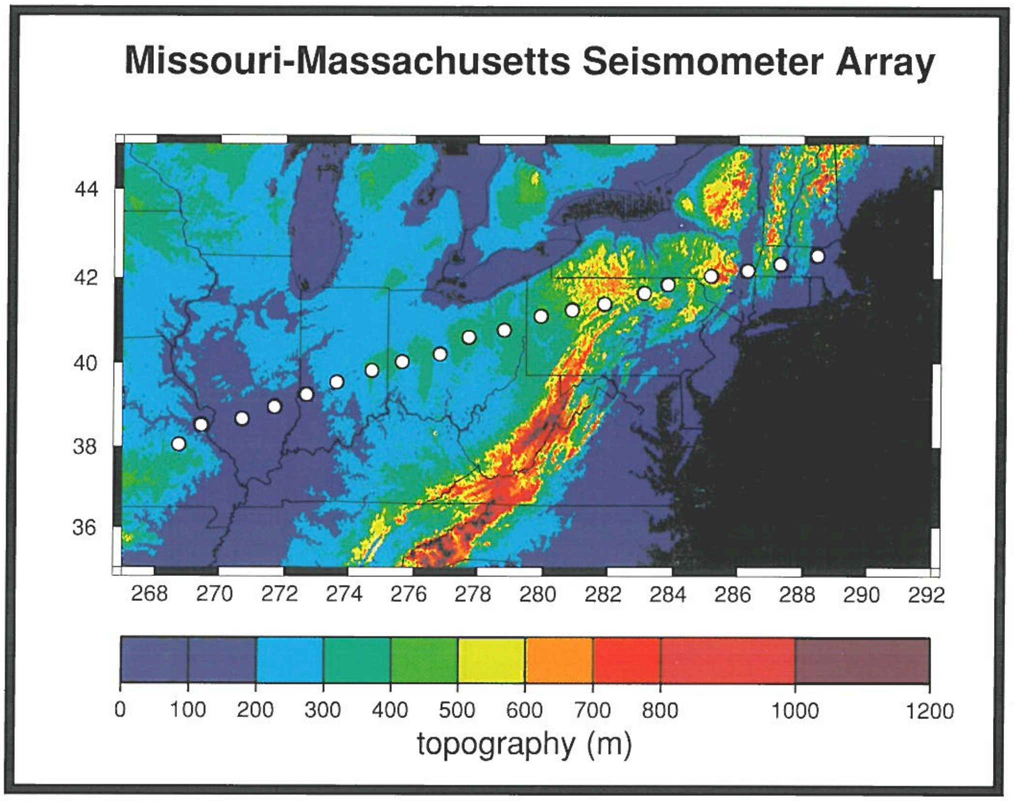
We can now appreciate that the variations we observe in geology at the surface can often be associated with profound variations in crust and upper mantle velocity structure. Not only does this correlation occur at the near-plate scales of tectonic provinces and continent-ocean differences, but there is increasing evidence that intraplate variation is large as well, particularly within continents. Is this the residual of previous episodes of plate tectonics, or is it an ongoing consequence of the evolution of sub-continental lithosphere? Are the scales of lateral heterogeneity in the upper mantle the same as the scales of geological heterogeneity observed in tectonized crust? Can we explain large variations in deformational style and physiography with simple crustal models, or are mantle mechanisms needed? The PASSCAL facility is ideal for addressing these questions on continents.

The 1992 Rocky Mountain Front PASSCAL experiment was designed to collect body-wave and surface wave data across a variegated province in the Colorado Rockies, where some of these issues can be addressed. Thirty broadband seismographs were deployed in a rectangular array stretching from eastern Utah, across the Rockies, onto the western Great Plains of eastern Colorado and western Kansas. Scientists from MIT, the University of Texas at Austin, the University of Oregon and Lamont-Doherty Earth Observatory, with assistance from the Colorado School of Mines, Colorado College, the University of Kansas, and the USGS, spent about 7 months collecting about 350 teleseisms and more than 100 regional events. The data were analyzed for body wave delays and attenuation, surface wave dispersion, boundary interaction phase (receiver function) variations, shear wave splitting from teleseisms and Pn propagation from regional events. From these analyses, a significant new view of the Laramide, its interaction with the western edge of the North American Craton, and the persistence of mantle involvement is emerging.

For example, A. Sheehan and others recently completed a study of the variations in crustal thickness using broadband teleseismic receiver functions. The results suggest only a slight thickening of the crust westward from the Great Plains to the Rocky Mountains. When these variations were used as constraints in simple mass balance calculations to model the available gravity data, no mechanism which restricted the compensation of the Rockies to the crust was viable. Sheehan et al. concluded that the Colorado Rockies require a significant amount of support from the mantle. Why should this be in what is now a relatively "quiet" province? Can such support mechanisms be stable over geologic time? Is there active upwelling just off the western edge of the North American Craton? This data set will provide a wealth of opportunities to study these and other questions.

The Missouri to Massachusetts Broadband Seismometer Deployment: Collaborative Studies of Mantle Structure

Karen Fischer
Brown University



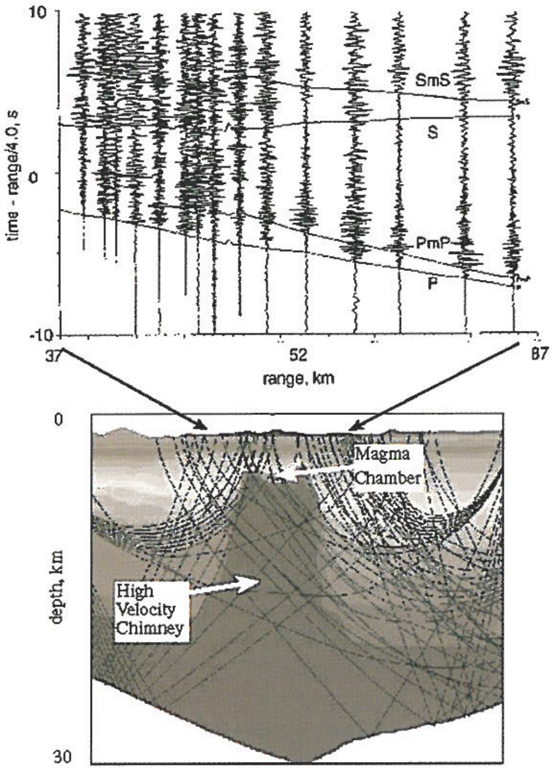
The Missouri to Massachusetts (MOMA) array comprises 18 portable broadband seismometers deployed in a line between the permanent IRIS/GSN stations at Cathedral Caves, Missouri (CCM), and Harvard, Massachusetts (HRV). The goal of the experiment is to constrain several fundamental aspects of mantle velocity structure: the properties and extent of actively subducting oceanic lithosphere, the seismic character of the core-mantle boundary, and the detailed structure of the upper mantle beneath the eastern United States.

Station spacing is roughly 90 km and the total of 20 broadband sensors covers a distance of 15.65°. The resulting density of high-quality, broadband seismometers reduces problems from spatial aliasing that occur with existing permanent stations, and improves the resolution available for the planned mantle structure studies by an order of magnitude. Of the portable instruments, 16 are from the IRIS/PASSCAL program. All sensors (7 Guralp CMG-3T's and 11 Streckeisen STS-2's) are sited in subsurface vaults, and data are being collected in continuous streams at 20 sps and 1 sps. Two stations are equipped with remote communication units that permit the station to be accessed via local telephone lines. These units are useful for monitoring station status and for rapid data extraction. Instrument deployment was completed in March, 1995, and the experiment will run for one year.

The structure of the core-mantle boundary, important in understanding the form of deep mantle convection, will be studied using core-diffracted *P* and *S* waves and *SKS*/*SKKS* amplitudes from the highly seismogenic Tonga region, as well as *PKP* and *SKP* phases from Indonesian earthquakes. Body waveforms from subduction zone earthquakes in the Aleutians, Kuril-Kamchatka, Peru-Chile, and Central America will be analyzed for evidence of perturbations due to slab velocity heterogeneity. Such waveform anomalies may provide new constraints on mineralogical and compositional boundaries within subducting slabs, and on slab geometry and extent within the mantle transition zone. Upper mantle structure directly beneath the array will be imaged by combining reflectivity forward modeling with waveform inversion methods using both body and surface waves. Shear-wave splitting in *SKS* phases will be used to constrain anisotropy beneath the stations and to study the relationship of inferred anisotropy to the orogenic history of the eastern United States. Information on sub-array heterogeneity will also aid in differentiating the effects of near-station structure from those caused by heterogeneity elsewhere along the phase path, and will permit more accurate analysis of waveform interactions with subducting slabs and the core-mantle boundary.

Undershooting of the Krafla Central Volcano on the Mid-Atlantic Plate Boundary in Iceland

William Menke
Lamont-Doherty Earth Observatory
Bryndis Brandsdottir
University of Iceland



The availability of three-component seismic systems, such as those from PASSCAL, has revolutionized studies of shear wave propagation in the earth's crust, since these waves are most easily observed on the horizontal component of ground motion. Shear waves studies are of particular interest in volcanic regions, since they provide a means of detecting molten magma within the Earth. Shear waves shadows form as seismic wave paths cross magma bodies, since shear waves are absorbed by the hot fluid.

We have used this technique to map the magma chamber of the Krafla central volcano, on the mid-Atlantic plate boundary in Iceland. The accompanying radial horizontal-component record section illustrates the technique. Seismic waves from an event at range=0 generate P and S waves which dive into the earth, undershooting the volcano (inset). The S wave is absorbed as it traverses the magma chamber, leading to its disappearance at a range of about 50 km. The Moho-reflected shear wave, SmS, which passes below the volcano at deeper depths is not shadowed, indicating that the magma is confined to shallow depths.

The inset shows our reconstruction of the volcano structure, and is based upon measurements of P wave traveltimes and S wave amplitudes from a several such record sections, corresponding to waves crossing the volcano in different directions.

Tomographic Images Illuminate Mount Rainier's Potential Volcanic Hazard

Jonathan M. Lees
Yale University

Mount Rainier is the most seismically active of all Cascade volcanoes, after the recently erupted Mount St. Helens. It is also the largest, standing nearly 4.5 km above sea level and covered by numerous glaciers. Well documented lahars and mudflows have been observed to have reached the Seattle area in the past, indicating the potential for major disaster in the event of a significant eruption event.

Mount Rainier was designated a Decade Volcano by IAVCEI because of its potential for major eruption and proximity to a large population area. Tomographic analysis of the Puget Sound region and at Mount St. Helens show significant similarity, suggesting that seismic velocity anomalies appear to delineate salient features of the magma plumbing system at Mount St. Helens and Mount Rainier, WA (Figure 1, 2, 3).

Details of the St. Helens inversion suggest a narrow conduit penetrating to approximately 9 km depth. At the top of the magma chamber a higher velocity body is observed which may be associated with repressurization. At Mount Rainier a large, low velocity body is observed below the volcanic edifice extending 9-17 km in depth. This feature portends the significant hazard that Mount Rainier represents in the Puget Sound region. More detailed inversions in the Rainier region will illuminate details of the conduit and magma chamber. If a high velocity cap to Rainier's magma chamber is observed, we may be able to formulate models relating structure to episodic eruptions.

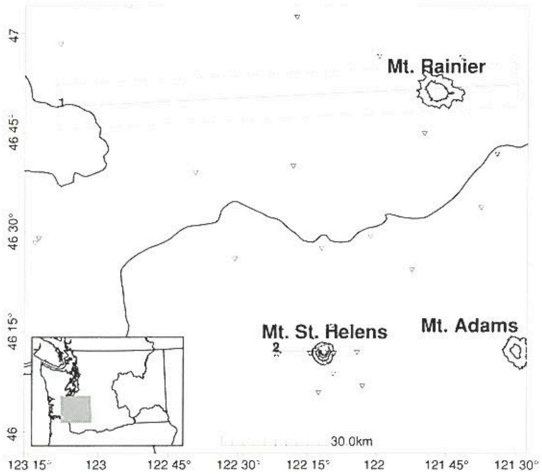


Figure 1: Map view of the Mount Rainier and Mount St. Helens regions, Washington. Rectangular boxes (1, 2) outline the volumes projected in Figures 2 and 3. Triangles are stations from the Western Washington seismic network.

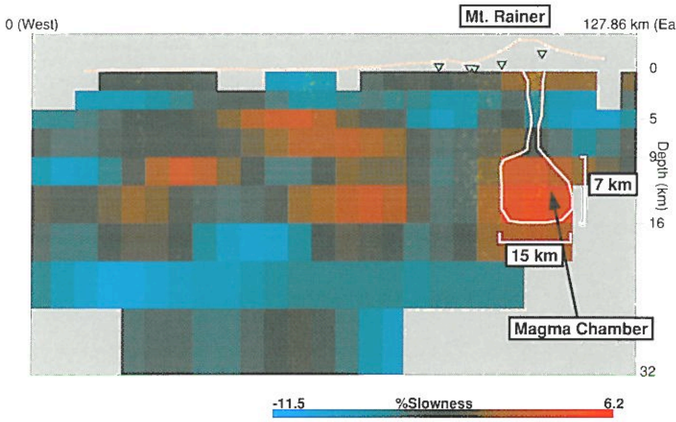


Figure 2: Vertical cross section of Mount Rainier. Red and blue colors are low and high velocity regions presented as percent perturbation from the background one-dimensional models. Small circles are projected seismicity. A line drawing of the proposed magma system below Rainier's ediface is an interpretation based on similarity with Mount St. Helens inversion in Figure 3. Focal mechanisms are front projections of seismicity, primarily located in the stoping region, color coded according to rake. Line drawing is taken from Pallister et al. (Pallister, et al., 1992)

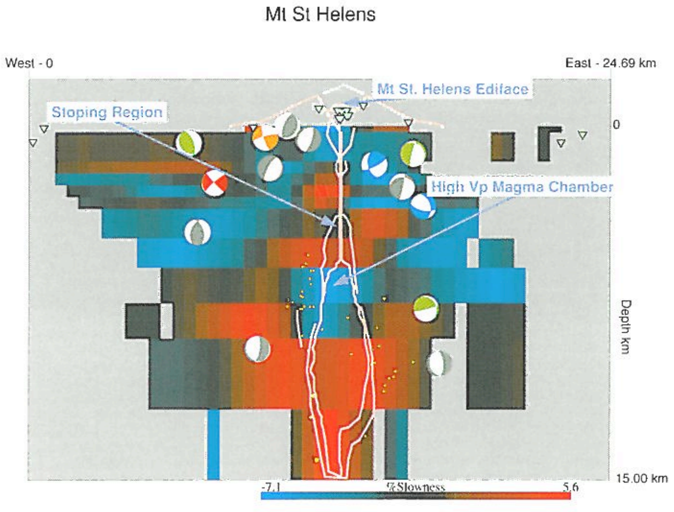


Figure 3: Mount St. Helens cross section.

Global Seismic Tomography

Adam Dziewonski
Harvard University

At the time of the first IRIS proposal, written 12 years ago, seismic tomography was still a controversial tool in Earth sciences. It became clear only several years later that the early 3-D models showed an essentially correct image of the large-wavelength pattern of seismic velocity in the mantle. Correlations with other geophysical signals, such as geoid, plate motions, petrology, geochemistry, and geomagnetism indicate that this part of the spectrum may be particularly important in explaining planetary scale processes.

This does not mean that regional scale investigations are not equally important. We shall never be able to achieve the resolution on the global scale equal to that obtained with temporary, dense deployments of portable instruments, in mapping the descending slabs, for example, or features such as the Rocky Mountain front. What is needed is to combine these two approaches through a local densification of the grid; attempts to do that may represent the most promising developments in the future. Both the GSN and PASSCAL components of IRIS will contribute.

The text below gives four snapshots of the tomographic results from the full depth range: from the crust to the inner core. The results presented were derived, with one exception, using data not only from the IRIS GSN stations, but also from other FDSN networks: GEOSCOPE, CDSN, MedNet. It is very clear that the existence of these stations is changing the way in which seismological research is done.

Why Tomography is Necessary to Understand the Mantle Processes

About 30 years ago, Toksoz and Anderson proposed the "purepath" method of surface wave dispersion. They assumed that the structure under a certain surface tectonic expression is the same at all depth. The method was widely used with an increasing diversity of parameterization, including rather fine steps in the seafloor age. Some people began asking "What if the structure under all shield regions is not identical throughout the upper mantle" or "What if the structure under the oceans is not a function of the age alone?". Such questions helped to motivate the development of three-dimensional mapping techniques, also known as seismic tomography. Tomography obtains a map of velocity anomalies at a certain depth, without *a priori* assumptions on the relationship between surface tectonics and its underlying velocity structure. The disadvantage of the tomographic approach, particularly when using the low order spherical harmonic expansion, is that it cannot resolve sharp boundaries or very narrow features.

It is surprising that until now seismologists have not turned backward from 3-D studies to check rigorously the assumptions underlying the "pure path" approach. Ekstrom et al. have gathered an extensive set of surface wave observations in a period range from 35 to 250 s. The number of paths for which satisfactory results exist ranges, depending on the period, from 5,000 to 10,000. Figure 1 shows the result of their attempt to explain their observations in terms of the six-region scheme of Jordan (GTR1); the results are not particularly sensitive to the specific form of regionalization adopted. At the shortest period (35 s), the six-region decomposition is capable of explaining 75% of the variance of the Rayleigh wave data and 88% of the Love wave data. This is comparable, particularly for the Love waves, to the variance reduction that is obtained using spherical harmonic expansion to degree 36 (96%), which involves determining 1369 parameters instead of 6. Clearly, at short periods regionalization works very well.

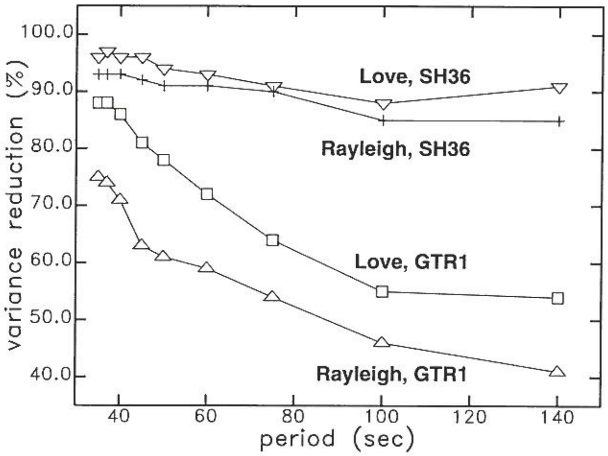


Figure 1

The variance reduction decreases substantially with the increasing period, or depth of penetration, of the surface waves. At 140 seconds, only 41% of the Rayleigh wave and 53% of the Love wave data variance is explained using regionalization. On the other hand, the use of the spherical harmonic expansion to degree 36 leads to 90% and 85% variance reductions for the Love and Rayleigh waves, respectively; the data at 140 s are less noisy than at 35 s period, but the signal is an order of magnitude smaller.

The conclusion from this experiment is as follows. The seismic properties of the crust and the upper part of the lithosphere are explained well by the tectonic regime or the age of the sea floor. The properties of the lower part of the lithosphere and the asthenosphere are less dependent on the conditions at the surface. This conclusion is based on the period dependence of the variance reduction as well as the difference between Rayleigh and Love wave data. At a given period, the Love waves penetrate less deeply into the structure than the Rayleigh waves and their dispersion is therefore more affected by the shallow structure.

In operational terms, this means that very dense path coverage is needed to resolve details of the structure below 50 km depth, or so, on the scale of 500 km. This need is not limited to the path density but it extends to the azimuthal coverage as well, because of the well-documented existence of azimuthal anisotropy, at a level of 1.5% or so. The exciting part of the tomographic approach is that it allows us to detect effects not predicted by plate tectonics; cooling of the plate erases the signature of these anomalies, thus the only opportunity to detect their existence is through seismic measurements.

What happens at the 670 km discontinuity?

The results presented by Masters et al. in 1982 were quite unexpected. There was no reason to anticipate that lateral heterogeneity in the transition zone would be dominated by degree two harmonics. The presence of a significant degree 2 signal in the transition zone was confirmed by later tomographic studies. In maps with angular degrees from 1—6 and 1—12 the transition zone anomaly shows up as wide regions of elevated shear velocities, primarily concentrated in the Western Pacific and under South America and South Atlantic. It has been suggested that these anomalies may represent the effect of "pooling" of cold subducted material. Some regional tomographic studies, such as by van der Hilst et al. and Fukao et al., have indicated that some slabs may deflect horizontally at the 670 km discontinuity and not penetrate into the lower mantle. Unfortunately, the resolution of regional tomography decreases rapidly away from the sources in the Wadati—Benioff zones, and it is not clear that the true width of the velocity anomaly can be resolved using this approach.

Modelling of mantle convection by Machetel and Weber, Peltier and Solheim and Tackley et al. identified the endothermic phase transformation associated with the 670 km discontinuity as a likely cause of episodic flow across the discontinuity. The question is whether there are predictions made by the convection models which can be tested against the seismological data. Jordan et al. concluded that the convection models and the tomographic models were incompatible, suggesting that the seismic models are more consistent with a continuous flow of the material across the upper—lower mantle boundary. However, the tomographic models such as WM13/U4L8, in which the upper and lower mantle are described by separate parameterization, show a change in the spectral distribution of heterogeneity on both sides of the boundary. This is illustrated in Figure 2, in which the first panel shows velocity anomalies just above the boundary, and the other one, just below it. It is clear that the upper panel is dominated by longer wavelength features, while in the lower mantle the spectrum is shifted towards shorter wavelengths. This is very similar to predictions of Tackley et al. The other diagnostic, involving an increase in the anomalies near the discontinuity, is less reliable, because experience has shown that the amplitude of seismic anomalies cannot always be resolved well.

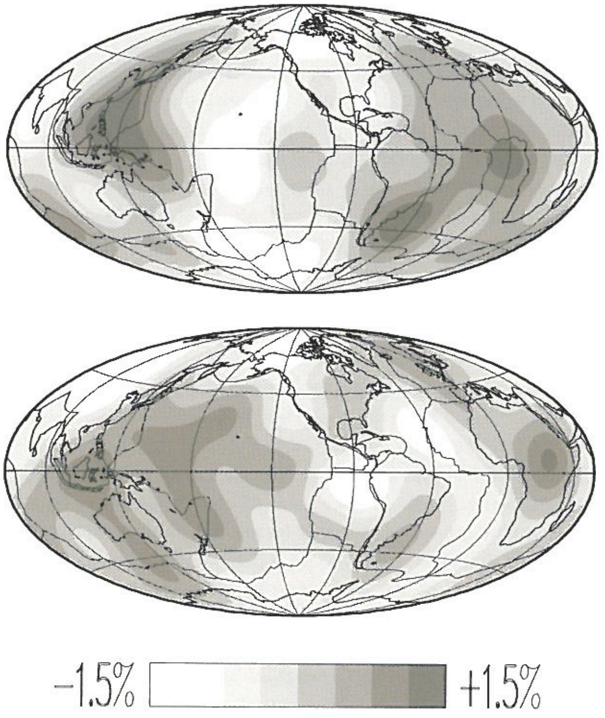


Figure 2

A resolution study by Johnson et al. demonstrates that we have sufficient data to resolve the spectral diagnostic. A challenge for the next few years will be to carry out experiments that will bridge the current gap between the regional and global scale images of subducted material in the transition zone.

Core—Mantle Boundary

Knowledge of the seismic velocity structure at the base of mantle is of great importance in Earth sciences. The origin of velocity anomalies in the deepest 150—300 km of the mantle, a region called D", is key to the understanding of the composition of the mantle, its evolution and the style of mantle convection . The seismic velocity discontinuity between D" and the rest of the mantle, if it exists, implies the presence of radial heterogeneity in composition or a phase change some 200 km above the core—mantle boundary (CMB).

In the "reflection" approach, seismologists focus on observation and interpretation of signals reflected or scattered from internal structures other than those defined in a reference Earth model. The amplitude of the observed signal depends on the gradient of the structure. In the "refraction" approach, which relies on travel-time anomalies, the signal is equal to the integral of the anomalies along the entire ray path. Thus, the refraction method has an advantage in recovering large-scale structure. Conversely, the reflection method has an advantage in locating rapid changes in seismic wave speed. It is easy to understand why these two methods would arrive at different answers. What is disturbing, however, is that, unlike the convergence of these approaches when applied to the upper mantle, present models of D" appear to give divergent pictures. The "reflection" approach indicates that D" is characterized by the presence of scatterers, as first shown by Cleary and Haddon, of 10—100 km dimensions. Lay and Helmberger proposed a horizontal discontinuity, on the order of 2—3%, in shear velocity some 200—300 km above the CMB in various parts of the world. Weber demonstrated rapid variation of the presence or absence of reflections from D". He concluded that representation of the D" discontinuity by a simple, nearly horizontal boundary is not valid, and that focusing— defocusing of the wave energy by the 3-D heterogeneity may play an important role in generating the observed waveform complexity.

On the other hand, global tomographic models show high level of heterogeneity at the base of the mantle, too large to be a low passed residual of highwave number structure. Su et al. have shown that the power spectrum of velocity anomalies in the lowermost

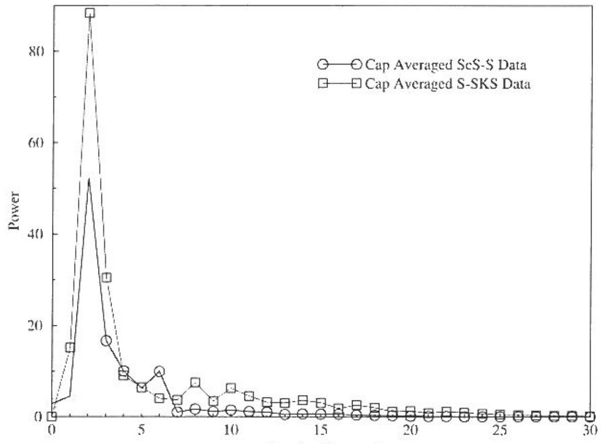


Figure 3

mantle is dominated by the gravest spherical harmonics, in particular, angular degrees 2 and 3. This is also visible in the pattern of data such as ScS-S residuals, whose power spectrum is shown in Figure 3. This distinct feature occurs not only in a model derived using an inversion procedure that may enhance large-scale features, but also in lightly smoothed data (5 degree cap averages).

The resolution tests performed by Su et al. indicate that the radial resolution of their model is rather poor in the lowermost mantle and that the possible distinct properties of the D" region could be averaged with those of the mantle above it. To improve the resolution in D" we need data that are highly sensitive to its properties. The differential travel times of S-SKS satisfy this requirement, particularly if one uses diffracted SH. Liu and Dziewonski have collected some 3,500 such observations in a distance range from 85 to 130 degrees. The diffracted SH has a considerably longer path in the D" region than ScS at, say, 60 degrees. Consequently, it should be more sensitive to the properties of this region. The power spectrum of the cap-averaged S-SKS residuals is also shown in Figure 3. It has essentially the same structure as the ScS-S data, other than its maximum power is about twice that of the latter.

We conclude from this that a very large-wavelength structure at the base of the mantle, extending at least 500 km above the CMB, is one of the fundamental properties of the Earth. At this time there is no explanation of this phenomenon in terms of modelling mantle convection, nor do we know the magnitude of the temperature and density perturbations associated with these large (3-4%) variations in shear velocity. As in the previous examples, it is necessary - through cooperation with geodynamicists, mineral physicists and geochemists - to gain better physical understanding of the processes involved before planning more detailed seismological experiments.

Inner Core Anisotropy

The fiftieth anniversary of the discovery of the inner core by Lehmann coincided with the first reports of a new property characterizing this region of the Earth. Pursuing two independent lines of evidence, Morelli et al. and Woodhouse et al. inferred that the inner core shows cylindrical anisotropy with the axis of symmetry aligned with the axis of rotation of the Earth. In both models the difference between the P-wave velocity along the axis and in the equatorial plane slightly exceeds +3% at the inner core boundary (ICB).

This finding has an important implication with respect to the constitution and evolution of the inner core: iron in the inner core is most likely in hexagonal closely packed coordination and the alignment of its crystals with respect to the axis of rotation could reveal the conditions at the time of crystallization. The causes of anisotropy proposed so far are degree one convection and freezing of epsilon-iron in the presence of a magnetic field. One might expect that a more detailed analysis would facilitate the inference of the physical mechanism leading to the preferential orientation of crystals.

A recent study involving analysis of 27 years of the ISC Bulletins indicates that the issue is more complex than the initial reports

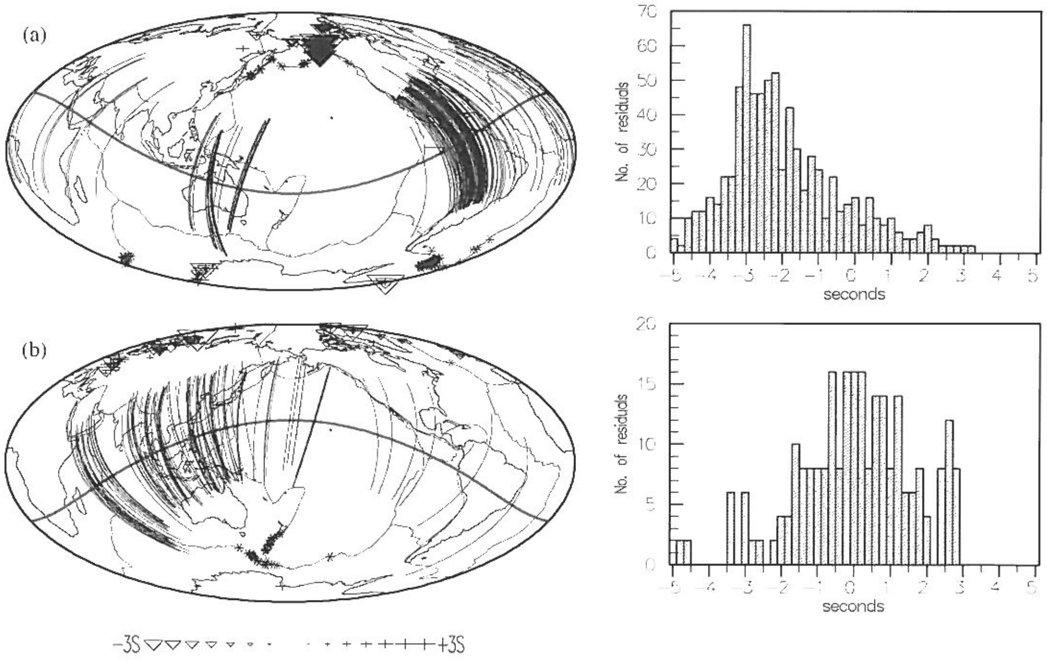


Figure 4

implied. This complexity contributed, in part, to the confusion with regard to the magnitude of the effect, as reported in various papers. Figure 4, comprising roughly 400 PKIKP observations out of a total of 400,000 is intended to demonstrate this complexity. Figure 4a shows a map of the rays observed in a distance range from 150 to 153 degrees that pass through the inner core having an angle between 60 and 70 degrees with the rotation axis and their bottoming point is within 10 degrees of the great circle with a pole at 65N and 180E. The location of the sources are shown as crosses and the size of the anomaly at the receiver is indicated by the type and size of the symbol.

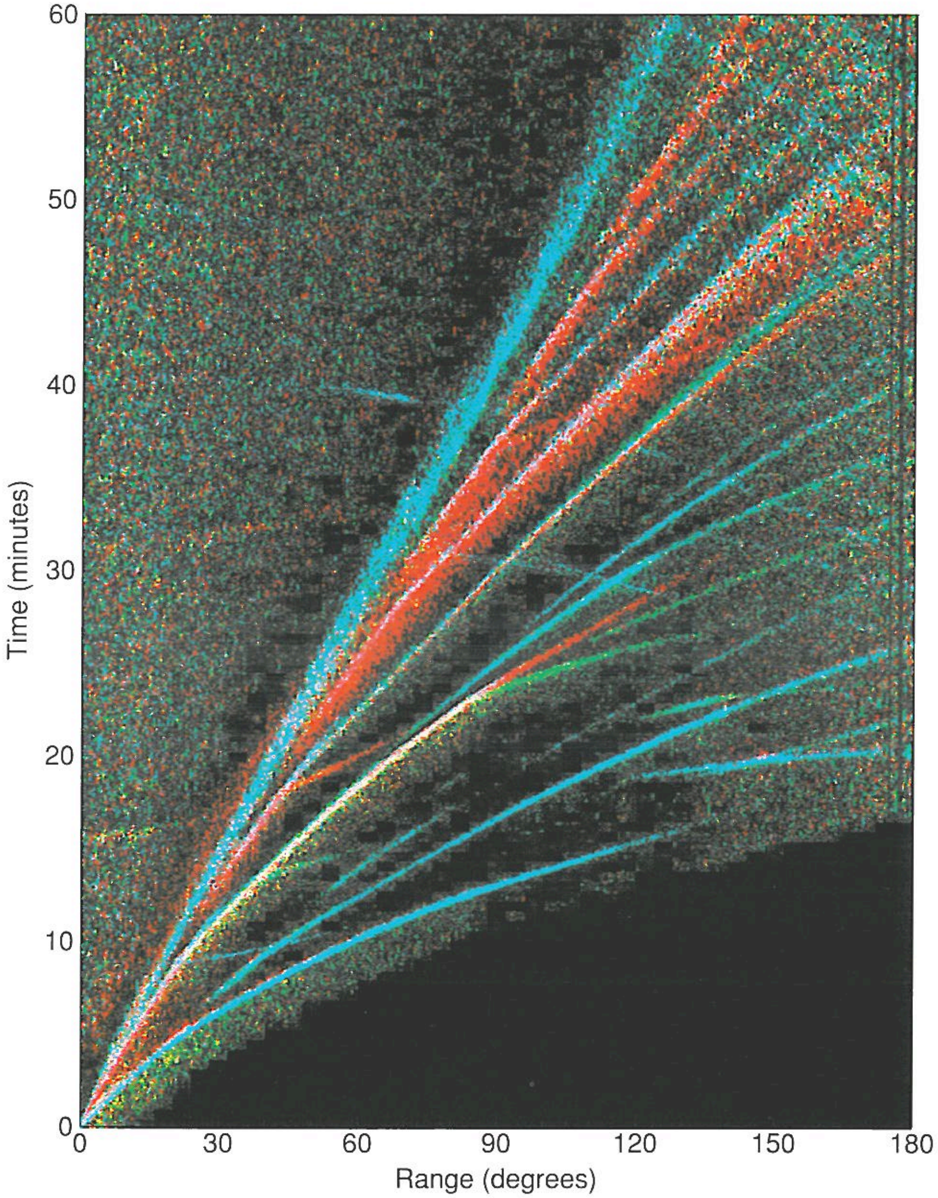
Most of the sources are in the S. Sandwich Islands and most of the receivers in Alaska. The residuals are predominantly negative; as shown by the histogram on the right. The average residual is -2.3 seconds. Figure 4b corresponds to the rays arriving in the same epicentral distance and having the same angle with the rotation axis, but the longitude of the great circle pole is in this case at 0 degrees. Most of the sources are near the Macquarie Ridge and most of the stations in northern Europe. The residuals have mixed signs, with the maximum in the histogram near zero (-0.1 s). If the axis of the cylindrical anisotropy were aligned with the axis of rotation, than the two histograms, or average residuals, should be the same; they clearly are not. One explanation, supported by the rest of the data, is that the optimum axis of symmetry is inclined with respect to the axis of rotation. Su and Dziewonski estimate this angle to be 10.5 degrees, with a standard error of 1 degree. Their additional findings include an increase in anisotropy near the center of the Earth and longitudinal variations with a periodicity of 180 and 90 degrees and amplitude on the order of 1 second.

The question of anisotropy in the inner core has attracted the attention of mineral physicists and geomagneticians. It would be fruitful to cooperate with these groups in designing seismic experiments aimed at resolving the issue of the type and cause of the inner core anisotropy.

Stacking of Global Data

Peter Shearer

University of California, San Diego



During the last five years, IRIS has accumulated a substantial archive of seismograms from global earthquakes. The ready availability of these data from the IRIS Data Management Center (DMC) make it possible to stack records from hundred of earthquakes to produce global seismic record sections and to image weak seismic phases that are not apparent on individual seismograms. The improved station coverage and broader frequency response of the IRIS stations promise that these images will resolve details of Earth's internal structure with higher resolution than prior studies.

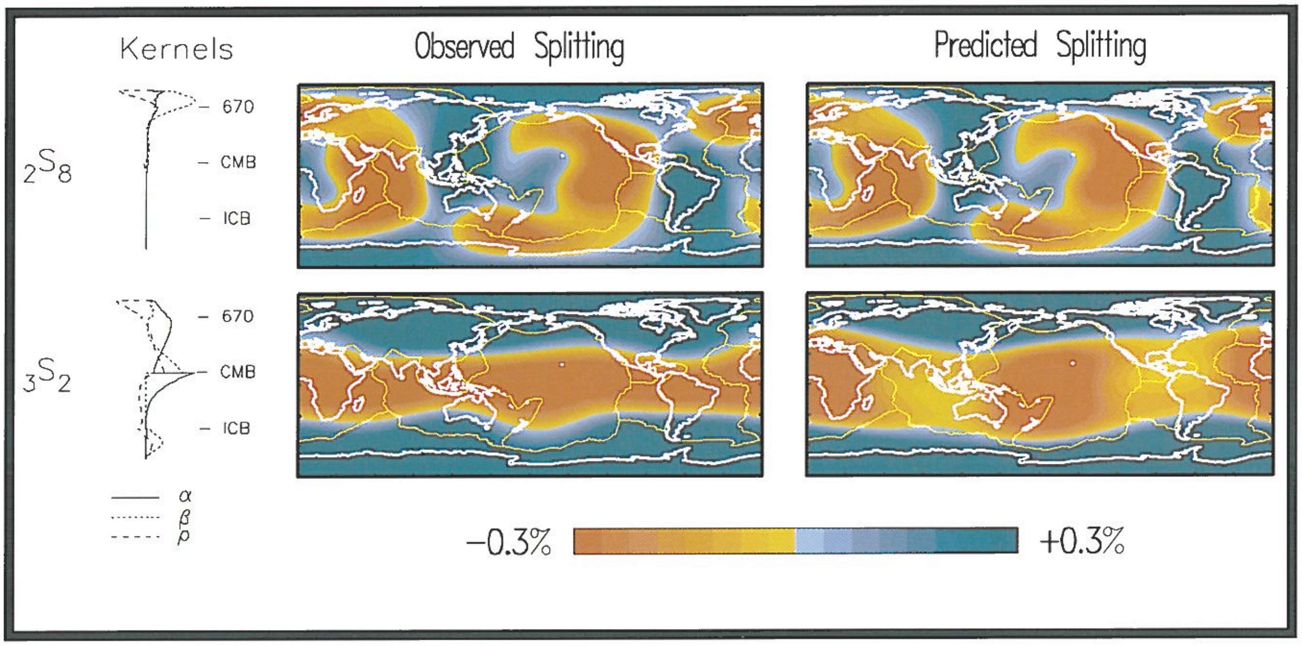
This is an image of seismic body waves generated by earthquakes (Mw>5.7) recorded by IRIS from 1990 to mid-1994. Approximately100,000 individual seismograms were processed in order to produce this image. In the past, accessing this number of global records would have been extremely difficult, since they would have been stored on many different computer tapes, often in different formats and archived at different institutions. Now, however, the data are available over the Internet from the IRIS DMC and may be obtained in identical format with a single request.

This accessibility is a key advantage for those who use seismic data for studying Earth structure, since random access to older data is of equal importance to records from the most recent earthquake. Many stacks are sorted by range or by midpoint location, and require seismograms from throughout the waveform archive, rather than from a particular source or receiver location.

As the IRIS data continue to accumulate, noise levels in waveform stacks will be reduced and increasingly subtle features in the wavefield will become resolvable. These include discontinuity phases from interfaces in both the upper mantle and the D" layer; these phases provide constraints on the amplitude, topography and sharpness of the discontinuities that are likely to play a key role in answering many outstanding questions regarding mantle compositition and dynamics.

Structure of the Mantle and Inner Core from Free Oscillations

Jeroen Tromp & John He
Harvard University



Every seismic free oscillation or normal mode of the Earth 'sees' Earth structure differently. Some modes are predominantly sensitive to the shear-speed structure of the mantle, other modes see a combination of shear and compressional speeds. There are observable modes that see all the way into the inner core, whereas others are confined to the crust. How a given normal mode samples the structure of the Earth is determined by kernels which describe a mode's sensitivity to compressional speed, shear speed and density as a function of depth.

In the left column of the figure the sensitivity of two normal modes to degree zero perturbations in compressional speed~α (solid line), shear speed~β (short-dashed line), and density~ρ (long-dashed line) is shown as a function of depth. The radii of the inner-core boundary (ICB), core-mantle-boundary (CMB) and the 670 km discontinuity (670) have been labeled. In the center column the observed splitting function, which is a function of latitude and longitude, is displayed. The splitting function may be regarded as a local radial average of the Earth's three-dimensional structure. The manner in which a mode averages the Earth's structure is determined by its sensitivity kernels, some of which are shown in the left column. Blue colors correspond on average to fast velocities whereas red colors reflect slow velocities. Mode $_2S_8$ is predominantly sensitive to structure in the mantle whereas $_3S_2$ sees all the way into the inner core; this difference in sensitivity is reflected in the observed splitting functions. For $_2S_8$ the splitting function predicted by mantle model SKS12WM13, determined by Liu & Dziewonski, is shown in the right column. Multiplet $_2S_8$ is predominantly sensitive to shear-speed perturbations and its splitting function is quite well predicted by shear velocity model SKS12WM13. The splitting of mode $_3S_2$ is severely underpredicted by mantle model SKS12WM12. A collection of about 20 such anomalously split modes has presently been identified. The anomalous splitting of most core-sensitive normal modes may be explained in terms of inner-core anisotropy of the same magnitude and radial distribution as inferred from the anomalous traveltimes of compressional waves that traverse the inner core. The splitting prediction of mode $_3S_2$ shown in the figure is based upon mantle model SKS12WM12 and an anisotropic inner core model.

Waveform Inversion of Body Waves by Mode Sums

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Xian Dong Li
University of California, Berkeley

The accumulation of high quality digital broadband data from the new generation Global Seismographic Network allows to combine recent theoretical developments in wave propagation with analysis of such data to achieve better resolution in global mantle tomographic modeling.

Classical waveform tomography relies on the "path average approximation" (PAVA), in which the sensitivity of seismic waves to lateral heterogeneity is restricted to the horizontally averaged structure along the slice of earth spanned between the source and the receiver. While valid for surface waves, this approximation fails to describe the ray character of body waves. In order to improve the resolution in the lower mantle, travel time data can be added to the inversion. This however only helps in some regions of the mantle, sampled by well isolated phases on the seismograms. Also, the sensitivity of the travel times to structure is generally assumed to be uniformly distributed along the ray. This assumption, valid in the high frequency limit, becomes less justified at lower frequencies, such as used in waveform inversions. On the other hand, it is possible to improve this situation by modifying the normal mode theory to include coupling terms between different normal mode branches that make up each bodywave train, which are ignored in the path average approximation.

While other, more exact approaches are being actively pursued, we have developed a procedure to invert waveforms on the global scale using the non-linear asymptotic coupling theory (NACT) which includes, to first order, coupling effects between appropriate mode branches. The data used presently are SH waveforms of surface waves as well as body waves of various types (S, multiple S, Sdiff, ScS...) at periods greater than 80 sec and 32 sec respectively. A total dataset of over 6000 surface wave and over 7000 body wave seismograms are included and the model is expressed in spherical harmonics up to degree and order 12. Our tests indicate a significant improvement in resolution of structure in the mid and lowermost mantle using the NACT technique as compared to the PAVA (Figure 1).

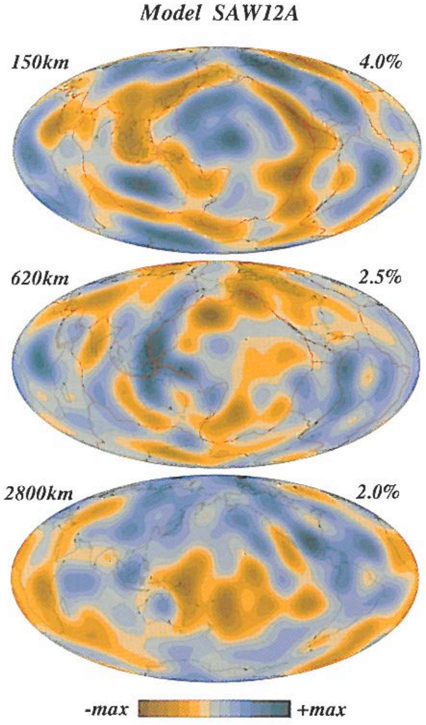


Figure 2: Maps showing lateral variations in S velocity at different depths for model SAW12A. The scale for each plot is shown in the upper right hand corner.

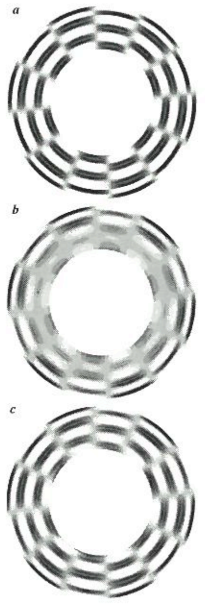


Figure 1: Checkerboard test results for comparative resolution of PAVA and NACT methods. a) depth cross-section in the mantle showing input checkerboard pattern; b) result after inversion using PAVA; c) result after inversion using NACT. The synthetic data distribution is that used in actual inversion of real data.

Another powerful procedure, not commonly applied so far in waveform modelling, is to assign, within each bodywave trace, we assign different weights to each wavegroup, which may contain more than one bodywave phase. This improves the sampling of certain regions in the mantle by emphasizing phase groups whose amplitudes have a good signal to noise ratio, but are overwhelmed by other phases in the seismogram.

Our current models show many features that are in agreement with other mantle tomographic models, but they also present several characteristics of interest to the current geodynamical debate (Figure 2)

1) slab related features in the western Pacific and south America (Figure 1) appear to extend across the 670 km discontinuity down to at least 800 km depth, in agreement with more detailed regional studies and numerical simulations with temperature dependent viscosity.
2) The profile of total rms amplitude of lateral heterogeneity as a function of depth is characterized by large amplitudes at the top and the bottom of the mantle, with a zone of increased rms near the core-mantle boundary confined to a narrower zone (about 350 km thick) than in some other models.
3) There is a zone of increased rms centered around the 670 km discontinuity, which we have tested to be a stable feature of our models.
4) The spectrum of our model as a function of depth is characterized by the fact that the region of increased rms around the 670 km discontinuity is strongly dominated by degree 2, similar to what is observed at the very bottom of the mantle, whereas in the mid-lower mantle, the spectrum is much more flat, possibly indicating the existence of a thermal boundary layer at the 670 km discontinuity.

There are still some gaps in the distribution of available data: the northern hemisphere is much better sampled than the more oceanic, southern hemisphere, resulting in poorer resolution in the lower half of the lower mantle in the southern ocean and Antarctica. The addition of global IRIS stations on islands in the southern Pacific and Atlantic ocean, as well as the deployment of semi-permanent broadband ocean floor observatories will enable to rectify this unbalance, which repeatedly brings up questions on the reliability of features seen by global seismic tomography, especially at shorter scales.

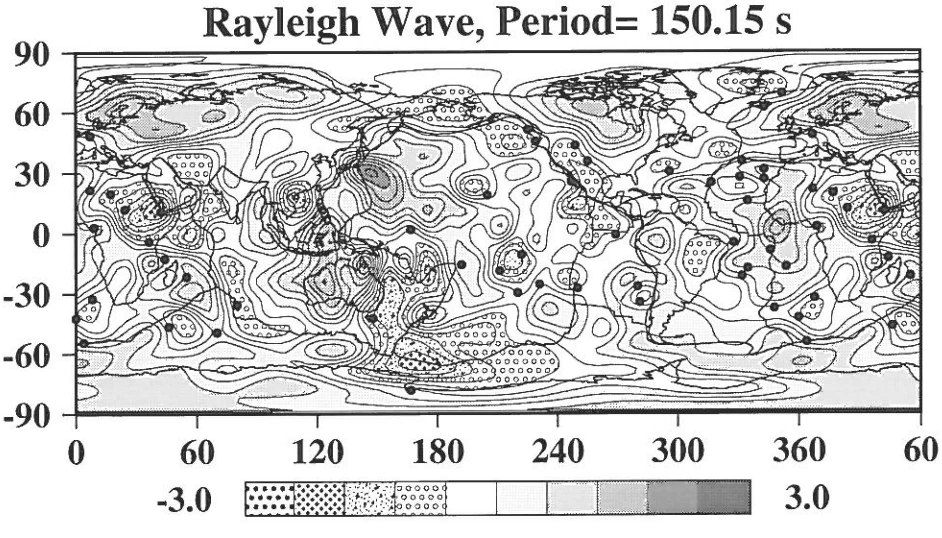
Global Surface-Wave Phase Velocity Variations

Yu-Shen Zhang and Thorne Lay
University of California, Santa Cruz

To understand the dynamical process inside the Earth, it is necessary to develop a detailed three-dimensional Earth model. We have collected all data of earthquakes with M> 6.0 recorded by GSN, GEOSCOPE and CDSN networks between January, 1980 and June, 1992, thanks to the development of the IRIS Data Management Center and investigated the global surface-wave phase velocity variations. Our dataset has about 30,000, high quality waveforms, for which fundamental mode R1, R2, G1, and G2 phase anomalies have been measured in the 85-300 s period range. This exceeds the data used in RG5.5 (Zhang andTanimoto, 1992, 1993) by a factor of two, with many noisy signals having been removed.

The discrepancies in previous seismic inversions involve magnitude differences and features associated with high order terms. To solve these problems, we introduced the statistic theory and Bayesian inference in the inversion process to find the optimal damping parameter and to stablize the inversion. The spherical harmonic expansion and block parameterization are two common model parameterization methods. We tested these two methods and found that the spherical harmonic expansion has stronger and more robust energy in the lower order terms than the block method, but the high order terms in the spherical harmonic method are unstable. Our final result is a joint inversion using these two methods; the low order terms are associated with a spherical harmonic expansion and the high order terms are estimated with a block method. We introduced the AIC method in the study, in which the optimal result,the closest approximation to the true earth structure, will have the maximum likelihood. We have performed two different kind of inversions, one without any correction, the other is with an a priori geophysical parameterized model. We found that a constant lateral resolution cannot be achieved as frequency varies, and the lateral resolution decreases as the period increases.

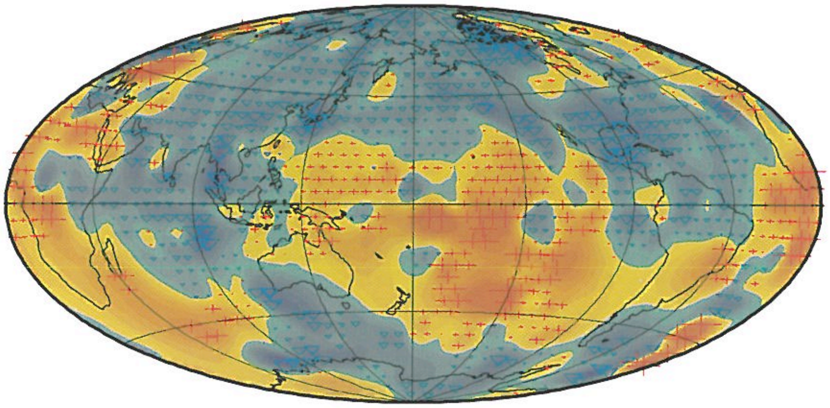
The figure shows the Rayleigh wave phase velocity variation without a priori information at a period of 150 s. The long-wavelength features are consistent with previous global and regional studies. For example, the old continental cratons have strong fast velocity anomalies and the phase velocity increases with age in the oceanic area. The more interesting point is that the hotspot features, especially hotspots near ridges, show up clearly, and indicate the difference between ridges and hotspots.



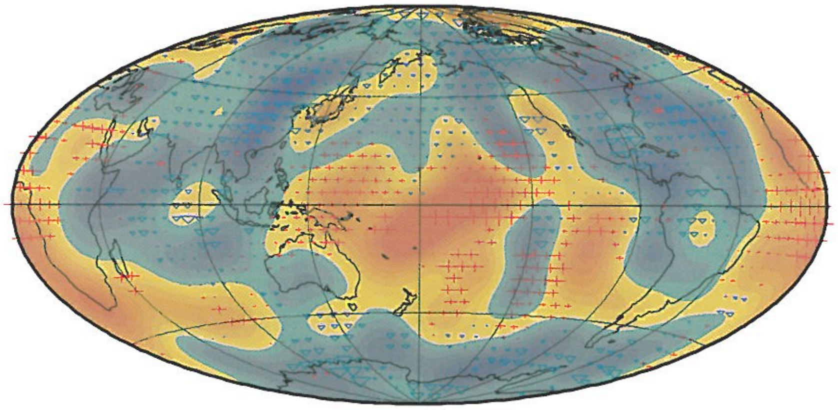
Rayleigh wave phase velocity variation at a period of 150 s. It is associated without a priori information. The solid circles are hotspot locations. The coastlines and plate boundary are also plotted in the map. The scale is at the bottom and the contour interval is half of the pattern interval.

Shear velocity in the Lowermost Mantle From S-SKS Differentials

Xian-Feng Liu
Harvard University



Over 2,600 measurements of S-SKS traveltime residuals averaged in 5 degrees spherical caps and their degree-36 expansion in spherical harmonics. Note the distinct pattern of negative anomalies in the Central Pacific and under Africa.

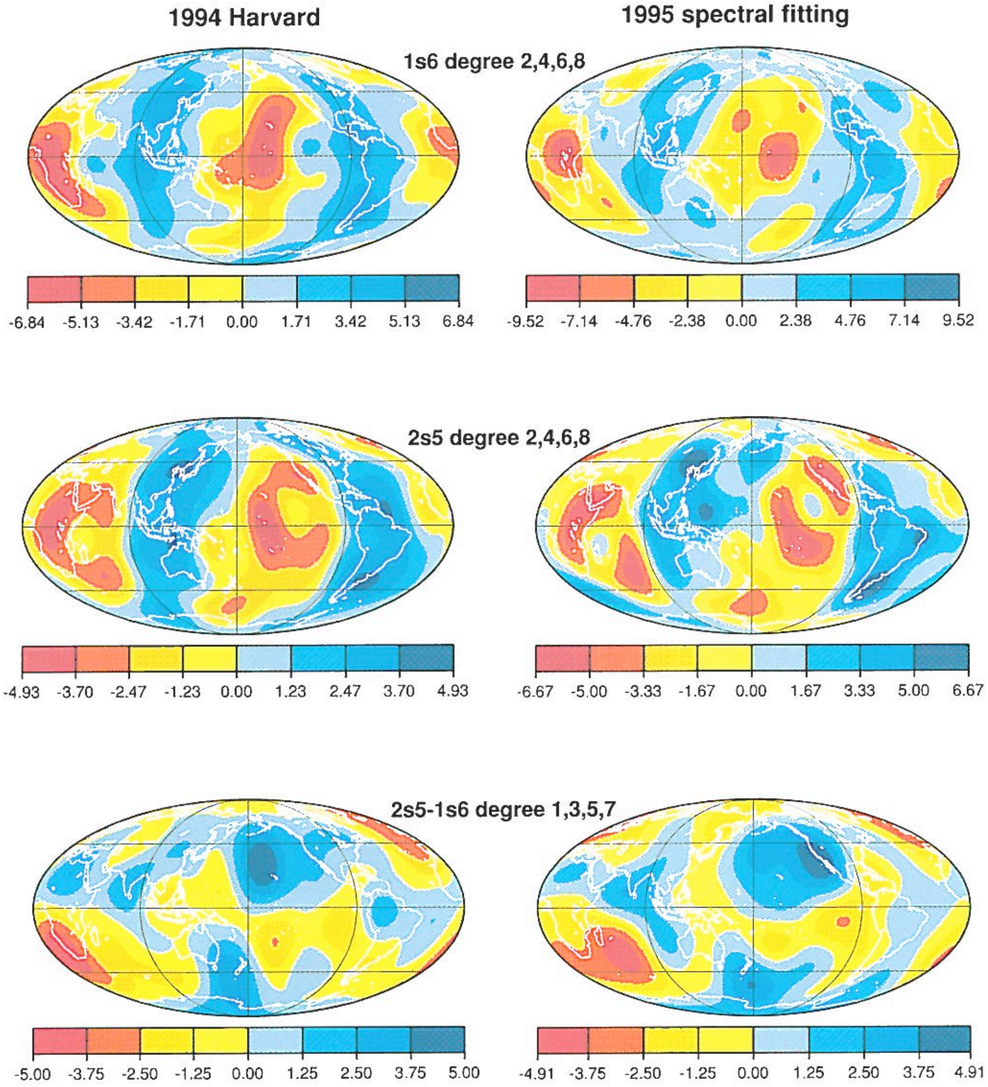


The whole mantle degree - 12 earth model SKS12_WM13 at the depth of 2800 km. The symbols predict S-SKS traveltimes for the measurements in the top map.

By matching the recorded seismogram with a synthetic that is calculated by normal mode summation with a cut-off period of 8 seconds, we have made over 2,600 measurements of S-SKS differential traveltime residuals. Combining this new data set, mainly sensitive to the shear wave velocity anomalies in the lowermost mantle, with other data, such as SS-S and ScS-S traveltimes and the waveform data, we have inverted for a new degree mantle 12 earth called SKS12-WM13. The resolution test shows that SKS12-WM13 has indeed improved the resolution in the lowermost mantle. The shear wave velocity anomalies of SKS12-WM13 are dominated by long wavelength structures, and have a pattern similar to the previous degree 12 model S12-WM13. However, the root-mean-square amplitude of velocity anomalies in SKS12-WM13 increases dramatically in the lowermost mantle and peaks at the core-mantle boundary. These features exist in other three-dimensional earth models, and may indicate strong compositional hetrogeneities in the lowermost mantle and that core-mantle reactions may be important in their origins. There is an excess of extreme slow velocity anamalies (-4.7%) relative to the fast one (3.6%) in our model SKS12-WM13. It may result from chemical reactions between the core mantle and the lower mantle material.

Analysis of Coupled Low Frequency Normal Modes

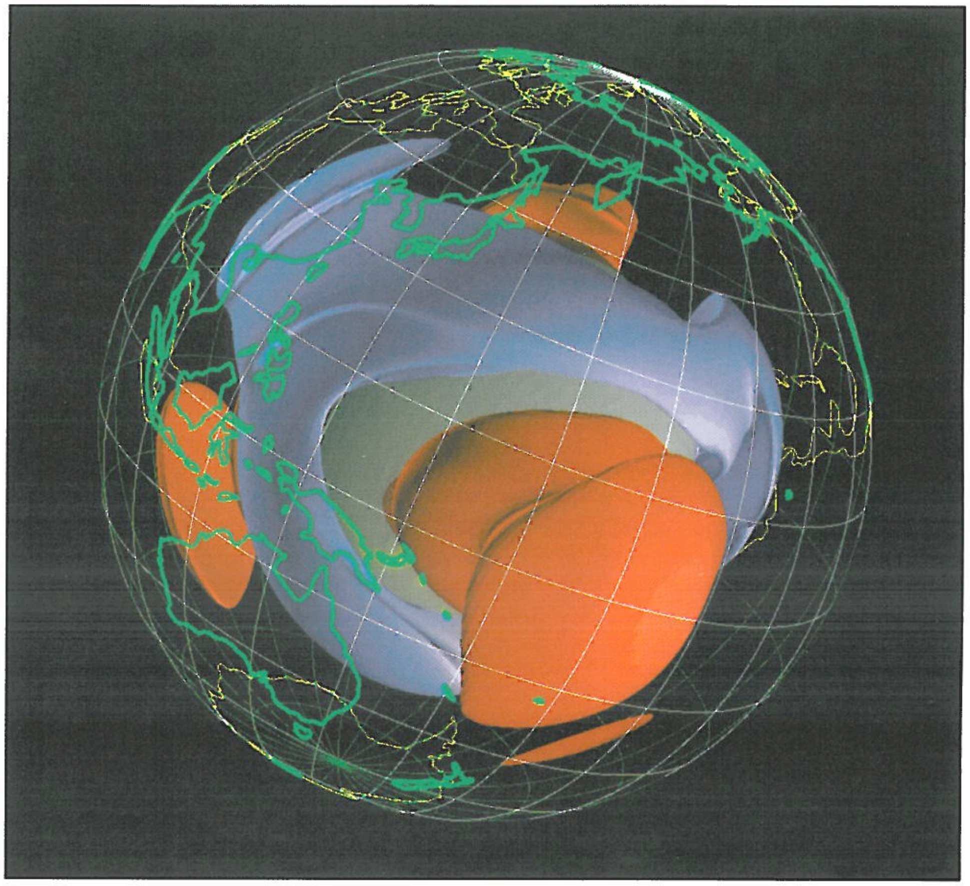
Joseph S. Resovsky and Michael H. Ritzwoller
University of Colorado, Boulder



Until recently, only the simplest normal mode constraints on models of mantle structure have existed, primarily because the available set of high signal-to-noise long-period seismic data was very limited. Precise measurements of signal of structure of degree greater than 4 and of inter-multiplet coupling were impossible. Each of these effects can bias degree 2 and 4 measurements, and coupling provides the only normal mode estimates of odd-degree structure. It is, thus, significant that, primarily due to the efforts of IRIS to expand the GSN and to disseminate broadband data, the large and deep earthquakes of the past few years have provided us with a greatly expanded high-quality low-frequency data set. Displayed in the accompanying figure are the results of a generalized spectral fitting regression for the pair of coupled overtone multiplets ${}_2S_5$-${}_1S_6$. The data employed are dominated by the waveforms from IRIS's GSN. Approximately 500 seismograms are used to estimate the 128 free parameters which describe the splitting and coupling of these multiplets by Earth structures of even and odd degrees 1-8. Compared to regressions of just a few years ago, this is more than a threefold increase in both data input and information output. The observed spherical harmonic structure coefficients are summed and mapped as splitting functions, on the right, which may be compared to the predictions of the Harvard model S12-WM13, shown on the left. The odd-degree splitting function (lower right), resulting from the measurement of inter-multiplet coupling coefficients, represents the first normal mode constraints on odd-degree structure. The confidence in this new result rests partially on the high correlation with the Harvard model, which was constructed using entirely different types of measurements. Both the magnitudes and correlations of the even and odd degree splitting functions agree quite well with the Harvard model up through degree 5. However, the observed splitting functions are enriched at shorter wavelengths relative to S12-WM13.

Shear Velocity Throughout the Mantle

Wei-jia Su and Adam Dziewonski
Harvard University

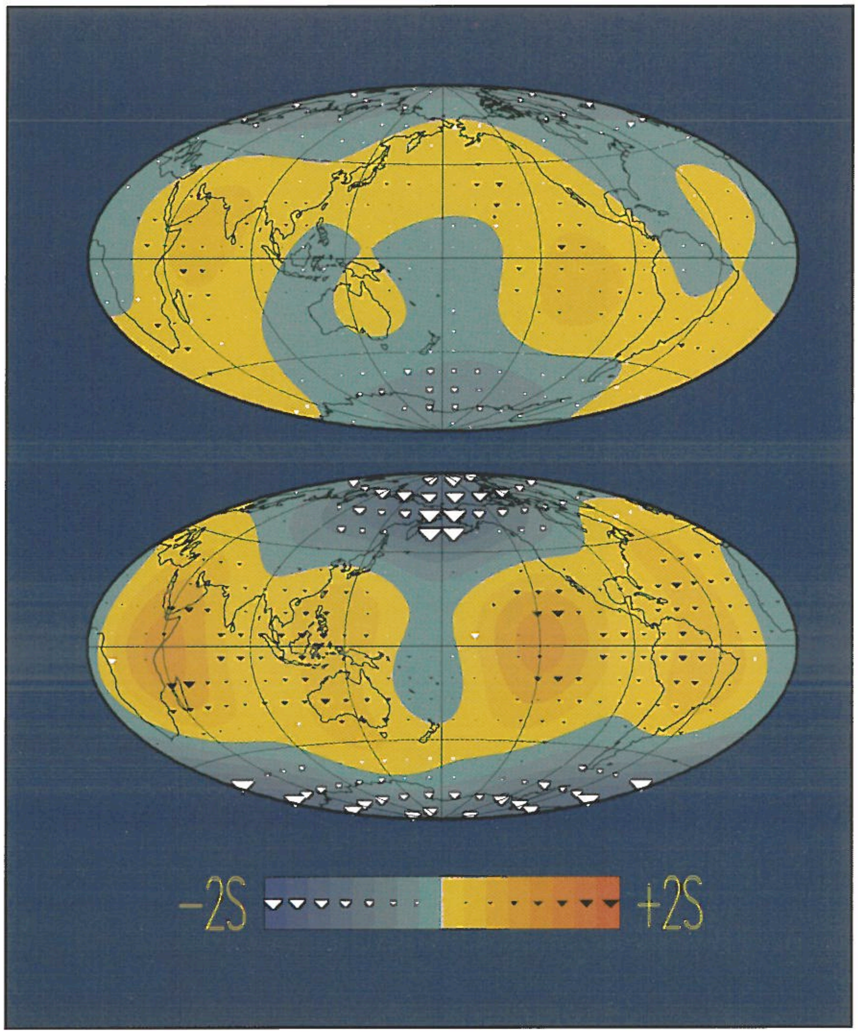


We obtain a three-dimensional model (S12-WM13, Su et al., 1994) of shear wave velocity heterogeneity within the Earth's mantle by inverting a large set of seismic data consisting of 27,000 long-period seismograms and 14,000 travel time observations. Compared with previous work, much of new data from stations of different seismic networks such as the Chinese Digital Seismographic Network and Geoscope has been used. The model is expanded in terms of spherical harmonics up to degree 12 to describe horizontal variations, and Chebyshev polynomials up to order 13 to describe radial variations. The model shows a clear pattern of slower-than-average shear velocities at shallow depths underlying the major segments of the world-wide ridge system. These anomalies extend to depths greater than 300 km and in some cases appear to continue into the lower mantle. There is also a good correlation between the major continental shields and fast-velocity perturbations at depths extending to 300-400 km. Some of the continental "roots" extend to depths greater than in other studies. The pattern of heterogeneity is more complex in the midmantle, where the power spectrum is almost flat and has a relatively low amplitude. The long wavelength part of the model shows, however, a clear pattern. The figure shows a three dimensional view of model S12-WM13 from depth 1000 km to the core-mantle boundary. The viewpoint is above the Pacific Ocean. The red represents the isosurface of seismic velocity 0.35% slow relative to PREM blue is the isosurface for of seismic velocity 0.35% faster. Only degrees 1-4 in the models are plotted. We see a ring surrounding the Pacific, and a big plume-like slow velocity volume arising from the CMB. The power spectrum of the model shows a rapid change at a depth of 1700 km. The power spectrum shifts from one which is almost flat in the midmantle to that dominated by degrees 2 and 3; this pattern continues to the core-mantle boundary. The model is dominated by a few megastructures of velocity heterogeneity below the depth of 2000 km, in agreement with previous studies. Among these megastructures are the "Pangea Trough," "Great African Plume," and "Equatorial Pacific Plume Group." The model predicts well the observed travel times and the waveforms of mantle waves and body waves.

Inner Core Anisotropy from Body Wave Travel Times

Wei-jia Su and Adam Dziewonski
Harvard University

In our most recent work, we investigate the cylindrical anisotropy of the inner core. We use the arrival times reported in the International Seismological Centre Bulletins for years 1964—1990. We select only earthquakes which have a good azimuthal coverage and a sufficiently large number of reporting stations. The earthquakes are relocated using corrections for lateral heterogeneity computed for our most recent three-dimensional mantle model. We use a total of 313,422 observations of the DF branch of PKP travel time anomalies reported by 2335 stations for 26,377 earthquakes. We process the data using cylindrical anisotropy stacking, that enhances the effects of anisotropy, but is expected to suppress the effects of lateral heterogeneity and random errors.The figure shows the residuals for epicentral distance ranges120°-130°(top panel) and 150°-153°.The top panel demonstrates that the signal could not have come from the mantle or outer core, since for this epicentral distance range, the ray just grazes the inner core. When the ray penetrates deeper, we see a clear signal inner core anisotropy. It also indicates that the axis of symmetry of anisotropy aligned tilted 10.5°±1° from the Earth's rotation axis in the direction 160°E±5° in the northern hemisphere. We determine a four-layer axisymmetric model of transverse anisotropy with each layer approximately 300 km thick. The model shows that the anisotropy is strongest (>3%) within the innermost part of the core. The travel time anomalies show significant (±1.5) longitudinal variations, even when the tilt of the axis of symmetry is considered. There is a substantial increase in the amplitude of the longitudinal variations,which are dominated by the second and fourth harmonics, for rays with bottoming depths deeper than 400 km below the inner core boundary. The measurable tilt of the axis of symmetry and the presence of significant non axisymmetric signal may provide important clues to the possible causes of anisotropy. The increase in the anisotropy in the innermost part of the core departs from earlier inferences that anisotropy may be limited to the outermost 200-300 km of the Earth's inner core.



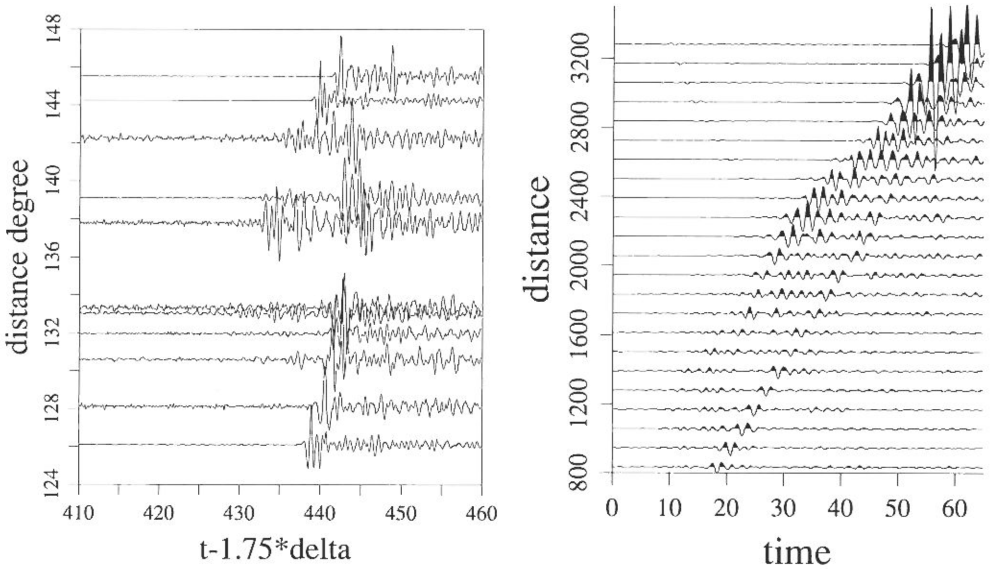
Scattering by Small-Scale Heterogeneity at the Core-Mantle Boundary

Xiao-Bi Xie and Thorne Lay
University of California, Santa Cruz

The D" region is a very heterogeneous layer at the base of the mantle that plays an important role as a major boundary layer inside the Earth. It is believed that the core is hotter than the mantle, thus heat enters D" from below, possibly with as much as a 1000 degree temperature drop.

The lateral variations in mantle ambient temperature associated with large-scale convection in the mantle modulate the heat flow out of the core, an effect that may drive flow of the uppermost layer of the core. The strong temperature increase in D" is likely to cause a great reduction in viscosity, and should therefore make the boundary layer much more prone to thermal instabilities than the stiff lithosphere. As a result, the thermal boundary layer is expected to be heterogeneous, but there may also be chemical heterogeneity due to primordial density stratification of the mantle, core-mantle chemical reaction products, and/or subducted chemically differentiated remanents of slabs or melting products. Studies of the core-mantle boundary are slowly revealing its structure. New IRIS data have played an important role in studying this region, and in reopening areas of early seismological investigation. An example of the latter involves scattering of PKP phases from D" heterogeneity that results in 'precursors to PKIKP'.

The figure on the left below is a composite of broadband signals recorded at IRIS stations for PKP phases in the range where these precursors are most evident. The strong arrival near 440 s is PKIKP, and the earlier energy is scattered from D". Analysis of these precursors has emphasized their scattering directions and envelopes, but until recently there has been little waveform modeling performed because the problem involves complex three-dimensional scattering at the base of the mantle. We have introduced a new waveform modeling capability using the elastic-complex phase screen method to simulate three-dimensional scattering from D". The method is based on an elastic one-way wave equation that neglects backscattered waves but correctly handles all the forward multiple-scattering effects. Based on a dual domain technique that shuttles between the space and wave number domains with FFTs, this method achieves a very high computation speed, allowing the three dimensional random scattering structure of D" to be explored.We are able to consider heterogeneities as small as 10 km and the synthesis of short-period signals. The right hand side of the figure shows preliminary synthetic seismograms computed for a scatttering layer just above the core mantle boundary. The PKP precursors exist in the arc of arrivals ahead of the PKP phase that moves out from 20 to 60 s. The relative amplitude and timing of the precursors can be used to explore the statistical characteristics of D" heterogeneity, which can then be related to the thermal and chemical properties of the boundary layer.



(Left) IRIS broadband waveforms for PKP phases.The DF branch arrives around 440 s in the reduced time plot, and the early arrivals are scattered from D". (Right) Synthetic waveforms computed for a random scattering layer in D" using the new elastic complex screen method. The DF branch arrives at 20s and moves back linearly with distance. The arc of arrivals ahead of this branch involves scattered precursors. The synthetics are not on the same reduction velocity as the data, and do not yet have the correct geometric spreading, but the scattering properties are all included.

Imaging Core-Mantle Boundary Scatterers using PKPdf Precursors

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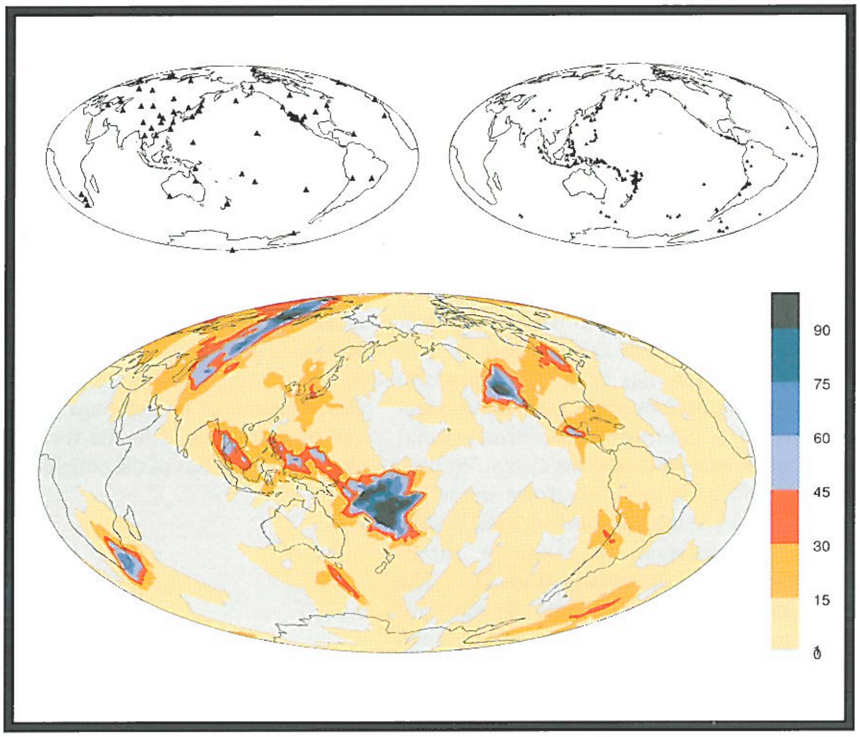

In the upper left figure we display the global network stations available during 1993. In the upper right we display the events greater than mb 6.0 that occurred in 1993 and were recorded between 120 and 140 degrees by these stations. In the lower figure the contours indicate the number of recordings in this dataset that could contain PKPdf precursor energy.

It is now well established that the lowermost few hundred kilometers of the mantle (henceforth termed the Core-Mantle Boundary Region or CMBR) is more heterogeneous than the mid-mantle. A major area of CMB research has involved observations of short-period precursors to PKPdf that arise from scattering at or near the CMB (e.g., Haddon, 1982). Theoretical modeling work has suggested that the observations can be explained either by small-scale (10 to 70 km) volumetric heterogeneity in the CMBR with 0.5% P velocity variations or by CMB topography with an rms amplitude of 280 m (Bataille & Flatte, 1988). Although heterogeneity has been detected within the CMBR at scale lengths from tens to thousands of kilometers (for a review see Lay, 1989 and references therein) the relationship between the small and large scale features is not known.

As with any medium that contains a broad spectrum of heterogeneities there is a dividing line between what can be described deterministically and what cannot be directly resolved and must be characterized statistically. This dividing line is determined not only by the scale range of the heterogeneities and the impedance contrast from the surrounding material, but the resolution of the imaging technique used to probe the medium and the intrinsic quality of the data (e.g. an absence of conflicting signals; low noise levels). Analyses of PKPdf precursors have generally assumed a stochastic approach to modeling the data. Thus, it is not known if the strength of the scattering varies with location on the CMB, or if there is any relationship between the position of the scatterers and the larger scale features seen in other studies.

Given the large recent increases in the quality and quantity of global seismic data, we believe that it may now be possible to obtain direct images of CMBR scatterers in certain well-sampled regions from PKPdf precursor data. We are currently involved in a comprehensive analysis of PKPdf precursors in broadband seismic data collected by the IRIS Global Seismographic Network.

The analysis will involve back-projecting the precursor energy recorded by the IRIS network stations into the CMBR or directly onto the CMB. By back-projecting energy from a large number of events we hope to resolve unambiguously prominent scatterers. Ultimately our goal is to relate our deterministic characterizations to the results of other CMB studies that infer small or large scale CMBR heterogeneity.

We illustrate the redundancy (fold) of coverage that may be achieved using global network data. We have considered deployments and events from broadband data obtained from the IRIS DMC for 1993. We have taken all available source-receiver pairs (within the range from 120 to 140 degrees - the range at which precursors are observed) and considered a global grid of scatterers at the CMB. We have used ray-tracing to determine how many times each scatterer might have produced a recorded PKPdf precursor. We expect high (greater than 30) fold over a region in the south Pacific covering 30 by 30 degrees and similar fold under North America and Europe. Large areas on the CMB have lower fold (one or greater); some areas are not sampled.

Seismic Evidence for Coherent Flow of the Lithosphere and Upper Mantle Beneath South America Since the Breakup of Gondwana

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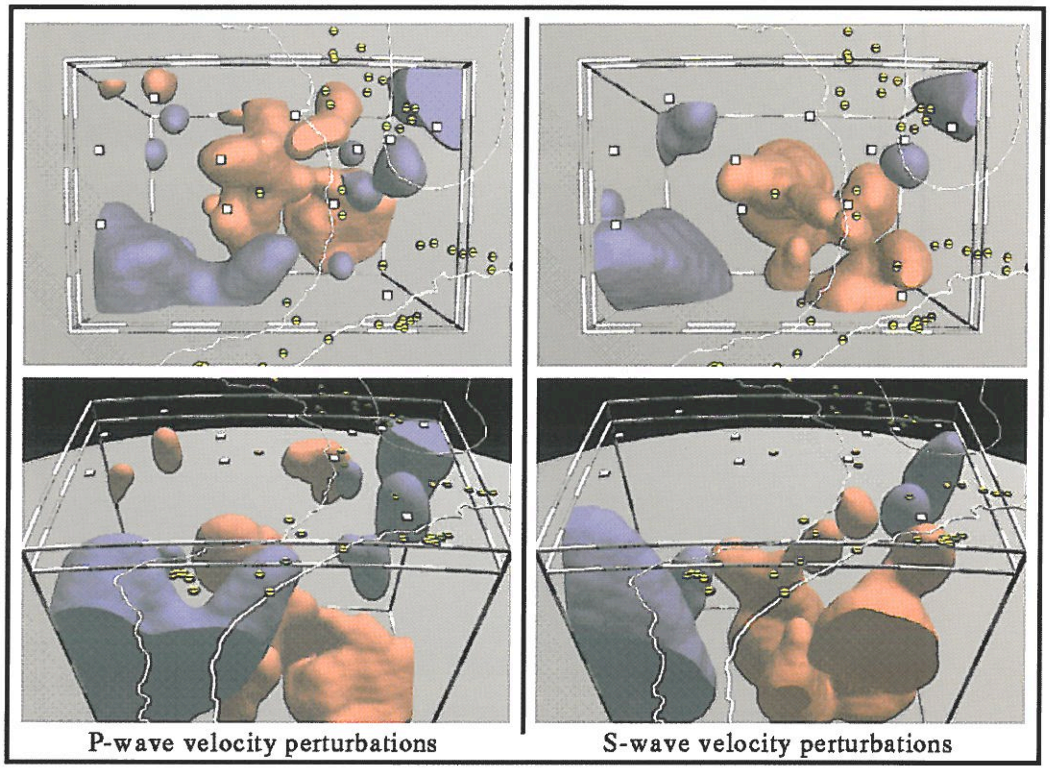

Figure 1. Perspective views of volumes enclosing high and low P-wave (left) and S-wave (right) velocity anomalies. The views are from 5000 km directly above the target region (top) and from an angle of 60 degrees from the vertical due South (bottom). The low velocity regions are enclosed by red surfaces and the high velocity by blue. Each encloses an equal volume of the target region, resulting in surfaces at 0.42% high- and 0.87% low-velocity for the P-wave model, and 0.5% high- and 1.375% low-velocity perturbation for the S-wave model. The underlying gray sphere is at 670 km depth. The seismic stations used in the inversion are shown as white squares and the yellow circles represent sites of Cretaceous alkalic volcanism,

Although the theory of plate tectonics explains well the major features that we observe on the Earth's surface, how those features are related to dynamical processes in the mantle beneath the plates remains controversial. The motion of lithospheric plates at the Earth's surface, for instance, is commonly considered to be largely decoupled from flow in the upper mantle beneath the lithosphere. There is evidence, however, that for some plates the lithospheric motion may be coupled to or even driven by flow in the underlying upper mantle. Seismic travel time inversion for the upper-mantle P- and S-wave velocity structures beneath the Brazilian shield (figure) suggest that the thermal residual of a Cretaceous plume is preserved in sub-lithospheric mantle near the region of its ascent about 100 Ma ago. The data constraining these models are teleseismic relative arrival times determined via a multi-channel cross correlation of waveforms recorded at 11 sites of the Brazilian Lithosphere Seismic Project (BLSP) broadband network in SE Brazil. This network takes advantage of portable instrument technology developed under the auspices of the IRIS PASSCAL program. The network traverses the four major tectonic provinces of the region - the Archean Sao Francisco craton, the surrounding late Proterozoic Brasiliano/Pan-African mobile belts, the intracratonic Parana basin, and the coastal Ribeira belt, an active transcurrent shear system. Despite having been independently inverted for, the P- and S-wave velocity perturbation models are remarkably consistent. Given the high absolute plate velocity of South America (3.5 cm/year), all residual thermal evidence for the plume in the deep upper mantle should have been left behind by the moving plate. That the signature has persisted close to its original relationship to the overlying continent since Cretaceous time indicates that the whole of the upper mantle has flowed coherently with the South American plate (figure). These results may support recent speculation by others that the South American plate is being driven by basal traction from sublithospheric upper mantle flow. The results presented here further suggest that, at least beneath South America, upper-mantle flow has been consistent with whole-mantle convection since the breakup of Gondwana.

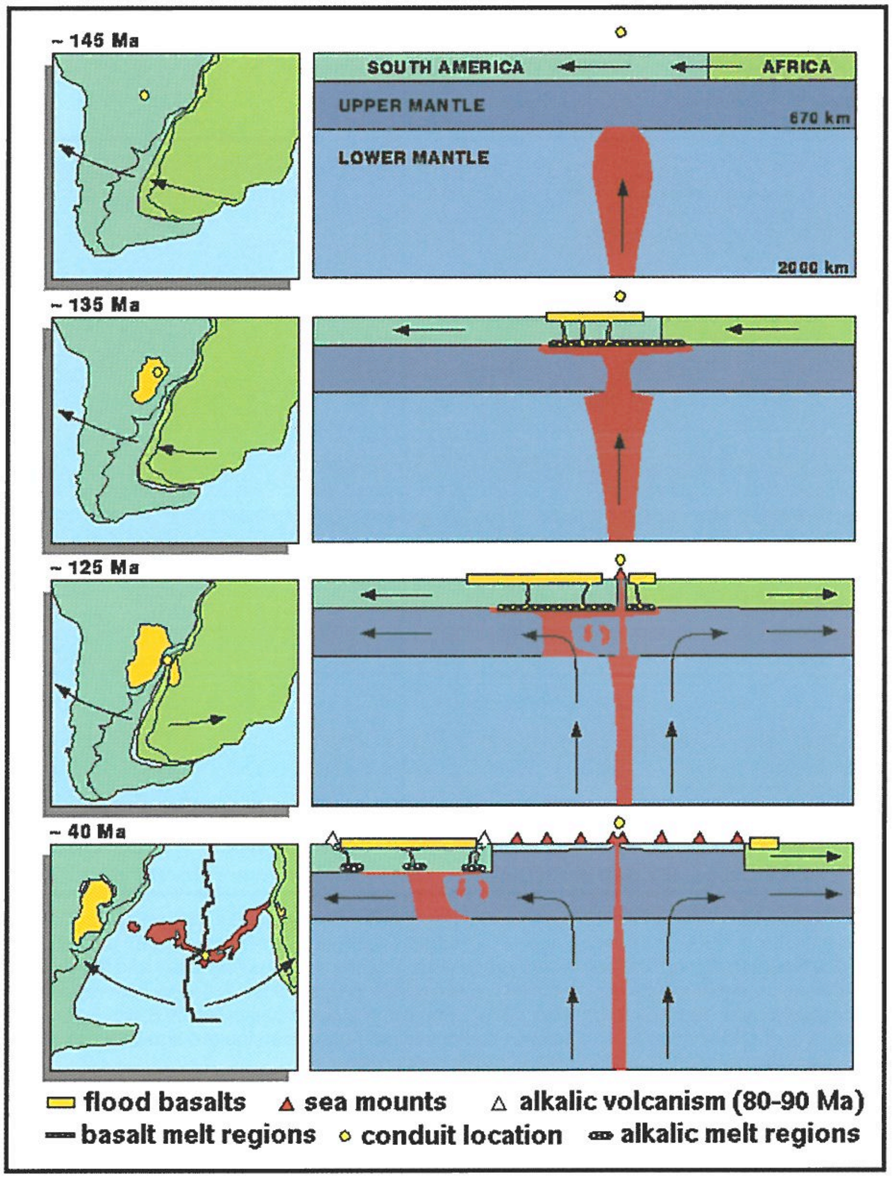

Figure 2. Cartoon schematic showing the principal stages of plume volcanism and upper mantle flow beneath SE Brazil. On the left are map views showing the breakup of Gondwana with the development of flood basalts and seamounts (after Turner et al., 1994). Shown on the right, the plume evolution proceeds as a series of ``snapshots" of a cross-section beneath SE Brazil and west Africa. The plume head evolution is based on Farnetani and Richards (1994) numerical modeling of emplacement of a plumehead from the lower mantle. Following that work, we assume here a viscosity contrast of 1 to 2 orders of magnitude between the upper and lower mantle, and between the upper mantle and the continental lithosphere. Frame 1 shows the plume rising from high viscosity lower mantle. Frame 2, the plume ascends along a relatively narrow conduit through the lower viscosity upper mantle and mushrooms into highly flattened body 700 or 800 km in radius beneath the Brazil/Africa continental lithosphere. Melting of plume head material and/or hydrous lithospheric mantle produced the Parana flood basalts over time interval 137—127 Ma. Frame 3 shows relationship at 125 Ma, immediately before the onset of oceanic spreading between Africa and Brazil. Plume tail material is now emerging on the axis of the northward propagating Mid-Atlantic Ridge. The final frame shows the relationship at 40 Ma. The Tristan da Cuhna hot spot has produced substantial segments of the Walvis Ridge and the Rio Grande Rise. Late stage alkalic volcanism is shown schematically around the margin of the Parana Basin, where small volume lamproites and kimberlites pushed through the weaker lithosphere of the Brasilia mobile belt.

Close-In *ScS* and *sScS* Reverberations from the June 9, 1994 Bolivian Earthquake

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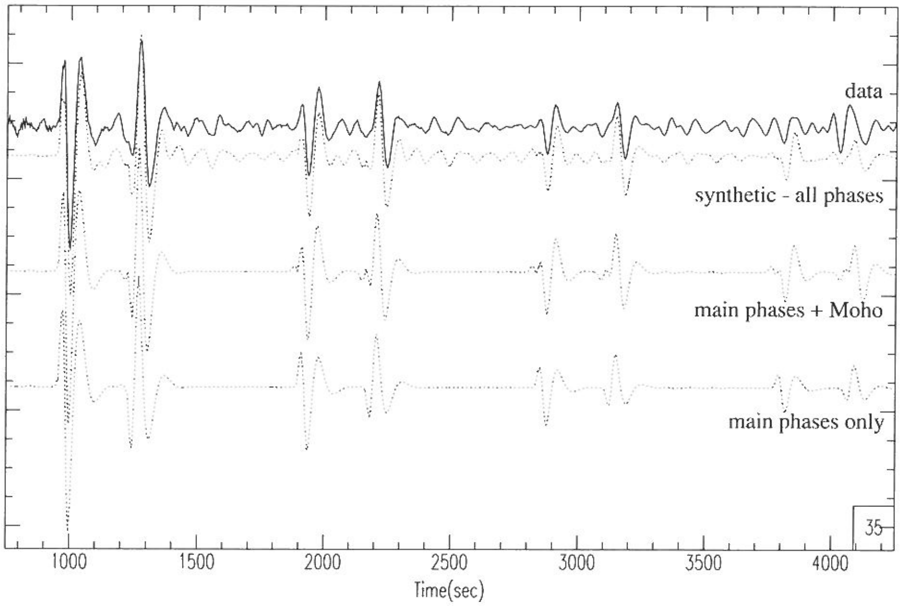

Example of radial component seismogram (low-passed at 100s) from the most western station in Bolivia (STO1), and comparison with synthetics. Traces are (from bottom): - CORE synthetic with main phases only. CORE synthetic with Moho phases included (note that Moho precursors alter the shape of sScS pulses, thus constraining the Moho depth). CORE synthetic with all discontinuities included. Additional phases seen are boundary interaction phases from D400, D600 and D230. Note that most of these phases are also seen in the data (top trace), allowing us to obtain single station path-averaged estimates of discontinuity depths.

Fourteen unique on-scale recording of the Bolivian earthquake of June 9, 1994 from two portable experiments (BANJO in Bolivia and BLSP in Brazil) were obtained and analyzed for *ScS* and *sScS* reverberations out to *sScS4*. These stations span the distance range 6° - 22°, sampling the mantle beneath South America along an EW line from the central Andes to the Brazilian Craton. We used the CORE method to obtain vertical shear wave travel times through the upper and lower mantle, and path-averaged locations of the Moho and 400 and 660 km discontinuities.

After elevation correction, mean travel time delays for *ScS* are 2s greater for BANJO than BLSP. Much of this can be explained by the very thick crust in Bolvia although about 0.6s remains, that can be attributed to subcontinental mantle variations. The average depth for D_{400} is 410 km for the BANJO stations and 395 km beneath Brazil, while the value for D_{660} is 700 km for BANJO and 675 km for BLSP. If we correct the BANJO values for the 2s in delay time (presumed to be in the upper mantle), then it will make both D_{400} and D_{660} about 10 km shallower beneath the BANJO stations. The difference D_{660} -D_{400}= D is 280 km and 290 km r espectively for the Brazilian and Bolivian stations. These values are much larger than the global average (around 245 km) and suggest 200° -300° colder temperatures in the region sampled by these waves. This is most plausibly explained by the reduced temperatures in the slab and surrounding region. In addition to estimating depths to known discontinuities, we also searched the upper and lower mantle for additional discontinuities. The only significant additional discontinuity we detected was at 200 km depth, with a shear wave impedance contrast of at least 5%.

Finally, we observe systematic variations in duration between *P*, *ScS* and *sScS* that can only be attributed to source finiteness. In particular these observations constrain strongly the inclination of an equivalent unilateral rupture velocity vector to be -17° (positive up from horizontal). The best fitting azimuth and rupture velocity are 33° and 1.8 km respectively, consistent with rupture models derived from subevent analysis of the *P* wave arrivals.

Lowermost Mantle Structure from Diffracted Shear Waves

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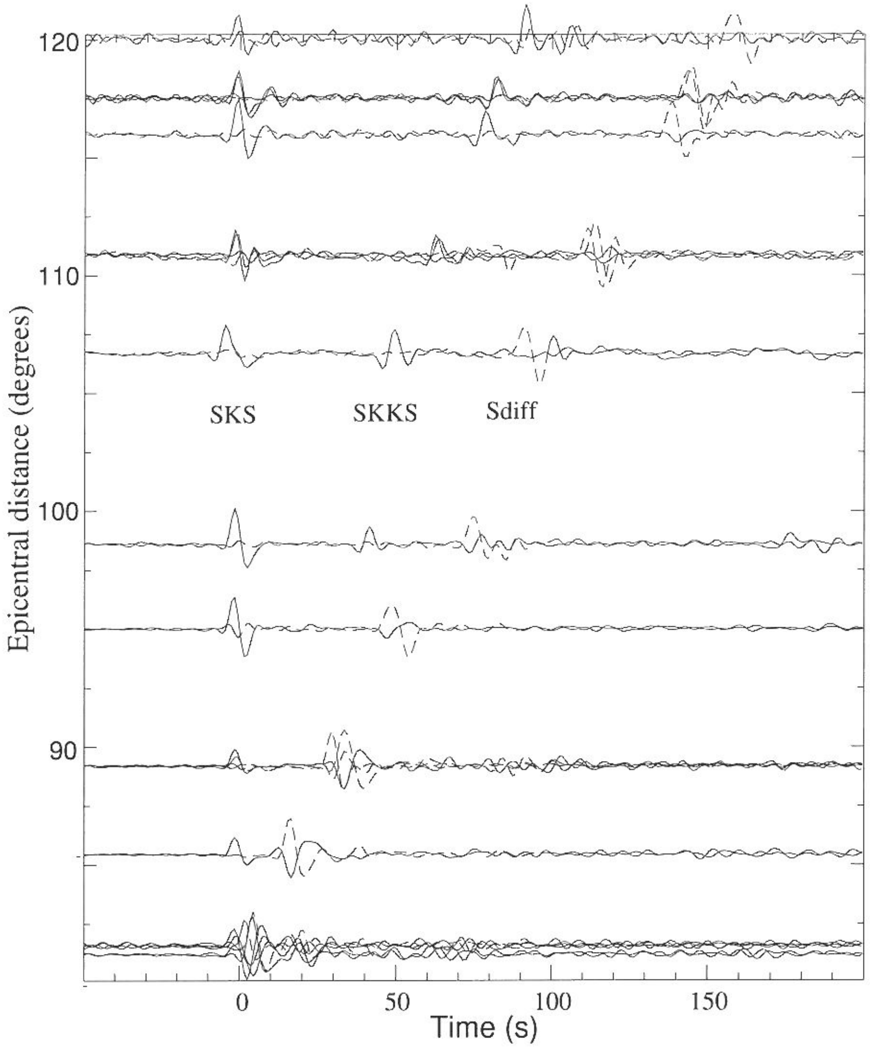

The plot above shows radial (solid lines) and transverse (dashed lines) component seismic recordings from North American IRIS stations for the Mw=6.4, 31 March, 1994, Fiji-Tonga earthquake. The recordings are aligned on the SKS phase. The largest seismic phases visible area SKS, SKKS and the diffracted S wave (Sdiff). This profile of broadband waveforms of core phases is of quite high quality, thanks to the dense distribution of IRIS stations.

Our research focuses on modeling the diffracted S wave signals in seismograms such as these. The diffracted S wave is most obvious on the transverse component seismograms. However, diffracted S wave energy can also be observed on the radial components, with amplitudes much larger than predicted by standard Earth models. The presence of strong, vertically polarized S wave energy is indicative of negative shear wave velocity gradients, azimuthal anisotropy or both at the base of the Earth's mantle.

Advances in Radial Attenuation Modeling Using Global Digital Data

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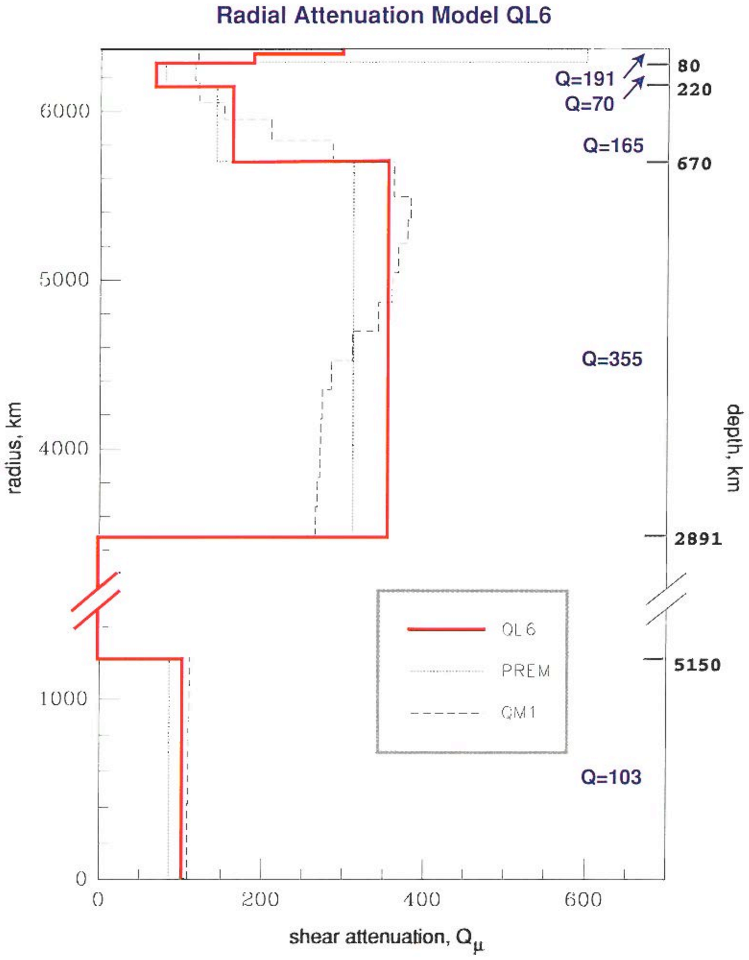
Seismic wave attenuation is described by the quality factor, Q, whose inverse is proportional to the fractional strain energy loss per wave cycle. Since wave attenuation is a consequence of non-elastic relaxation of seismic strain, it provides information on the variations of temperature, viscosity, and velocity dispersion within the Earth. In addition, the relative strength of dissipation during compression, Q_k, and shear, Q_μ, may be diagnostic of the mechanisms of anelastic attenuation active in the Earth.

Radial attenuation models based on observations of the decay of long-period ($T > 100$s) waves agree qualitatively on the variation of Q_μ and the necessity of Q_k, although appreciable differences currently exist in both the reported values of $Q_\mu(r)$ and $Q_k(r)$ and their continuity with depth. The abundance of high-quality digital data is leading to improved measurements of seismic wave attenuation, helping to resolve these questions. Two examples of recent advances in radial attenuation modeling facilitated by global digital data are:

1) Measurements of long-period surface wave attenuation indicate that shear dissipation in the shallow mantle is greater than that of two extensively used models, PREM and QM1. We have incorporated these surface wave measurements in an inversion for a new radial model of anelasticity.

The model, named QL6 is characterized by an increase in the level of shear attenuation (decrease in Q_μ) in the upper 220 kilometers of the mantle, a simple, discontinuous radial structure for Q_μ which explains the data, and a dominant source of compressional attenuation located within the upper mantle.

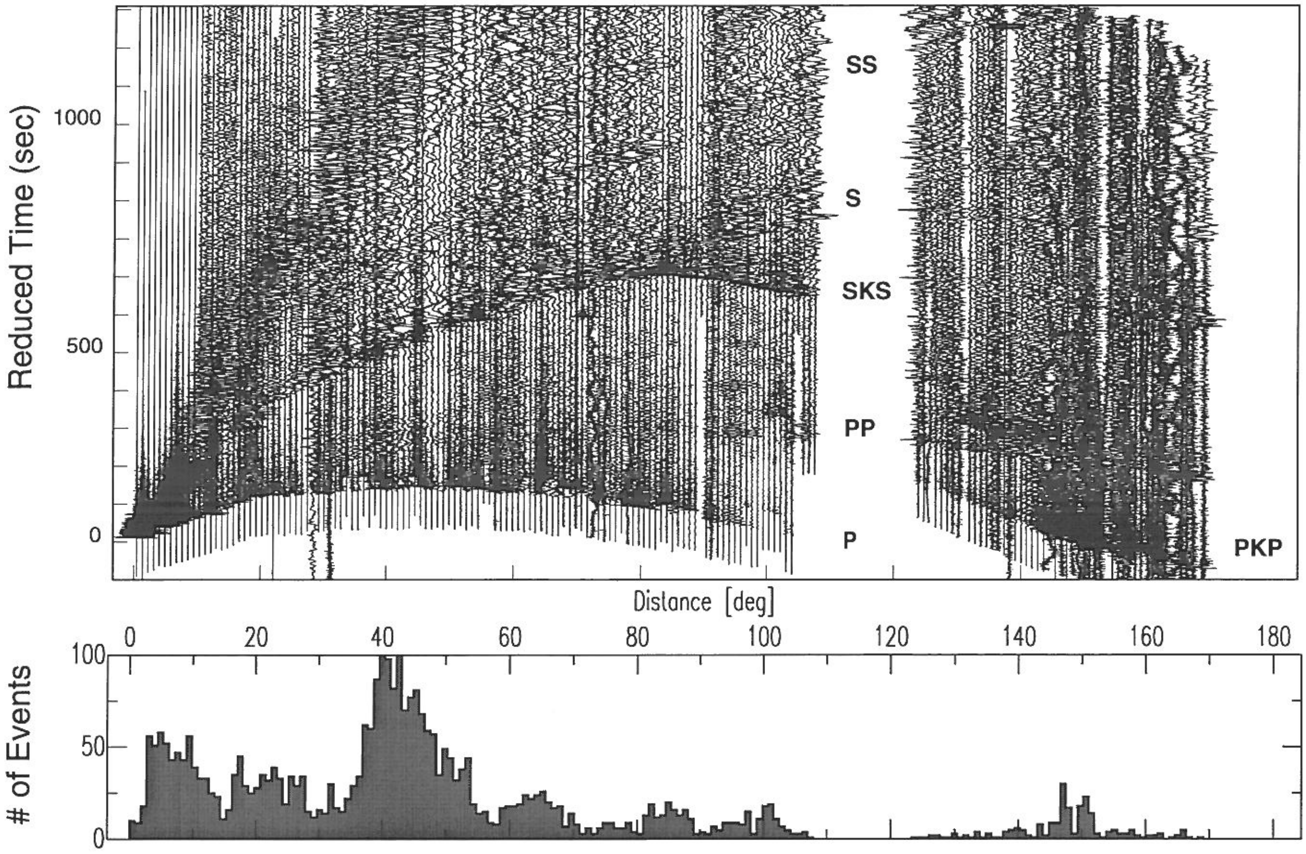
2) The GSN recordings of the historic June 9, 1994 Bolivia and the October 4, 1994 Kuril Islands earthquakes are providing additional insights into the anelastic structure of the Earth. Measurements of the dominantly compressional radial oscillations following the Bolivia earthquake indicate that compressional attenuation in the majority of the mantle is consistent with solid state dissipation mechanisms ($Q_\mu/Q_k \sim 1$-2%), but also suggest that compressional attenuation is more prominent in the asthenosphere ($Q_\mu/Q_k > 20\%$), perhaps indicative of thermoelastic damping or the presence of partial melt.



The radial attenuation model, QL6, compared to the models QM1 and PREM. The depth range and Q_μ values for each of the five layers are indicated on the right axis. The model includes a crustal layer (depth: 3.0-24.4 kilometers) with Q_μ fixed at 300. Compressional attenuation is restricted to the upper mantle with Q_K=950. In contrast, PREM has finite compressional attenuation in the inner core (Q_K=1327) and mantle (Q_K=58,000) while model QM1 has compressional attenuation in the outer core (Q_K=12,000) and upper mantle (Q_K =2920).

PASSCAL Views the World from Tibet

T.J. Owens
University of South Carolina



The unique contribution of PASSCAL broadband experiments in global studies of Earth structure was perhaps initial underestimated by the IRIS community. However, the availablility of portable broadband sensors has led to rapid expansion of PASSCAL experiments that target sub-lithospheric structure. In addition, almost any PASSCAL broadband experiment has the potential to contribute to studies of global earth structure. Most PASSCAL broadband experiments have two characteristics coveted by those studying deep structure: dense station spacing as little as 1/50th of the GSN station spacing, and spatial coverage in areas not covered by GSN sites. The drawback, of course, is the limited recording period. However, even a one-year recording period can provide significant coverage. In addition, the opportunity to target specific problems with a detailed experiment largely outweighs the limitations. This composite record section assembled from the 1991-92 Tibetan Plateau Broadband Seismic Experiment dramatically illustrates the global coverage provided by PASSCAL experiments. The record section shows the radial component of motion with a reducing velocity of 0.125 deg/sec (13.8 km/sec). Traces selected are the highest signal-to-noise ratio trace in each 100 km source-receiver separation bin for which data are available. The histogram plots the total number of recorded events in each 100 km bin. As many as 115 traces are available in some 100km distance bins. Much of this data is being utilized to determine lithospheric structure beneath the Tibetan Plateau. However, it is also being used to study the core-mantle boundary with the diffracted waves recorded at distances greater than 120 deg and upper mantle structure in other parts of Asia using multi-bounce body waves. Thus, the data set has proven useful for studies that are significantly different from that proposed by the original investigators.

A role of IRIS in Public Policy

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This essay concerns a practical application of seismology, namely monitoring compliance with a Comprehensive Test Ban Treaty (CTBT), that both stems from and contributes to the science-driven programs that are the basis for most IRIS members' participation in IRIS activities.

The process of nuclear weapons development is intimately associated with programs of nuclear testing, and for this reason the pros and cons of a CTBT have been debated longer and more vigorously than any other subject in nuclear arms control. Negotiations that began in 1958 led after five years to an atmospheric/space/underwater test ban rather than a CTBT, in large part because of perceptions that seismological methods were inadequate to monitor nuclear explosions carried out underground. After three more decades of intermittent efforts, CTBT negotiations resumed again in earnest in January 1994 in Geneva, this time in the 37-member Conference on Disarmament. A major arms control decision was reached on May 11, 1995, when the Non-Proliferation Treaty (NPT) was extended indefinitely. The NPT in effect includes a CTBT for all signatories that are non-nuclear weapons states. As part of the process of agreeing to the extension, it was specifically recognized that achievement of the obligations of the NPT included "The completion by the Conference on Disarmament of the negotiations on a universal and internationally and effectively verifiable Comprehensive Nuclear-Test-Ban Treaty no later than 1996" which of course would bind the nuclear weapons states. A CTBT thus appears at last to be in prospect, though much work will be necessary over the next year, including work on the verification system.

From 1961 to 1990, more than 1500 nuclear explosions were carried out underground - an average of about one per week - as the five present-day nuclear weapons states (China, France, Russia, UK, US) built and deployed their various tactical and strategic systems. In this period, seismological methods of explosion monitoring were extensively developed in the context of a need for information on the nuclear weapons of potential adversaries. The US academic research community in seismology contributed greatly to the national effort in these years, by developing discriminants between earthquakes and explosions, and methods of yield estimation, that became used routinely in operational monitoring.

Looking to the future from the perspective of the mid-1990's, there is still a major role for seismology in monitoring nuclear explosions. But because the context is now so different - being arms control rather than military intelligence - the actual work of seismic monitoring will be done in different ways. The technical goals have changed, from yield estimation of sanctioned explosions at known test sites, to an emphasis on discrimination and a search for treaty violators on a global basis. The changes are far deeper than this, however. Technical issues extend from station site selection and data acquisition to methods of data analysis and the characterization of data centers that will do the work. Policy issues extend from protocols for result assessment to the different forums worldwide in which new interactions will be necessary between policymakers and their technical advisors.

Some of these points emerge in the words of John Holum, Director of the U.S. Arms Control and Disarmament Agency (which has the lead role in coordinating US policy at the Geneva negotiations):

> "Today, in a changed world, we anticipate an international verification regime for the CTBT that will include a far-reaching system of exchanges of technical information derived from seismic instruments, sensors of radionuclides in the atmosphere, and possibly other kinds of sensors of infrasound or hydroacoustic signals and the like. Consensus is already emerging that seismology will play a key role — indeed, that it probably will be the backbone of the treaty's verification regime.
>
> " It is already obvious, of course, that any such regime will require funding. We do not yet know how much, but it is clear that countries must be prepared — on national security grounds — to underwrite the necessary international verification arrangements. A substantial commitment will be required, for example, in seismic stations, communications, and organizational infrastructure."
>
> *From written remarks by John Holum, April 20, 1994, in a panel sponsored by the UN in New York, on the status of the Comprehensive Test Ban Treaty Negotiations.*

In practice, the US will monitor a CTBT via three quite different organizational efforts: by so-called National Technical Means, the set of methods that the US government can bring to bear unilaterally; by participating in the International Monitoring System whose duties and specifications are now being negotiated in the CTBT Protocol on Verification; and also by taking advantage of other resources such as programs of data acquisition whose primary purpose is not treaty monitoring.

The lead responsibility for developing National Technical Means for nuclear explosion monitoring lies with the US Air Force, which operates the US Atomic Energy Detection System.

For the international verification regime, the scale of efforts in seismology that the US anticipates to monitor a CTBT is given in a US working paper (CD/NTB/WP.53, 18 May 1994) presented at the Conference on Disarmament. These efforts include "A global system of seismic stations reporting data to an International Data Center ... The US believes that the international seismic system should consist of about 50-60 primary stations [continuously sending data to the IDC in near real time] and more than 100 auxiliary stations [supplying data to the IDC on demand]. The costs of primary stations could range between 250,000 and 10 million dollars, and each auxiliary station will cost between 200 thousand and 2 million dollars. A prototype of this network, and the associated IDC, is currently being tested under the auspices of the Group of Scientific Experts, who have provided the Conference on Disarmament with technical advice on seismic monitoring for almost 20 years. IRIS stations are participating in the GSE network, which is still growing. The GSE IDC is currently reporting, only two days in arrears, an average of about 60 located global events per day. It is easy to find examples of the importance of IRIS stations in supplying high-quality data that was crucial in characterizing certain seismic events of interest to the GSE.

In addition to the role of seismographic stations that will be a part of the International Monitoring System, the US has also recognized the contribution that "other seismological resources" and "open stations" can make, to the verification regime. The following two paragraphs are taken verbatim from another US working paper presented in Geneva (CD/NTB/WP.96, 3 June 1994):

> "Other Seismological Resources. Other open scientific resources in the field of seismology would be available for use in treaty monitoring applications such as the calibration of ISMS [International Seismic Monitoring System] stations and products, verification research, and resolution of difficult seismic events. Such open data could be important to Treaty monitoring. These resources include the products of international, national, and regional data centers and waveform data from open stations. They include seismic data collection and processing activities that are currently part of national and international data exchanges for earthquake monitoring and basic seismological research. The Treaty would recognize the existence of these resources, recognize their value for supplementary monitoring and support their accessibility both for the reasons for which they were established and for Treaty-related purposes.
>
> " Open stations. There are many seismic stations including those of local, national, regional and global seismic networks, e.g., those operated by members of the Federation of Digital Seismographic Networks, that meet high technical standards and have "dial-up" communications capability for waveform data. Such data could be accessed directly, as needed, to supplement treaty monitoring. The international exchange of open stations data should be encouraged, and States with such high-quality stations should be encouraged to "certify" them for inclusion in the ISMS network."

IRIS has contributed in very specific ways to all three types of organizational efforts in explosion monitoring. For example, the US national efforts in explosion monitoring have included new stations in the Southern hemisphere, the Global Telemetered Seismographic Network funded by the US Air Force, which uses data-loggers essentially of IRIS design. For the international efforts currently coordinated by the GSE, the IRIS stations in Russia provided crucial data on January 15, 1995, to enable interested parties to characterize an unusual seismic source (mb = 4.6) in the Urals as a likely mine collapse, and specifically not a large explosion. In the context of other seismological resources, IRIS GSN stations around the world and JSP stations in Central Asia have contributed important data when needed.

For some purposes, it is relevant to justify the claim that IRIS contributes to explosion monitoring, by giving pertinent examples of IRIS data that have been used to resolve problem events. This is an anecdotal approach. But in the context of building up an international verification regime that can inspire confidence in a new treaty, IRIS has a far more important and more general role to play than can be explained by any anecdote. This larger role stems from the fact that the Consortium helps to coordinate so many activities of leading seismologists around the world. Thus, a major strenth of IRIS's contributions to explosion monitoring comes from the Consortium's place at the forefront of: negotiations with instrument designers, establishing new communication links, seismic data management, archive design and operation, development of new data products, support for regional seismicity studies around the world, active programs of cooperative research in countries that the US is surely desirous of monitoring, support for R & D in verification techniques, and operation of stations in regions not covered by other US national efforts nor by current ISMS plans. Working with the USGS, IRIS also offers technical assistance to the national efforts of numerous foreign countries to build and operate regional networks. In this sense, IRIS's contribututes to explosion monitoring comes through infrastructure, through coordination of resources such as people as well as equipment and databases, and through the educational programs of IRIS member institutions. It is for these reasons, that in addition to the support provided for IRIS science programs via NSF, the US Congress has appropriated funds for IRIS in recent years through the Department of Defense to accelerate the deployment of the GSN, and for the work of the Joint Seismic Program.

In summary, IRIS has had and will continue to have a major role in monitoring compliance with a new treaty that has been an arms control objective for decades. The basis for IRIS's contribution is completely apolitical, and stems from the quality and utility of IRIS data, the quality of relevant IRIS programs (for example the Joint Seismic Program, through which we have come to know so much about explosion monitoring on territory of the former Soviet Union), and the freedom that the academic community has to report its work to policymakers.

Contributions of IRIS Data to Nuclear Monitoring

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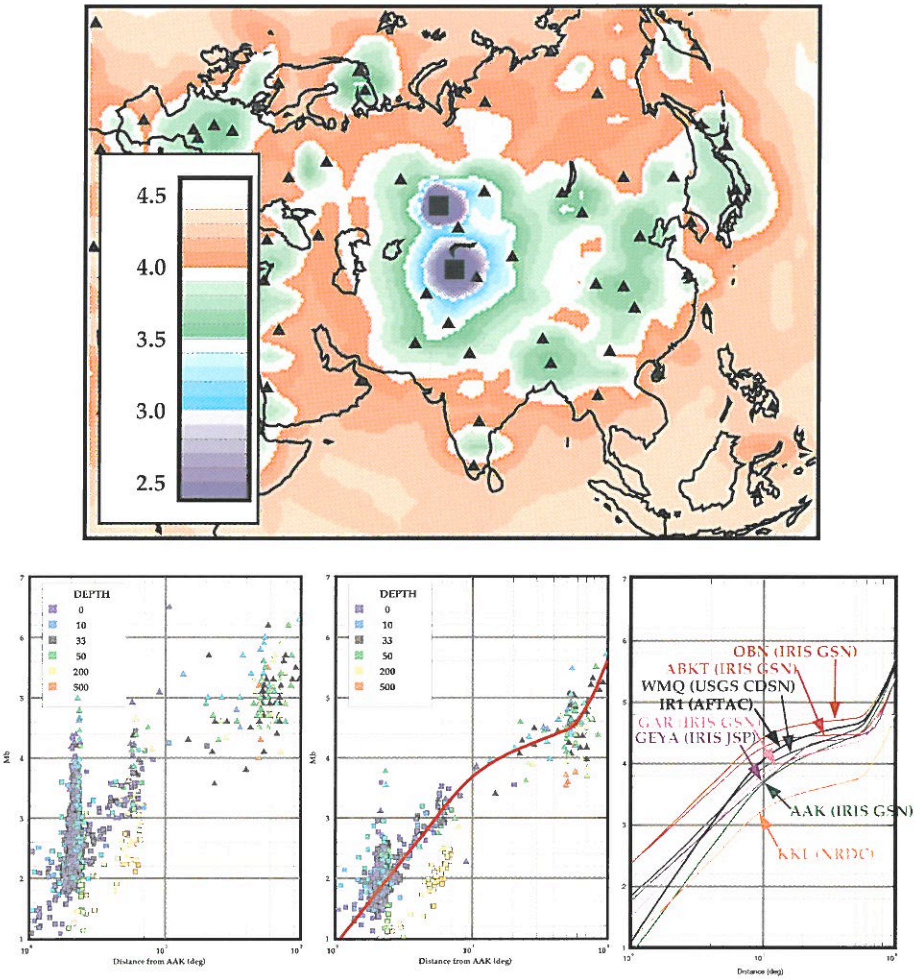
University of Colorado

Since 1988, when the IRIS Joint Seismic Program (JSP) was established between the U.S. and the U.S.S.R., IRIS has played a pivotal role in the establishment of new seismic observatories throughout the world and especially in the vast and previously inaccessible regions of Central Asia. After the demise of the Soviet Union, this prolific increase has, if anything, accelerated. We expect the large numbers of seismic observatories from the IRIS deployments to contribute significantly toward solving the problems associated with nuclear monitoring especially in the context of nuclear nonproliferation. At the Joint Seismic Program Center (JSPC) we have conducted a study to quantify the capabilities of IRIS data using waveform data from the Central Asia region recorded by various components of the IRIS JSP, including the Global Seismic Network (GSN) and the JSP network in Kyrgyzstan, as well as other open data from the Chinese Digital Seismic Network (CDSN) and GEOSCOPE. Our intent was to quantify the detection capabilities of IRIS sites in order to predict detection and location magnitude threshold contours based upon observations of noise levels and signal propagation characteristics in the study region.

We accomplished these analyses through the production of a number of event bulletins. These bulletins were produced in traditional fashion by measuring seismic arrival onset times from the waveform data and using these arrival times to locate events and/or to correlate observed arrivals with events from existing catalogs. In addition to the onset times, we also computed signal to noise levels for each P arrival. Event Mb magnitudes were computed using either the reported PDE Mbvalues or JSP network average Mb estimates for events that were not listed in the PDE. The Mb estimates from the JSP network data were corrected to produce zero mean statistics for the PDE relative residuals. Single site Mb vs. distance functions give us the raw information for determining single site detection magnitude thresholds.

In the accompanying figure, we show such a function in the bottom left hand panel that was produced from events recorded at station AAK in the JSP Kyrgyz network. Triangles represent events that were in the PDE catalog, squares represent events that were not in the PDE catalog and the symbols are color coded according to event depth with yellow-orange representing deep events and blue-green-purple representing shallow events. We developed and applied a P-wave method based on the signal-to-noise ratio for scaling observed event magnitudes to equivalent threshold magnitudes. This method does not depend upon the more traditional magnitude-frequency functions and is not susceptible to biases related to performance of the data acquisition systems which is a problem with the triggered datastreams.

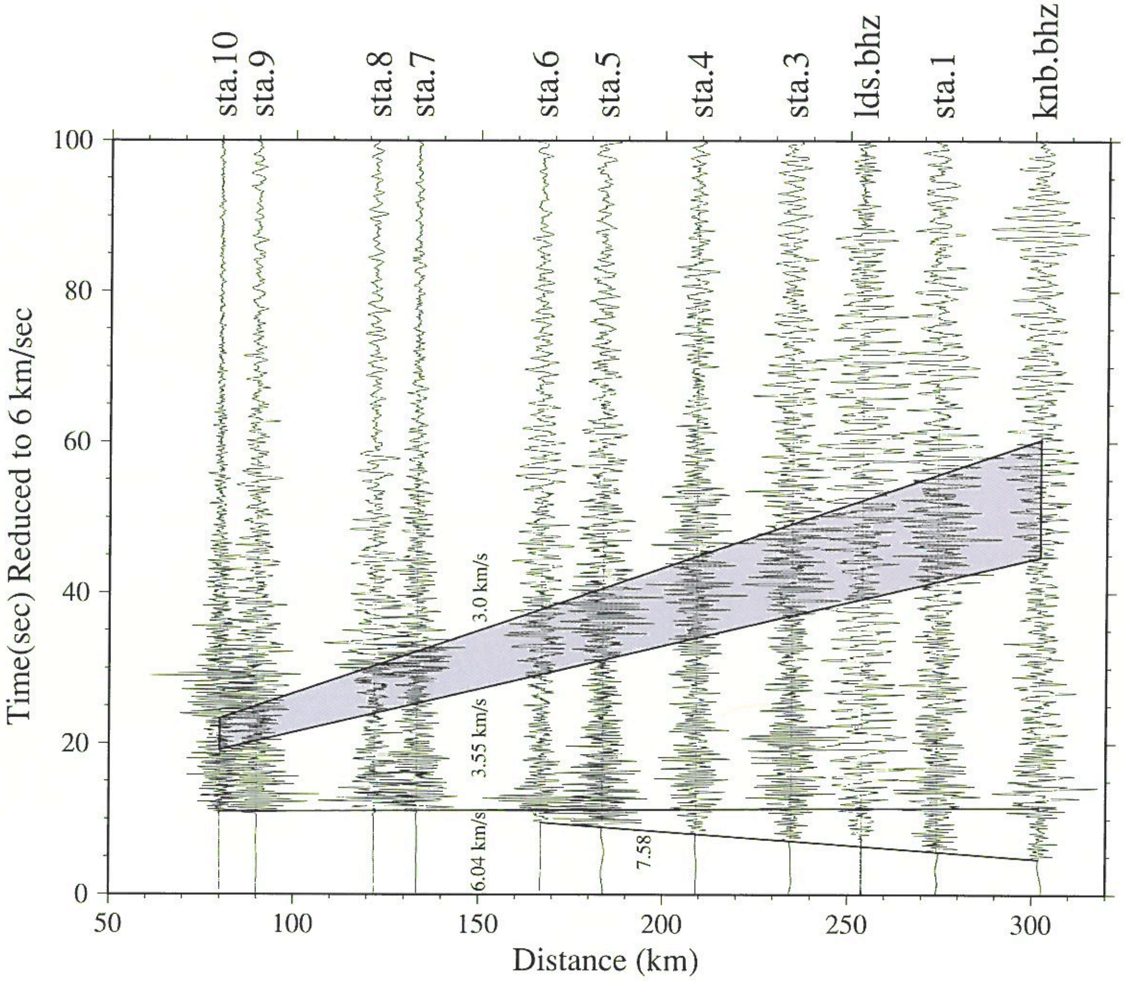


In addition, the method requires far fewer events to produce accurate threshold estimates. An example of the scaled threshold magnitudes can be seen in the bottom center panel for station AAK. In this case we scaled the magnitudes to an equivalent signal to noise threshold value of 2.0. We can see that the magnitude scatter seen in the left hand panel is considerably reduced and the populations of shallow and deep events are clearly separate as one would expect. We have fit a characteristic Mb-distance threshold function for shallow events and this is shown as the solid red line. The results of applying this method to a variety of IRIS GSN/JSP stations as well as a CDSN station are shown in the bottom right hand panel. We have also analyzed the NRDC station KKL that was operated in Kazakhstan during 1987 and the AFTAC Iran long period array (IR1) and we show long-period threshold values for these sites for comparison. Once we have estimates of single site detection thresholds, it is relatively straightforward to make network location threshold estimates. By gridding out the event locations we can compute distances to each station, look up the threshold magnitude values for those distances, order by increasing magnitude, and pick off the N-th value from the list as our location threshold where n is the number of stations criterion.

Location threshold magnitude contours are shown in the top panel using a list of existing and proposed GSN stations, GEOSCOPE, MEDNET and CDSN stations, the JSP Kyrgyz network and a proposed JSP Broadband array in Kazakhstan near Borovoye. The number of stations criterion used was four and we counted the Broadband array as two stations to account for the independent azimuth and slowness estimates that are determined by the array. We can see that that the IRIS data resources make significant contributions toward the detection and location capabilities of the Central Asia region. By combining global stations with local network and arrays we can bring a comprehensive range of seismic data resources to bear upon the scientific and technical problems relevant to nuclear monitoring.

A Broadband Recording of NPE

Mark Tinker and Terry Wallace
University of Arizona

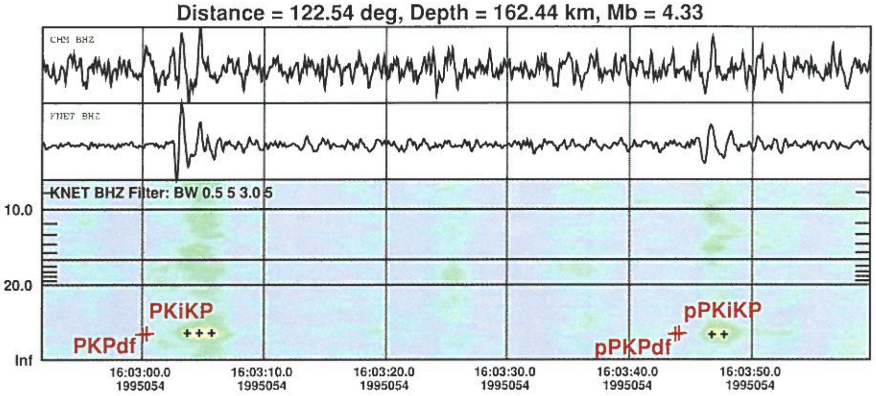


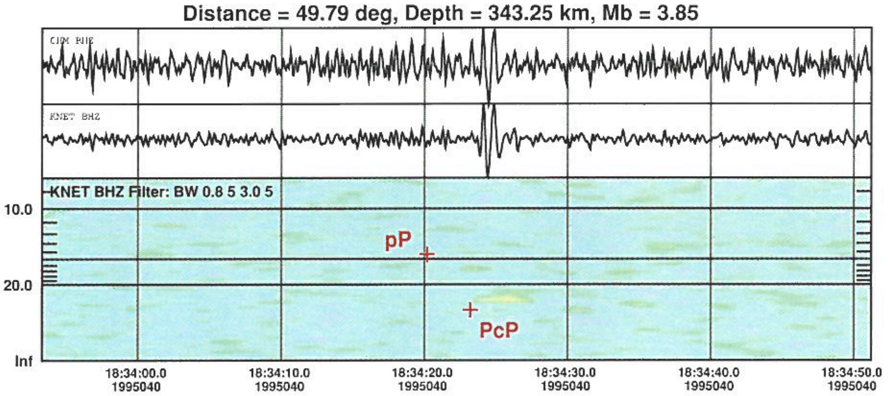
A large chemical explosion known as the Non-Proliferation Experiment (NPE) was detonated at the Nevada Test Site (NTS) to investigate a number of monitoring issues. DOE excavated a large cylindrical chamber (15.2 meters in diameter by 5.5 meters in height) 390 meters under Rainier Mesa, which was filled with approximately 1.29 million kilograms of a pasty looking 30/70 emulsion to ANFO (ammonium nitrate and fuel oil) blend. This entire volume was detonated successfully at one minute past midnight on September 22, 1993. A portion of this multi-fold experiment focused on local and regional seismic surface measurements. The purpose of these include, 1) verifying possible differences between the seismic signature from a nuclear and chemical explosion, 2) investigating the evolution of regional seismic phases as they propagate across major tectonic provinces, and 3) determining the effects a change in geologic environments has on seismic discriminates.

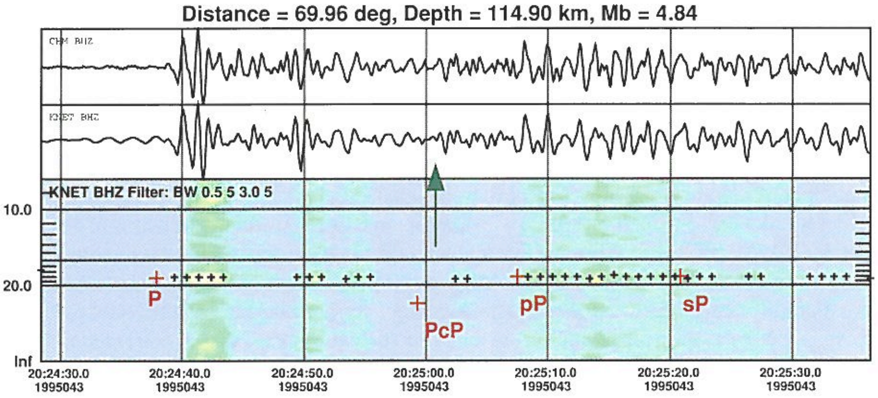
Members of the Southern Arizona Seismic Observatory at the University of Arizona participated in NPE by recording the explosion on an east-west broadband seismic profile. Ten broadband stations were installed on a line trending east from the Nevada Test Site to the Lawrence Livermore National Laboratory permanent seismic station KNB at Kanab, Utah. The closest station to the shot point is 73 km, from which the remaining stations were located at approximately 20 km intervals. Station KNB is 302 km from the shot point. Thus, the profile covers the transition between the Basin and Range and the Colorado Plateau. The purpose of this profile was to investigate the development of regional seismic phases and to explore the effects a change in geologic environments has on seismic discriminants. As seen in the figure, analysis has revealed the Basin and Range - Colorado Plateau transition is distinguished by a significant seismic phase change between stations 4 and 5 where there is a marked change in the amplitude of Pn. Furthermore, there is a pronounced shear wave (S wave). Intuitively, an explosion would only produce a compressional wave (P wave) that propagates in all directions. The slow apparent Pn velocity of 7.58 km/sec can be modeled as a Moho dipping away from NTS to the east in accordance with the thicker Colorado Plateau and having an actual Pn velocity of 8.0 km/sec . The shaded velocity window brackets 3.55 and 3.0 km/sec, or approximately the Lg phase. Lg does not fully develop until station 6.

Correlation Analysis Using Teleseismic Events Recorded by the JSP Kyrgyz Network for Crust and Upper Mantle Time Residuals

Danny Harvey
University of Colorado







As part of the IRIS Joint Seismic Program, an approximately 200 km aperture radio telemetered broadband network of 10 sites was installed in the Central Asian Republic of Kyrgyzstan. This network has been in operation since the fall of 1991. The network is situated along the Northern Tien Shan range west of Lake Issyk-kul and provides a unique observational opportunity for this region of complex continental tectonic activity.

We have recently finished a study aimed at determining the feasibility of using the Kyrgyz network as a seismic array for teleseismic events. By "array" we mean a gather of data from spatially distributed sites which exhibits some waveform coherence from site to site and is suitable for array processing, such as stacking. Its use as a surface wave array was obvious and data from the network have been used for surface wave array based analyses. However, we were interested in determining how well the array would work for body waves at much higher frequencies.

In the course of creating event bulletins from the Kyrgyz Network data, we noticed that the teleseismic P arrivals usually exhibited reasonably coherent waveforms across the network at frequencies up to 2.0 Hz. This suggested that it would be possible to use the network as an array for teleseismic P arrivals. However, attempts at standard slant-stack beam forming were unsuccessful even after we estimated and applied fixed time and amplitude statics corrections for each station. It became apparent that the "statics" corrections were not static at all, but were highly dependent on event back azimuth and distance.

In order to resolve the statics problem, we analyzed several hundred teleseismic events that were recorded over several years by computing cross correlation functions between a reference station and each of the other stations in the network for each P arrival. This was done by first applying travel time based time shifts to each seismogram using the reported event locations in the PDE. The cross correlation functions were then computed and the peaks were read automatically to determine the optimum time and amplitude shifts that would line up the phases in both time and amplitude across the network. Several thousand cross correlation functions were produced in the course of the analysis.

The results of this analysis for seven of the network stations are summarized in the accompanying figure. The time residuals in seconds are color coded and are plotted according to their back azimuths and predicted slownesses in the square plots that overlay the map. The reference station was CHM and a receiver elevation correction was applied. The outer bold circles in the residual plots correspond to a slowness of 0.1 sec/km and the inner bold circles correspond to a slowness of 0.05 sec/km. These plots show strong systematic variations in the time residuals. When we apply the back azimuth and slowness varying time and amplitude corrections to the individual traces, we find that the Kyrgyz network performs very well as a teleseismic array up to a frequency of several Hz.

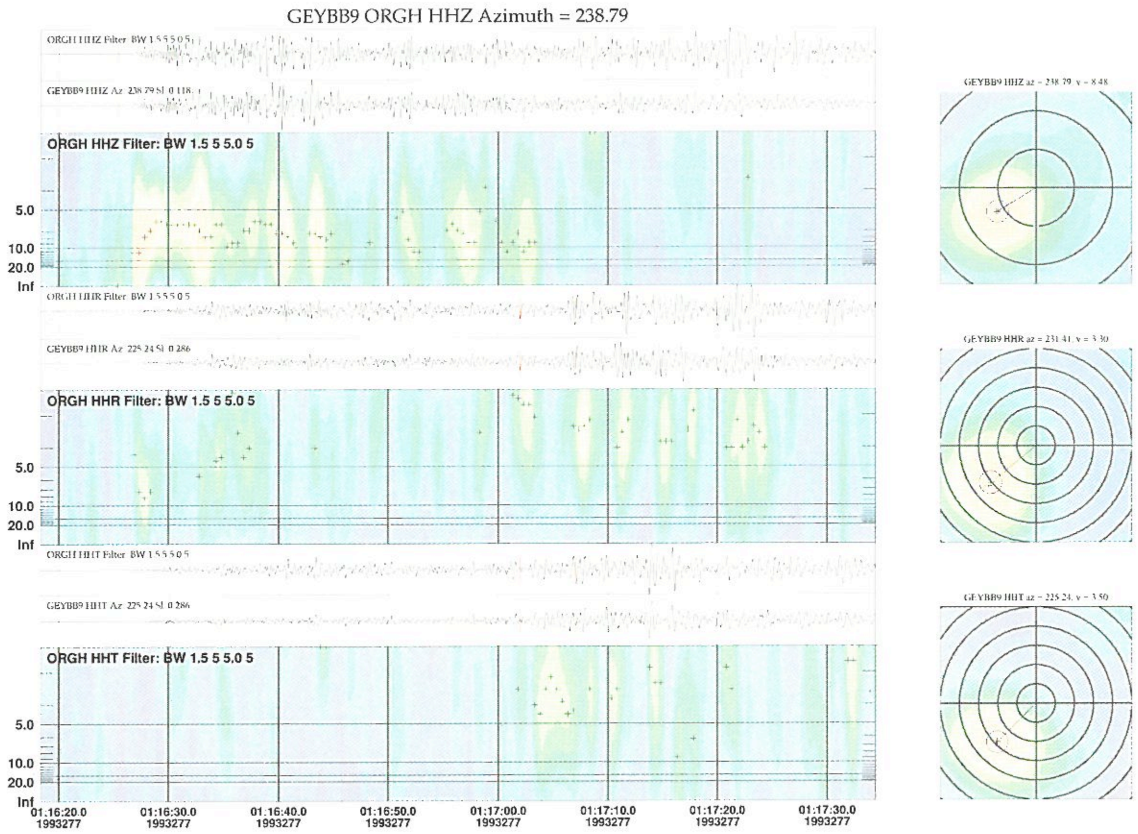
The variations in the time residuals that we have observed are consistent with a fairly deep low velocity zone that is aligned with the axis of the mountains and extends from about 50 to 100 km in depth. This could be due to either deep crustal roots associated with the mountains or a low velocity ablation zone similar to the zone that has been proposed for the Hindu Kush region.

A study is currently being conducted to combine these residuals with single station receiver functions to infer an underlying 3-dimensional crust and upper mantle velocity model. We have made some preliminary assessments using other similar broadband networks, some with apertures up to 1000 km, and have found that most, if not all, data from broadband passive source PASSCAL experiments, along with permanent regional networks and sufficiently clustered groups of GSN stations, would be amenable to the analysis we have described here. Not only would this provide observations that could be used in determining the local crust and upper mantle structures, but it would also provide us with a set of new and powerful teleseismic arrays that could be useful for a variety of global earth problems.

Results from the Geyokcha Seismic Array Experiment

Danny Harvey
University of Colorado

As part of the IRIS Joint Seismic Program, a small aperture seismic array was installed and operated during 1993 and 1994 near Ashkhabad the capital city of Turkmenistan, at a site named Geyokcha. The array was co-located with the IRIS Global Seismic Network station ABKT. The collection of seismic array data from this site is important since this is a site that is being proposed by the U.S. government as a primary site for the establishment of a new permanent seismic array for monitoring underground nuclear testing.



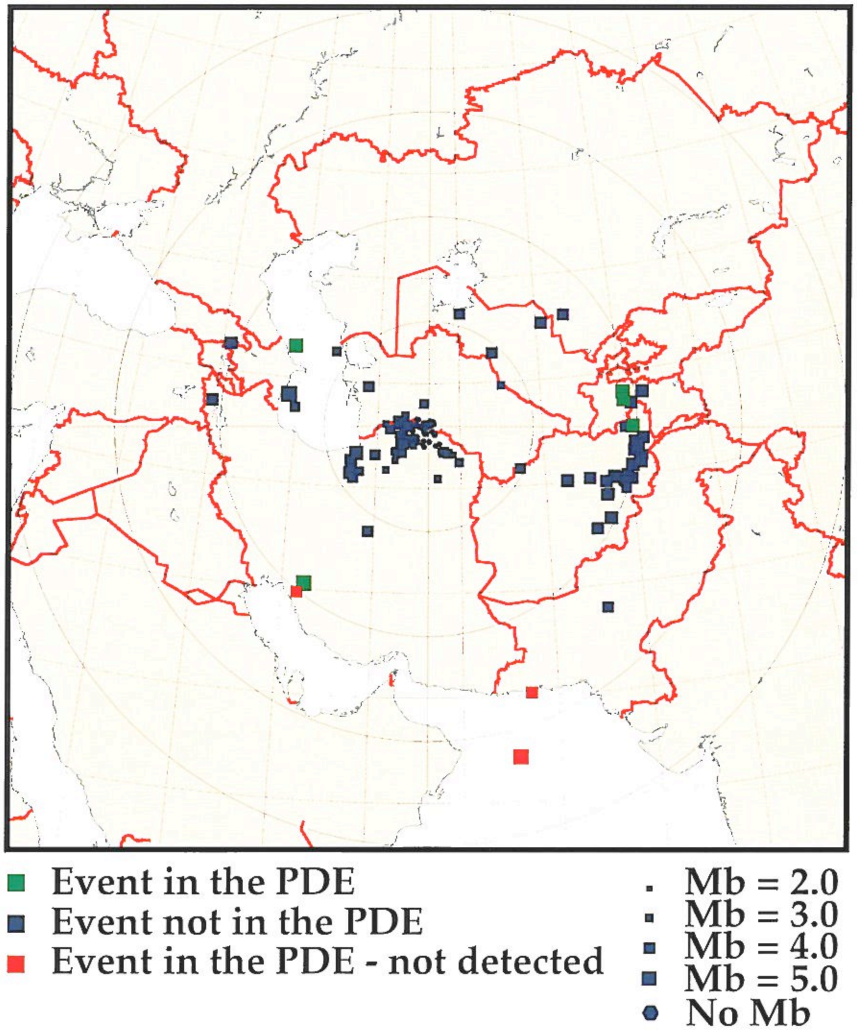
The results from this JSP experiment give us insights into the nature of regional wave propagation in this area and the suitability of this site for the location of a permanent regional array for monitoring purposes. The experiment was designed to look primarily at the regional and local wave propagation characteristics and thus the array was designed with a small aperture (about half of the NORESS array aperture or about one tenth of a typical AFTAC array aperture) to insure that the higher frequencies would be coherent across the array.

We applied standard slant-stack time domain array processing techniques to analyze the data and the results of this processing for a typical event at about 250 km distance can be seen in the top panel of the accompanying figure. The array sensors were all 3-component and included a mix of broadband STS-II sensors and high frequency geophone sensors. The results shown here come from the broadband 3-component sensors. The three square color contour plots on the right are the results of east-west north-south slowness domain processing (sometimes referred to as F-K processing) for a P-arrival time window on the vertical component for the topmost figure and a S-arrival time window on the radial and transverse components for the bottom two plots. The back azimuth for rotating the horizontal components came automatically from the slowness domain analysis of the vertical component. The circles are at increments of 0.1 sec/km. The P and S wave back azimuths and slownesses are clearly indicated by the peak values shown as orange.

Using the observed back azimuths from the slowness domain analysis, we next compute slowness-time domain semblance estimates over the entire event time window at fixed azimuths which are shown to the left of the slowness domain plots. These semblance estimates are computed by dividing unnormalized raw stack power by the sum of the individual site powers for each point in the slowness-time grid, and thus they give us an indication of where in the slowness-time domain the incoming wavefield is spatially coherent. This ability to decompose the wavefield into spatially coherent and incoherent parts is one of the advantages of seismic array data over single site data.

Also shown in the plots to the left are the original data from the central site in the array with the best beam stack below. We can see from the array processing results that the S-waves are not spatially coherent on the vertical component and that a 3-component array would be necessary to resolve the S-waves on the horizontal components. This characteristic of the S-wave is apparent for most of the events that we analyzed. This figure also illustrates the wavefield identification information that a seismic array produces. We can clearly see the slowness transition at the beginning of the P-wave from Pn to Pg and observations of this type can aid efforts to infer upper mantle and crustal structure. Also, the array enhances the S-arrival and gives us a means for picking out the small emergent Sn arrival that can be seen on the transverse component. The bottom map shows the

Events from geyocha, centered at ABKT

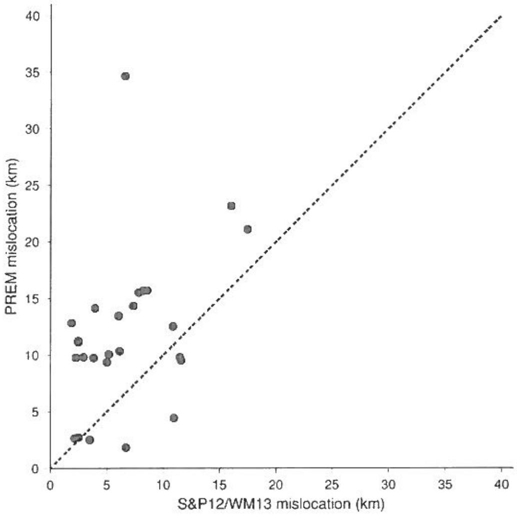


seismicity determined from the array over a one month period of time. We can see that although the array has good local (within five degrees) detection capability, its regional detection capability is strongly anisotropic with good detection capability to the east and west and relatively poor detection capability to the south toward Iran.

Based upon these results, we think that this is not a particularly good site for a permanent regional seismic array especially for monitoring the areas to the south. If a regional array were to be installed at this site it would be very important to make it a full 3-component array, in order to see the S and Lg waves. The Geyokcha array experiment has shown us the importance of short term exploratory array deployments for assessing potential permanent array sites and the data from this experiment illustrate the potential power of seismic arrays as enhanced observational tools.

Improving Teleseismic Event Locations Using a 3-D Earth Model

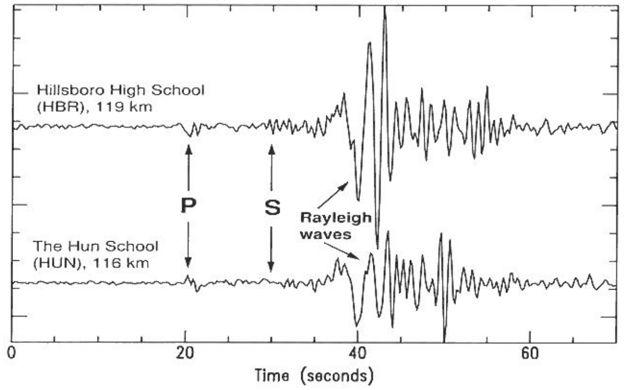
Gideon P. Smith, Goran Ekstrom
Harvard University



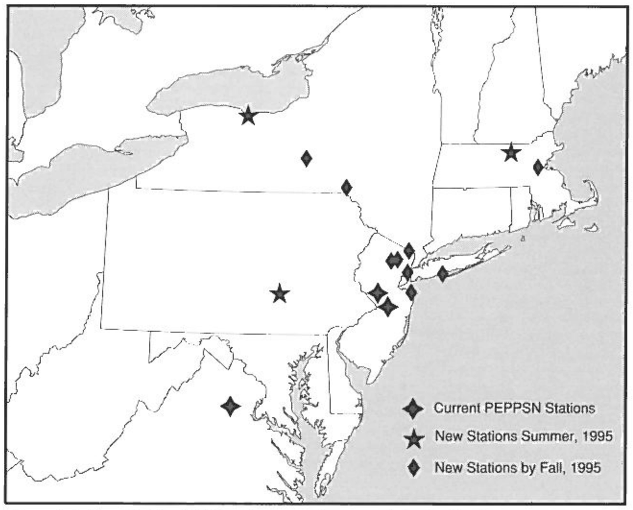
Improving our ability to locate events accurately has become an increasingly interesting scientific and political problem. Earthquake and explosion event locations are critically dependent on the accuracy of predicted travel-times. Traditionally travel-times are calculated from 1-D models of seismic velocities. Various data sets have been used to produce such models useful for global event location since the early work of Jeffreys and Bullen. However, departures from the spherically symmetric Earth are evident on many length scales. Prior to the current study it was unclear whether recent refinements in 1-D Earth models would result in a significantly improved ability to locate events accurately. A comparison was made between seismic event locations derived from standard spherically symmetric Earth models (JB, PREM, IASP91), and a recent Earth model (S&P12/WM13) which incorporates large scale lateral heterogeneity of P and S wave velocities in the mantle. Events with known hypocentral coordinates were located in the different Earth models using standard methods. Two sets of events were considered: a data-set of 26 explosions, primarily nuclear weapons test explosions and peaceful nuclear explosions in the U.S. and former U.S.S.R.; and a published data-set of 82 well-located earthquakes with a more even global distribution. IASP91 and PREM were shown to offer similar improvements in event location and origin time estimates with respect to the JB model. The three-dimensional model S&P12/WM13 offers improvement in event locations over all three one-dimensional models. This improvement in location is demonstrated in the above figure which shows the mislocation due to the S&P12/WM13 model versus that due to the PREM model for each of the explosion events. The location errors are systematically smaller using the S&P12/WM13 model. For the explosion events, the average mislocation distance is reduced by approximately 40%; for the earthquakes the improvements are smaller. Corrections for crustal thickness beneath source and receiver are found to be of similar magnitude to the mantle corrections. Surprisingly, we achieve the best locations by ignoring variations in the crustal thickness.

PEPP - Princeton Earth Physics Project

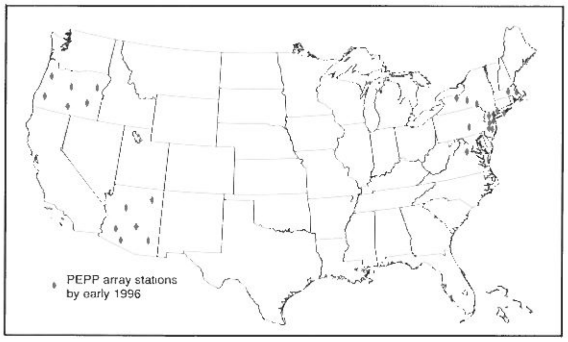
Guust Nolet
Princeton University



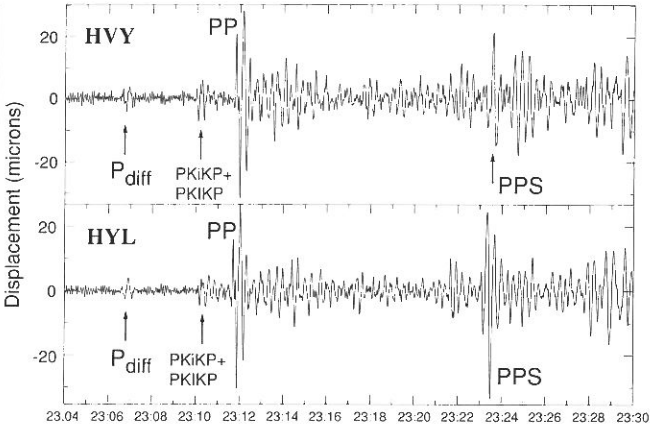
Two recordings of the January 16, 1994 magnitude 4.6 earthquake near Reading, PA made at two school stations. The upper seismogram is from the Hillsboro High School (station HBR), while the lower one is from the Hun School (station HUN). These stations were at distances of 1196 and 116km, respectively, from the earthquake.



Map of stations in the PEPP seismograph network in the Northeast, showing stations slated for installation up to the Fall of 1995.



Stations in the PEPP seismograph network by early 1996, including stations in the Northeast and stations in Arizona (supported by the University of Arizona) and Oregon (supported by Oregon State University).



Early portions of seismograms recorded at PEPP stations HVY and HYL from the February 5, 1995 New Zealand earthquake (M_S=7.5). These stations are roughly 13,500 km from the epicenter. At this distance we can observe waves interact with Earth's core, like P_{diff}, PKiKP, and PKIKP. The wave PP is a mantle P-wave with a surface bounce-point midway between epicenter and station.

The Princeton Earth Physics Project (PEPP) is an NSF-funded educational and scientific initiative. It offers new opportunities for research, teaching, and learning in the earth sciences for students and teachers, and promises to generate enormous quantities of earthquake data for seismologists through the installation of broad-band seismometers in high schools (and middle schools and small colleges) nationwide. The project also received partial funding initially through an IRIS sub-contract for seismometer development.

Seismometer deployment in high schools, a key aspect of PEPP, involves teachers and students in real earthquake monitoring and data collection. The instruments are low-cost broad-band one- and three-component sensors currently being developed for PEPP; we will begin deployment of these instruments in the summer of 1995. Each school PEPP station records the seismometer signal on a dedicated PC with timing sufficiently accurate for most seismological work, including earthquake location and tomography. Using the Internet, schools upload their recorded earthquake seismograms to a database at Princeton. Teachers can also share data directly across the Internet in order to conduct research or locate small local earthquakes. The PEPP database is accessible through the WWW (using Mosaic or Netscape). From it, users can obtain network-wide data from recent and past earthquakes, global hypocenter information, and many other types of information useful in both research and teaching. Schools can analyze their seismograms using a user-friendly analysis program for both Macs and PCs that PEPP is designing.

Another large part of PEPP is its new, innovative, computer-based earth science and physics curriculum we are designing (in collaboration with Tom Snyder Productions and TERC, in Boston). This curriculum goes far beyond the simple earthquake location method found in most textbooks: it engages students in the use of real seismological data to learn about Earth structure, earthquakes, and the societal impacts of earthquake research.

Wave Propagation

B.L.N. Kennett
Australian National University

The active development of a comprehensive global network through the IRIS GSN program with the complementary use of portable stations through PASSCAL has opened up a wide range of seismic wave propagation issues ranging from the gravest normal modes, which sample the whole Earth, to local experiments, which focus on the upper crust, or the details of an aftershock sequence.

Rapid advances in seismic instrumentation over the last two decades make feasible a high fidelity record of ground motion in digital form with a very broad range of frequency content. For fixed stations such as in the IRIS GSN network the frequency range extends from 0.002 Hz to about 10 Hz (or somewhat higher if ancillary seismometers are used to add higher frequency content). For portable stations using PASSCAL equipment it is possible to get a usable frequency range of at least 0.01 Hz to 30 Hz, with relatively simple field installations.

With such recording systems, the information content of a seismic record is very rich. Figure 1 shows an event from Tonga recorded at a field site in the Northern Territory of Australia using a PASSCAL type configuration of a Guralp CMG3-ESP seismometer and a Reftek 72A02 recorder. The three-component records of ground velocity are unfiltered and so show the dramatic range in frequency content between the high frequency P at the onset of the signal, the lower frequency S wave and the low frequency surface waves (LQ, LR). The great circle between the event and the receiver lies very close to east-west and as a result the records are nearly naturally polarized. SH waves with horizontal polarization are predominantly on the North-South component transverse to the path. The Love waves (LQ) are perceptible some time earlier on the N-S component than the Rayleigh waves (LR) on the vertical and radial (E-W) component.

The records from such a single station contain a very large amount of information about the Earth, but extraction of such information content can be enhanced when a number of high-fidelity systems are deployed in an area. For example, Figure 2 shows a composite record section built up from a number of different events spanning the distance range from 10 to 100 degrees which enables the evolution of the seismic wave-field as a function of distance to be followed in some detail. The vertical component records are displayed with correction to surface focus; the travel time curves for the major phases from the iasp91 model are superimposed on the seismograms as dotted lines.

In Figure 2 we can see the differences in record character arising from the individual events recorded at a number of stations. The influence of a single event can be minimized by stacking together the records from many events in a narrow distance range and then displaying the stacked traces in a record section. Such methods have proved valuable in diverse studies from regional scales through to sections for the whole Earth. Stacking enhances coherent features and can be valuable in the study of secondary phases occurring close in time to much larger arrivals, such as the precursors to PKPPKP (P'P') which provide direct information on upper mantle discontinuities.

At higher frequencies the use of high densities of short-period seismometers in PASSCAL array experiments also leads to unprecedented detail in the representation of the seismic wave-field, and once again stacking techniques can be valuable in enhancing the features of the propagation process.

Such high quality observations require a comparable quality of theoretical prediction for optimum interpretation. The development of calculation techniques for wave propagation studies has been profoundly influenced by the character of the available observations. Many of the methods still in common use were being developed when analogue records forced a clear separation into higher frequency techniques for 'bodywaves' which penetrate deep into the Earth and lower frequency methods for 'surface waves' which are confined to the outer layers.

There is a need for the development of "broadband" theory to match the dramatic improvement in the quality of observations, so that more of the information content in the observations can be exploited.

Many of the techniques in common use for calculating the effects of Earth structure on seismic wave propagation are based in large measure on the use of radial reference models, with the influence of three-dimensional structure within the Earth represented by small changes from the reference model. Such perturbation schemes have formed the basis of most work on the imaging of large-scale features within the Earth on scales greater than around 2000 km. As the volume of high quality data increases and the path coverage is improved by the addition of extra stations, notably through the operations of IRIS, the resolution of shallower structure has improved in such global tomographic studies. The improved resolution has generally revealed larger amplitudes for the estimated 3-D deviations from the radial reference model.

The seismic wave-field for the whole Earth can be represented directly in terms of the free oscillations of a spherical Earth specified by a radial reference model. Using such normal mode summation it is natural to represent 3-D heterogeneity via a spherical harmonic expansion so that there is a common basis for both wave-field and structure. For smaller scale problems it may be more appropriate to use alternative basis functions e.g., a direct Fourier representation which can be derived from an asymptotic expansion of the spherical harmonics.

The amplitude of the 3-D variations in velocity, which have now been estimated, is large enough that the accuracy of a treatment based on small deviations from a radial reference model has to be questioned, especially for the outer layers of the Earth. Larger levels of heterogeneity may be handled by allowing for coupling between different modal contributions, however such calculations are rather intensive. It is probably preferable to make a first-order perturbation treatment about an initial 3-D model but this requires a new class of theoretical development.

The progress in high performance computation in recent years has increased the importance of direct numerical simulation of the wave-field using mostly finite difference techniques. However, the demands of full 3-D calculations are very large indeed and so far are limited to a modest number of wavelengths away from the source. This allows examination of whole Earth problems at low frequencies or smaller sectors at high frequencies. The principal difficulty in expanding such calculations comes in memory requirements rather than computation speed.

Nearly all other representations of the wave-field in a 3-D model depend on the superposition of a set of suitable basis functions. For an aspherical reference structure it is still possible to use a spherical harmonic basis but the resulting coefficients would not have a direct physical interpretation. A number of promising procedures are under development that combine discretization procedures with expansion techniques with the object of representing a large part of the wave-field.

Ultimately we would like to be able to include three-dimensional structure on a wide range of scales but, at the present stage of computational development, it is important to include the largest regions of heterogeneity. The strongest mantle velocity contrasts occur in the neighborhood of subduction zones, in which occur the majority of earthquakes. It is important that the influence of the velocity contrasts in the neighborhood of the source are taken into consideration for higher frequency studies, the most appropriate techniques are likely to be some modification of ray theory such as the Gaussian beam method. 3-D structure is also important in active tectonic regions, e.g., central Asia, where there are complex and rapid changes in crustal thickness and crustal properties, which present difficulties for the study of seismic wave propagation comparable to the transition between thick continental and thinner oceanic crust.

The increasing density of fixed stations in the GSN network has placed more high quality stations close to seismic belts, and this provides many opportunities for combined source and structural studies using broadband records, which can be supplemented by temporary deployments of PASSCAL stations. At short distances the propagation effects tend to be simple and the broad frequency range of the recorder gives a direct window on source processes. As the distance between source and receiver increases, attention has to be given to the multiple propagation processes occurring in the crust. By selective low-pass filtering, the main structural features such as crustal thickness can often be extracted. High frequency records, however, present a greater challenge.

When we survey the full field of wave propagation studies we can see a clear hierarchy of approaches which will contribute to an understanding of the interaction of the wavefield and seismic structure over the broad frequency range available in the observations. At low frequencies the influence of large-scale structures can be included via a perturbation procedure about a reference model which may be radially stratified. As the frequency increases and the wavelengths shorten, the influence of medium-scale structure can be included by numerical calculations for a deterministic structure with well-defined seismic parameters. Such calculations will be able to represent the major phases on a seismic record but will leave much of the detail arising from small-scale structure in the Earth unexplained. The influence of small-scale structure will, in general, be too complex to describe via a specific model and will require a stochastic treatment to simulate the nature of the contribution. Such stochastic procedures have already proved valuable in scattering descriptions of coda and attenuation but have potential in a variety of other propagation problems.

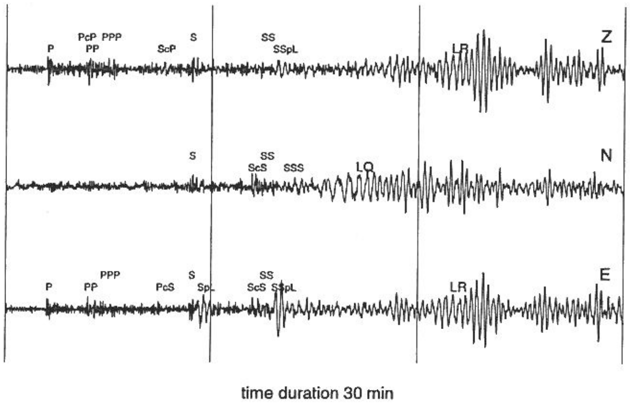


Figure 1: A set of three-component recordings of a shallow event at 48 degrees from a portable broad-band recorder. No filtering has been applied and the full frequency content of the seismic wavefield can be seen, from higher frequency body wave phases at the beginning of the record to the large amplitude lower frequency surface wave arrivals at the tail.

The characterization of scales of heterogeneity will depend on the nature of the problem under consideration and will scale by the size of the region under consideration. Although we can expect a similar general pattern in a study of the whole Earth using GSN records and a regional PASSCAL array experiment, the frequencies at which the style of analysis changes will be rather different.

Apart from the need to incorporate the influence of 3-D heterogeneity into wave propagation studies, we can recognize a number of challenges for the future.

So far most seismic wave modelling has been carried out for isotropic media, but there is increasing evidence for pervasive anisotropy in the outer parts of the Earth. It is also possible that part of the complex heterogeneity patterns in D" just above the core-mantle boundary have their origin in anisotropic effects. In the deepest earth an anisotropic inner core provides a means of matching the splitting of certain classes of free oscillation multiplets and the time differentials between PKIKP phases traversing the inner core on different paths. Most work on anisotropy has concentrated on rather simple models with a few layers of homogeneous anisotropy in which the propagation patterns are complex but amenable to analysis. However, once gradients in anisotropy are included the complexity of the wavefield is dramatically increased even for a radially stratified model. The formal structure of the influence of anisotropy resembles that for 3-D heterogeneity, and a full treatment of heterogeneous media will need to take account of anisotropic effects.

Another area of development which can be anticipated is the integration of complex source models in wave propagation studies to provide a full description of the generation and evolution of the wave field. Most current work on seismic wave propagation employs rather simple approximations for the seismic source such as a point moment-tensor with a specified time history; source complexity can be included by adding additional point sources to simulate propagation effects.

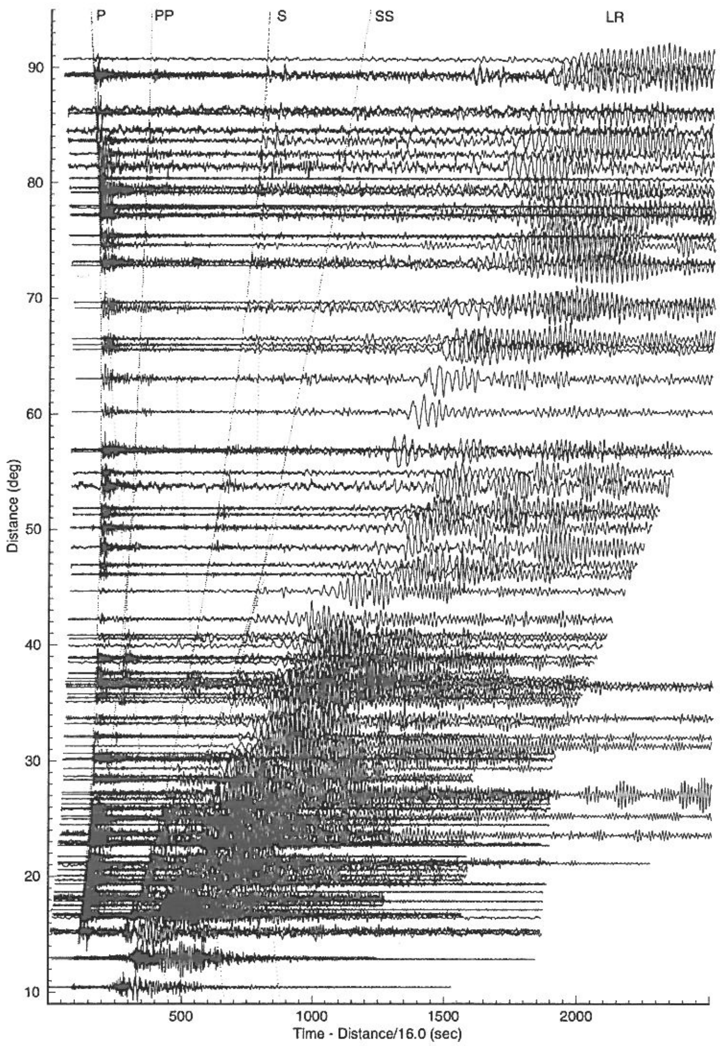


Figure 2: Composite record section of vertical ground motion, assembled from a number of events recorded at an array of portable broad-band recorders.

Wavefield Decomposition and Characterization Using Three-Component Seismic Array Data

G.S. Wagner and T.J. Owens
University of South Carolina

Much of what we know about the earthquake source process and earth structure and composition has been inferred from elastic waveform data. Three-component seismic array data provide the best available sampling of the elastic wavefield. IRIS has provided considerable support for truly pioneering experiments employing state-of-the-art technologies to collect high-quality, digital, broadband three-component seismic array data. These data have considerable advantages over more commonly available data from vertical-component arrays, and isolated single- and three-component sensors.

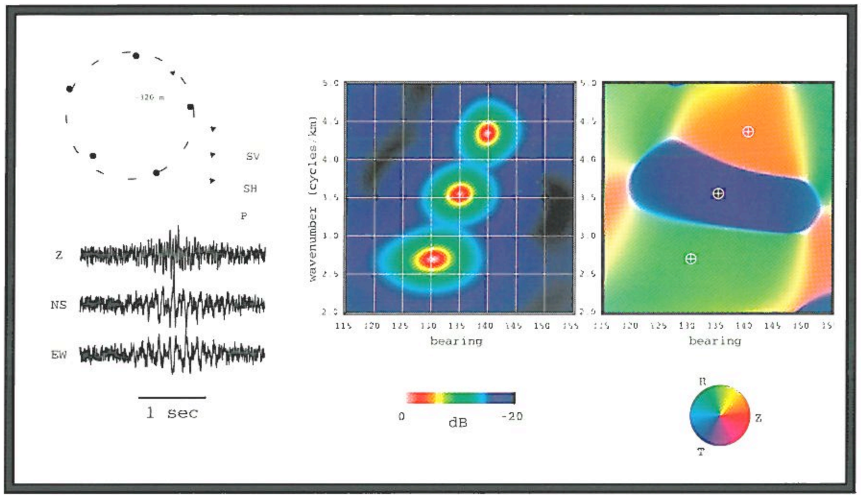


Figure 1 illustrates the ability to separate diversely polarized superimposed signals using three-component array data and recently developed high-resolution multidimensional digital signal processing algorithms. The array geometry, and the superimposed synthetic P,SV,SH waveforms (with noise) are shown to the left. The incidence angel for theP and SV phases is 25\deg. The center image shows the broadband wavenumber spectrum; the three-signals are clearly resolved using the high-resolution algorithm. The left image shows the magnitude of the vertical, radial and tangential components (Z,R,T) of the polarization-state vector. Wavetype identification is straight forward using the direction-of-energy-flux and particle motion information provided by three-component array data. For this simulation, the SV phase has predominantly radial motion with a slight vertical component, the SH phase has entirely tangential motion, and the P phase has predominantly vertical motion with a slight radial component.

With three-component array data, our analysis is not restricted to the vertically polarized component of the wavefield. This is crucial for a comprehensive analysis of the elastic wavefield in that the vertically polarized component of the wavefield is oblivious to a potentially significant portion of P, SV and Rayleigh waves, and completely oblivious to SH and Love waves. Vertical-component array data, therefor, severely degrade our ability to detect and obtain accurate waveform estimates for the various vector wavetypes the comprise the elastic wavefield. With vertical-component array data we are, in essence, seeing only shades of blue in the rainbow of information provided by the elastic wavefield. Elastic wavefield decomposition using single-sensor three-component data is plagued by numerous problems and ambiguities. Even in an ideal situation, and regardless of the analysis approach, it is not possible to determine both a signal's propagation direction and its wavetype based solely on the particle motion observed at an isolated sensor. The two principal shortcomings in elastic wavefield decomposition using single-sensor three-component data are that we cannot separate superimposed signals and noise, and that we do not know the direction of energyflux. If it were possible to separate superimposed signals and noise, and to determine the signals' propagation direction, the estimates provided by polarization analysis would be more reliable. Three-component array data affords us the ability to do just that by allowing us to conduct polarization analysis on isolated signals whose propagation directions are known. Our ability to realize the full potential of three-component seismic array data is contingent on our ability to develop processing algorithms that allow us to exploit and fully utilize the abundance of information provided by the elastic wavefield.

Recently developed multidimensional digital signal processing algorithms represent the first to solve simultaneously the wavefront and polarization problems inherent in the analysis of three-component array data. These routines, and the increased availability of three-component seismic array data are exciting developments for observational seismology. They allow us to fully address many fundamental questions about elastic wave propagation that simply cannot be answered conclusively using data from vertical-component arrays, or networks of isolated sensors. In short, the combination of these data and processing routines provide unprecedented insight into the nature of elastic wave propagation in the Earth.

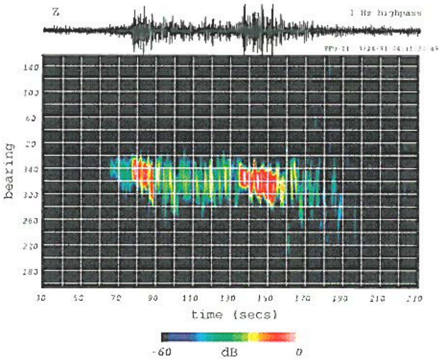
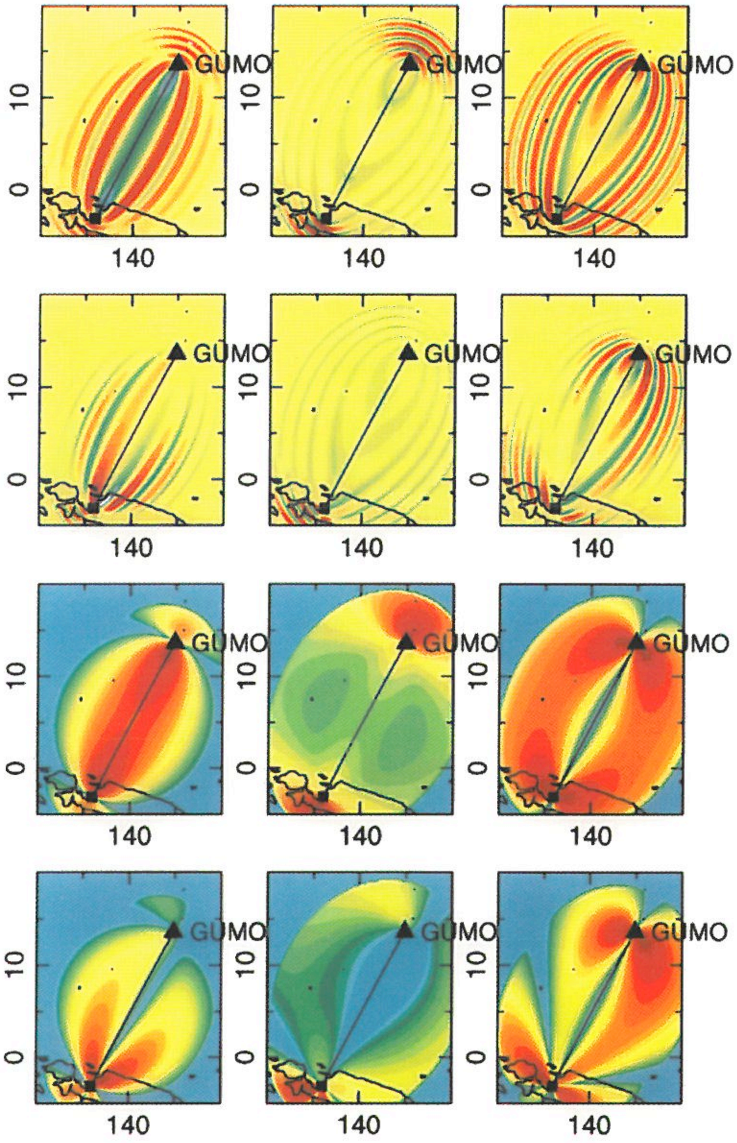


Figure 2 shows a bearing-time record (BTR) for a regional event recorded at the IRIS broadband three-component array located at Pinon Flat Observatory, CA. Three-component array BTRs provide a time-history of the power flux density and propagation direction of direct and scattered P,SV,SH and surface waves crossing the array. The 1~Hz highpass filtered vertical-component record from the array's center site is shown above the BTR for comparison. The back-azimuth to the source is approximately 335\deg. The diverse and considerably off-azimuth propagation directions of the deterministic phases and coda is merely a reflection of the laterally heterogeneous nature of the crustal structure in southern California. It is interesting to note that the apparent west-ward bias in the signals' propagationdirection is consistent with the structural fabric of the region (i.e. NW trending faults, mountains). We also note that the coda does not appear to be the product of back-scattering from randomly distributed heterogeneities. The forward scattered nature of both the P and S coda has fairly significant implications regarding both the distribution and nature of crustal heterogeneities.

Scattered Surface Waves

Thomas Meier and Guust Nolet
Princeton University

One of the major challenges in the next decade will be to interpret the scattered and multi-pathed signals in broadband, digital seismograms. These signals are the most direct indication of lateral heterogeneity. Since the reliability of the seismic signal has significantly increased with the advent of the IRIS GSN and other global networks, since the quantity of such data is growing at a rapid pace, and since the computing power of workstations now allows for cpu intensive data processing, we expect a growing interest in the interpretation of surface waves that travel off the great circle path. For weak heterogeneity, Born theory provides one of the most straightforward ways to interpret scattered surface wave energy, and gives insight into the relative importance of scattering processes, as this figure demonstrates. To construct this figure, we placed scatterers on a latitude/longitude grid around a path from New Guinea to station GUMO and plotted the phase and intensity of the scattered wave. The resulting maps are the surface wave equivalent of 'Fresnel zones' for body wave rays. The scatterers have a depth extent of 440 km. The first column shows scattering from the fundamental Rayleigh mode, the second from the first higher mode, the third from the fundamental Love mode, each to the fundamental Rayleigh mode. The first two rows are the real part of the perturbation for a single frequency (20 mHz) without and with the source radiation pattern incorporated. The color scale is linear, recalibrated for every column. The curves of constant phase are not pure ellipses when scattering occurs between modes with different wavenumber, as in the second and third column. The amplitudes are influenced by the excitation, the scattering angle, the divergence and by anelastic damping. The bottom row shows the total scattered energy (logarithmic scaling) in a time window (2.8-8.0 km/s apparent group velocity) for the frequency band 6-30 mHz. To show the influence of the radiation pattern the total scattered energy is plotted in the third row without the excitation term.

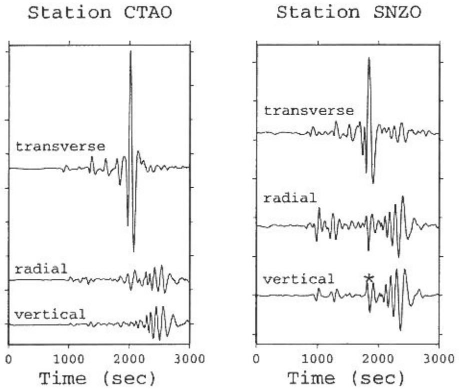


Anisotropy and Long-Period Surface Wave Scattering

Jeffrey Park and Yang Yu
Yale University

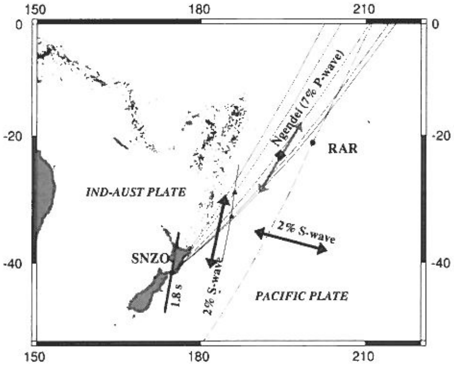
Since the hypothesis of Harry Hess that olivine crystals orient themselves in response to the bulk deformation of ultramafic rock, there has been an increasing body of seismic evidence that the upper mantle is anisotropic. Azimuthal anisotropy of a few percent in the uppermost mantle can cause substantial coupling between spheroidal and toroidal seismic free oscillations, both fundamental and higher-modes. Modest lateral gradients of anisotropy are sufficient to generate significant waveform anomalies in long-period (T>70 sec) surface waves, leading to Love-to-Rayleigh ('quasi-Love') and Rayleigh-to-Love ('quasi-Rayleigh') converted surface wave phases. These are best observed for shallow events near the Rayleigh and Love source-radiation minima, respectively.

The group velocity and dispersion behavior of the fundamental and overtone surface waves make quasi-Love waves much easier to observe than quasi-Rayleigh, though clear examples of the latter can be found. Spheroidal-toroidal coupling caused by isotropic lateral structure is too weak to account for the long-period observations without velocity perturbations in excess of 20—30%, so long-period Rayleigh-Love scattering can "fingerprint" upper mantle anisotropic structure. Deformation-related anisotropy appears to vary on 500-1000-km length scales in the upper 300 km of the Earth. Full GSN coverage and broadband PASSCAL deployments in tectonically active regions will be needed to investigate fully the relation between mantle and surface deformation. By comparing synthetic seismograms for various isotropic and anisotropic models, we conclude that lateral gradients of anisotropy are necessary to explain quasi-Love observations from a variety of seismic stations and propagation paths, from the Western Pacific and Hawaii to Tibet and the western US. The lattice-preferred orientation (LPO) of olivine and orthopyroxene, which occurs as a by-product of peridotite deformation, is a likely cause of these observations. Anisotropy due to thin horizontal layering is a less likely cause, because anisotropy with a vertical axis of symmetry does not induce strong coupling. Successful modelling of quasi-Love waves may help constrain deformation variations, and therefore mantle flow, where olivine and orthopyroxene are present, primarily in the upper 400 kilometers of the mantle.

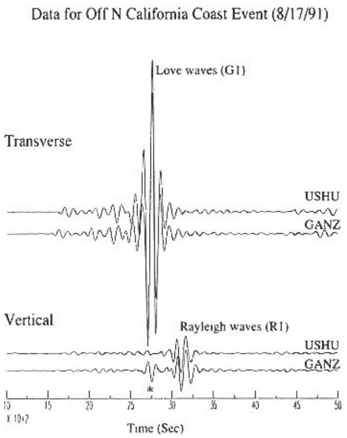

Station CTAO

Station SNZO

GSN data from the 28 June 1992 Landers earthquake (NEIC surface wave magnitude (M_S=7.5), recorded at observatories SNZO (South Karori, New Zealand) and CTAO (Charters Towers, Australia). The data are low pass filtered at 10 mHz (100-s period). The horizontal components are rotated to the radial and transverse components, parallel and normal, respectively, to the source-receiver great circle. The asterisk marks the quasi-Love waveform anomaly.



An anisotropic Earth model for the quasi-Love waves observed at station SNZO. The line in front of the Tonga-Kermadec subduction zone indicates the position of a strong anisotropic gradient, caused by a sharp rotation in the orientation of fast S-wave velocity. The black arrows show the fast S-wave velocity direction on either side of this transition. The solid and dashed lines show the great circle paths with quasi-Love waveform anomalies. NEIC epicenters outline the boundary between the Pacific plate and the Indo-Australian plate. Shallow P-anisotropy the Ngendei seismic refraction experiment is shown for comparison. The symbol at SNZO indicates the fast polarization inferred from the direction of SKS splitting (1.8 seconds).


Data for Off N California Coast Event (8/17/91)

Seismic data recorded at two broadband portable PASSCAL stations USHU and GANZ for the 08/17/91 M_S=7.1 earthquake, off the northern California coast. The data are low passed at 10 mHz. There is no QL waveform anomaly at station USHU. In contrast, the asterisk marks a strong QL wave precursor to the Rayleigh wavepacket R1 at station GANZ. This behavior indicates a strong anisotropic gradient in the mantle beneath the Tangula Shan mountain range, between the two stations in southeastern Tibet.

Subsurface Imaging using the Piñon Flat Broadband Array

Michael Hedlin and Frank Vernon
University of California, San Diego

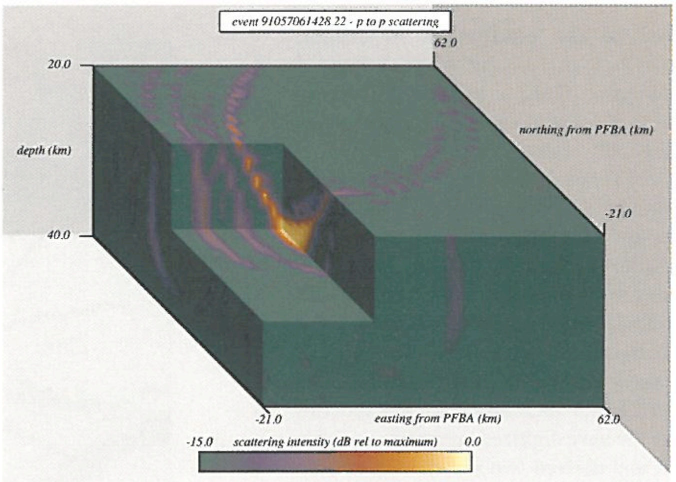


Figure 2 Three dimensional volume imaged using the event displayed in Figure 1. The energy is concentrated at a depth of 30 km near the intersection of the San Andreas and Landers fault zones. The elliptical smears of energy a e due to the relatively limited ability of the small-aperture array to resolve slowness. The beaded nature of the energy distribution is an artifact of the gridding

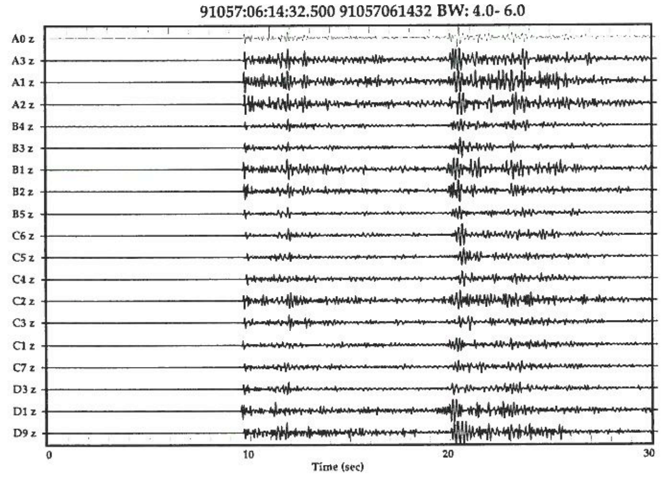


Figure 1 Vertical component triggered-mode recordings of an event that occurred roughly 85 km to the northeast of the Pinon Flat Broadband Array in southern California. Note the phase arriving 2.25 s after the onset energy . The recordings have been band-passed between 4 and 6 Hz.

Active Source Imaging. For decades seismologists have used array, or network, recordings of seismic energy to characterize, or image, the Earth's interior. Most subsurface imaging has been performed using active sources (e.g. vibroseis, explosions) to illuminate subsurface velocity contrasts. The most common technique is seismic reflection profiling widely used in oil exploration. In this method a large number seismometers (geophones) are deployed, most commonly in linear arrays, and used to record back-scattered waves, or echos, returning from the Earth. The recordings of the echos are processed to produce an image of the subsurface. The most important processing technique, used since the 1940's, is seismic migration, which is a means to convert redundant recordings of the echos, made at a range of source-receiver offsets, into subsurface images. In this technique subsurface impedance contrasts are moved (migrated) to the correct locations and diffractions are collapsed. A common form of migration is based on the summation of wave amplitudes along wavefront surfaces. Surface integration, or Kirchhoff, techniques are perhaps the easiest of the modern methods to conceptualize and are readily applied to irregularly sampled datasets. In essence a velocity model is used to predict where, in the data volume, a wavefront due to a scatterer at a particular location should exist. This location is imaged by integrating along the wavefront to constructively interfere any energy that might be arriving from that location.

Comparatively little use has been made of earthquakes to characterize scatterers within the Earth or at the free-surface. Several attempts have been made to locate scatterers both near the receiver and near the source. In our approach the recordings are migrated by considering a 3 dimensional grid of "candidate" scatterers. Rays are shot through an assumed velocity model from the event directly to each receiver and via each candidate scatterer. Considering each scatter in turn, the array, or network, data are then tuned to the scattered wave vector through beam forming (after suppressing the energy that has propagated directly from the event). The time-delay calculated for the sub-volume determines the portion of the beamformed time-series that is attributed to the sub-volume. In these two steps any coherent energy that might be due to scattering is enhanced and attributed to the scatterer (provided that the velocity model is accurate). By stacking multiple events and deconvolving the incident signal from the array records we were able to enhance image resolution. We have generalized the migration technique to use 3 component small aperture array or regional network data. In essence the 3 component station records are rotated into physical coordinates to enhance a particular type of particle motion and then migrated.

An analysis of local earthquakes recorded in 1991 by the Piñon Flat Broadband Array (a 6 km aperture, 28 element 3-component deployment) revealed a subset of events located to the north and north-east that generated P wave coda dominated by a discrete phase arriving from the north of the array with a high apparent velocity. In the example shown in Figure 1 the event is located 36°E of N from the array (at a range of 85 km), the late phase arrives 2.25 s after onset from 14°E of N at a phase velocity of 11 km/s. Three component Kirchhoff migration of these records, directed at P to P scattering, locates a bright secondary source of energy 30 km north of the array in the deep crust near the intersection of the Landers and San Andreas faults (Figure 2). Analysis of ANZA network data suggests that this energy is due either to a discrete scatterer at Moho depth or to reflection from a locally tilted Moho.

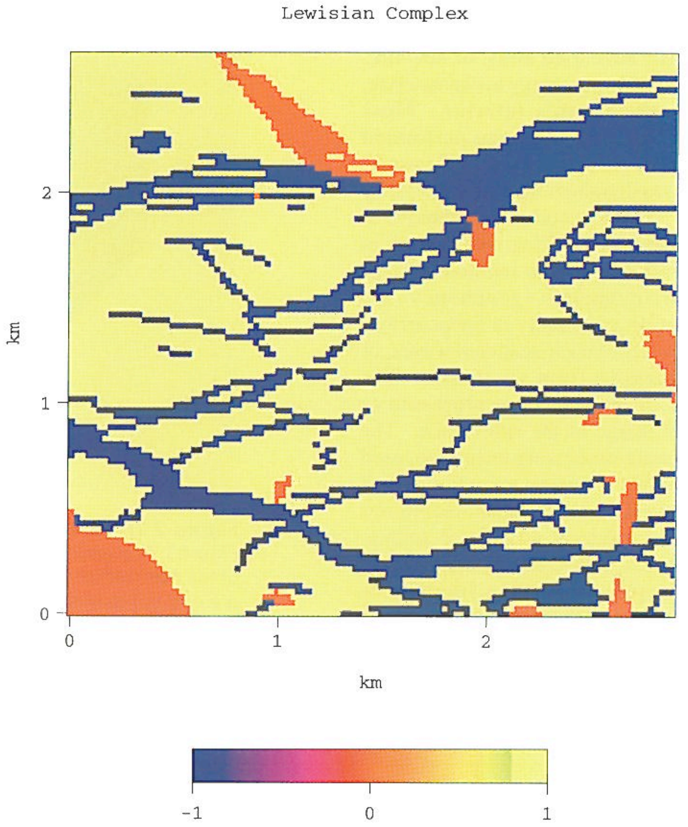
Stochastic Models for Crystalline Rocks and Their Seismic Implications

Alan Levander and John Goff
Rice University and the University of Texas Institute for Geophysics

One of the challenges in crustal seismology the advent of deep crustal reflection profiling in the late 1970s is to develop a seismologically convenient yet geologically realistic means of quantifying fine scale crustal structures (~100m) which produce complex reflection patterns. Complex reflectivity has been recognized in crustal sections of all ages, notably in regions of Phanerozoic extension, but also in Archean and Proterozoic terranes.

To represent accurately the complex structures exposed in exhumed middle and lower crustal metamorphic and igneous rocks, we have digitized numerous geologic maps and derived two statistical functions from the digital maps which can be used to develop stochastic models for seismic forward modeling. The first function is the two-dimensional autocovariance function, which describes the fabric of the exposed rocks (Figure 1). The second is the seismic velocity probability density function, which describes the abundance and modality of the various rock types as expressed by their seismic velocity (Figure 1).

To date we have analyzed nine maps from metamorphic, igneous, and accretionary terranes, representing rocks from the upper, middle, and lower crust. All maps have self-affine (fractal) fabrics, but have a range of outer scales (50m to 3.5km), and fractal dimension (2.45-2.8). The velocities also show a variety possible density functions, ranging from Gaussian to bimodal. Synthetic seismograms for composite models of the crust are remarkably consistent with seismic reflection and refraction data (Figure 2).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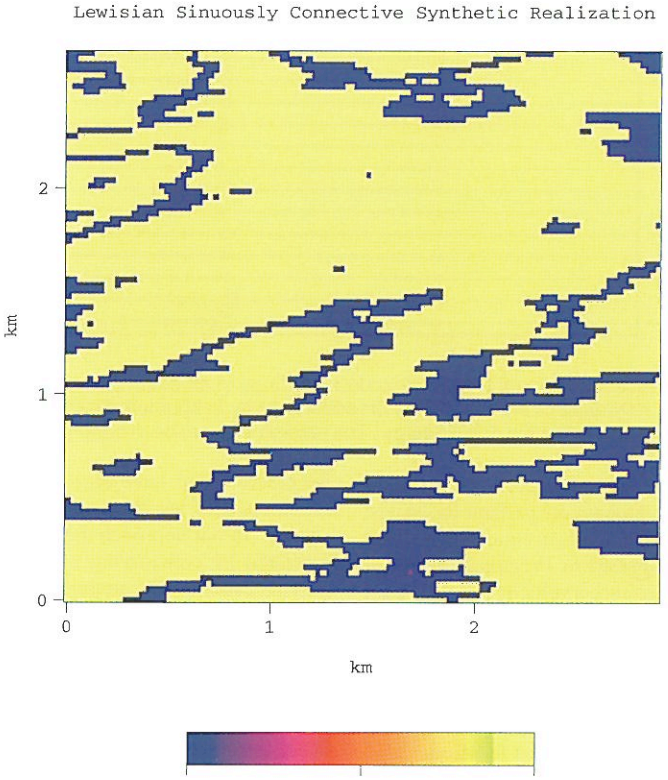
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Waves at the Ocean-Sediment Interface

Robert Odom
University of Washington

The ocean-sediment interface can be highly variables exhibiting heterogeneity both vertically and laterally and on many scales. The heterogeneity can be deterministic at large scales as, for example, the ocean shallows as the shore is approached, thus tilting the interface with respect to the water surface in a well defined manner. The average material properties of the bottom vary from province to province, and on finer scales the heterogeneity can fluctuate randomly both geometrically and materially. The sediment cover on the bottom can have shear speeds less than 100 m/s at the water sediment interfaces increasing to 1 km/s or more in just a few 10's or 100's of meters. Sediment Q's can be low enough ($Q \sim 10$), so that the use of first order perturbation theory for attenuation in modal calculations comes into question. Anisotropy in the form of transverse isotropy is a common characteristic of marine sediments, and can have a significant effect on the propagation of elastic waves in the water - sediment system. Because the interface waves have most of their energy concentrated in a narrow region about the interface, they are very sensitive to the presence of heterogeneities, and are easily scattered. Coupling between the interface modes occurs because of the heterogeneity, although we find that the presence of transverse isotropy seems to suppress the intermode coupling from what would occur for an equivalent isotropic medium. The generation and propagation characteristics of ocean crustal guided phases P_o and S_o, and the sound-channel-guided T phases are still not completely understood. Although reverberation in the water column and sediments at the receiver sites account for many of the characteristics of these phases a number of features including the coda duration and decay rates are still not well modeled. Along-path scattering may account for some as yet unexplained aspects of these signals. An elastic-wave diffusion theory can be developed directly from the coupled mode representation for the elastic wavefield in an attempt to extract information from complicated strongly scattered ocean bottom signals. Seafloor seismic stations developed in the IRIS five-year plan would significantly enhance our understanding of the propagation characteristics of ocean-sediment interface waves including their generation and the scattering mechanisms that can strongly affect them. A significant amount of ocean floor seismic noise is carried by the interface waves, so a clear understanding of them will enhance the interpretation of signals recorded at seafloor based seismic stations. The presence of an array of seafloor stations would permit large scale (basin scale) tomographic inversions to be carried out for seafloor structure. The analytical, theoretical and data processing techniques required to study the ocean-sediment interface waves share much in common with techniques employed for studying regional seismic phases such as Lg. Consequently new techniques developed for the ocean floor studies feed directly back into application to regional phases, and the related area of nuclear test ban verification research.

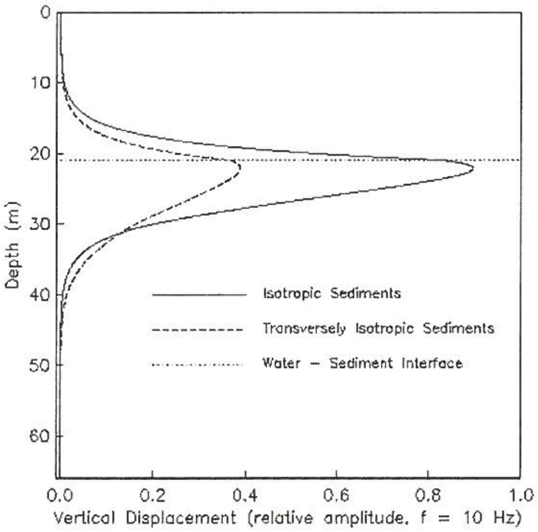


Figure 1. The vertical displacement for the fundamental Scholte wave eigen-function at the water - sediment interface for a transversely isotropic sediment layer (dashed line) and an equivalent isotropic (TI) sediment layer for a frequency of 10 Hz. The modes have been normalized to carry the same energy. Note that the peak amplitude of the TI eigen-function is less than 1/2 that of the eigen-function for the isotropic case. This is due to the increased stiffness in the horizontal direction for the TI medium.

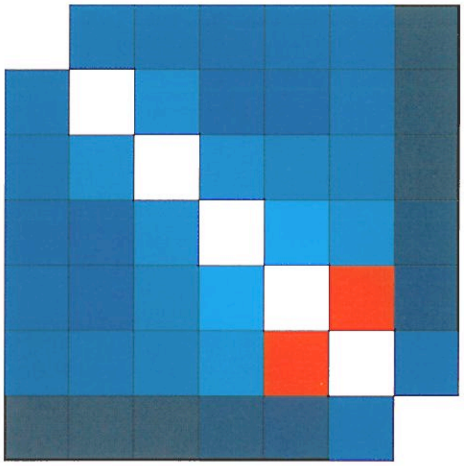


Figure 2. The intermode coupling matrix for a transversely isotropic medium. Red is stronger coupling, blue is weaker. The frequency is 20 Hz, and coupling among the fundamental and first five overtone modes is indicated. The local mode phases are chosen so that the diagonal is zero, so the diagonal is all white. The matrix is numbered so the upper left hand corner is (0,0), where "0" indicated the fundamental mode. The strongest coupling is between the overtone modes 4 and 5.

Ray Perturbation Theory

Roel Snieder
Utrecht University

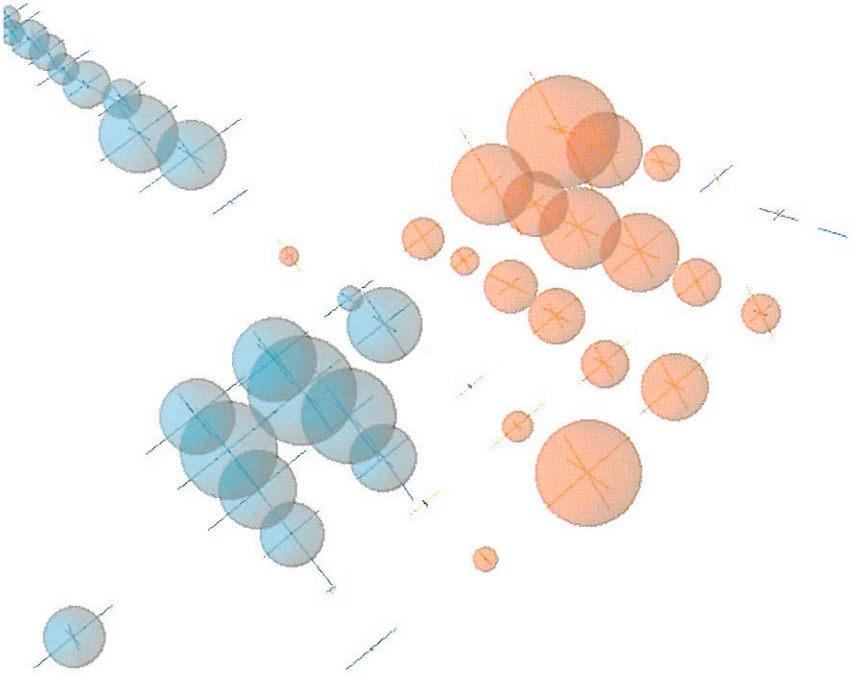
Seismic energy in the Earth propagates predominantly along rays. It is for this reason that ray theory is a powerful tool for modelling seismic waves and for constructing Earth models from seismological data. Examples can be found not only in travel time inversion. Modeling and inversion of both body waves and surface waves is frequently based on ray theory. Rays of first arrivals are curves of minimum travel time. This means that the rays seek the regions of the highest velocity and that the ray positions depend on the velocity model. This renders the inverse problem where the seismic velocity is estimated from seismological data nonlinear; changes in the velocity model have an effect on the way that the wavefield samples the Earth. This effect is systematic because ray bending always reduces the travel time along rays. Ignoring this may lead to a bias in reconstructed Earth models. The bending of rays due to changes in the velocity model depends on the gradient of the seismic velocity. Improvements in the global coverage with seismological stations leads to seismological models with a steadily increasing resolution. The corresponding increase of the velocity gradients makes the systematic effect of ray bending more of growing importance.

Ray perturbation theory is a powerful tool to describe the effect of changes in the velocity model on ray positions and travel times. It is based on the idea that a references slowness model is modified by a small peturbation: $u_0(\mathbf{r})$ ' $u_0(\mathbf{r}) + eu_1(\mathbf{r})$. (The slowness is the inverse of the velocity.) The small parameter e facilitates a systematic perturbation treatment. Suppose that one has an estimate $\mathbf{r}_0$ of a reference ray in the reference medium. In ray peteurbation theory the ray in the peturbed medium is given by $\mathbf{r} = \mathbf{r}_0 + e\mathbf{r}_1 + \ldots$, where $e\mathbf{r}_1$ is the peturbation of the ray position due to the slowness peturbation. Ray perturbation theory leads to a simple linear equation for the ray peturbation: $\mathbf{L}\mathbf{r}_1 = \mathbf{R}$, where $\mathbf{L}$ is a second order differential operator and the forcing term R depends on the slowness peturbation. In addition to this, the second order peturbation of the travel time also falls from ray perturbation theory: $T = T_0 + eT_1 + e^2T_2 + \ldots$. Expressions for the first (T_1) and second order (T_2) travel time peturbation can be found in a straightforward manner.

The linear equations for the ray peturbation can be solved extremely efficiently using judicious choice of the model parameterization. This makes ray perturbation theory ideally suited for large-scale inversions of seismological data. Presently this technique is applied to non-linear global inversions for the *P*-velocity structure of the Earth. In addition, ray peturbation theory can also be used to employ amplitude information in inversions for the velocity inside the Earth.

Understanding High-frequency Wave Propagation: Experimental Evidence from Small-aperture, Three-component Arrays

Gary L. Pavlis
Indiana University



Snapshot from animated visualization to study site resonance effects. The input data are a set of averaged spectral ratios processed to estimate spectral amplification at that site. For each station we have average spectral ratio estimates for each of three components plus total power on all three components. The array geometry is a 6 by 6 grid of sensors with 11 sensors extending outward from the grid along two orthogonal arms. This array is viewed in 3-D from the northwest and above the surface of the earth. At each seismometer location we draw four objects: (1) three orthogonal lines, and (2) a semitransparent sphere. The lengths of each line segment and the radius of each sphere are scaled to the logarithm of the median spectral ratio at that station. The lines represent the result at a given frequency for each of the three individual components,drawn along the direction with which they are associated in 3-space. The spheres display the results of the median spectral ratios of total power on all three components at each station. This allows one to simultaneously see which components are anomalous. The lines are orange and the spheres are red when the median spectral ratio is positive (amplitude is consistently larger than the array average), while the lines and spheres are both blue when the ratio is negative. The number in the lower left corner is the frequency for which the data are being displayed.

It is not widely appreciated that the most dramatic seismic velocity contrast on the entire planet is literally right under our feet. It is not unusual for the shear wave velocities of soil to be less than the sound speed in air. Almost everywhere the shear velocity of soil is 10% or less of the P velocity of the underlying bedrock. Furthermore, except in unusual circumstances (e.g. glacial deposits on top of ice-polished bedrock) the weathered layer is outrageously heterogeneous. Weathering processes tend to accentuate initial rock heterogeneity because of vast differences in the stability of different rock forming minerals.

Every geophysicist has learned in "ground roll" and its importance as a noise source in seismic reflection data. Ground roll is a high frequency Rayleigh wave whose propagation is controlled by the strong waveguide formed by the soil-bedrock interface and the free surface.

High-frequency body waves are intensely scattered when they interact with the weathered layer. First, P to S conversions can occur according to conventional layered model scattering theory. Second, more complex scattering occurs because of lateral variation in the weathered layer. We are finding strong evidence from recent small-aperture array experiments that upward propagating signals from local earthquakes are intensely scattered into a complex mish-mash of waves trapped in the weathered layer.

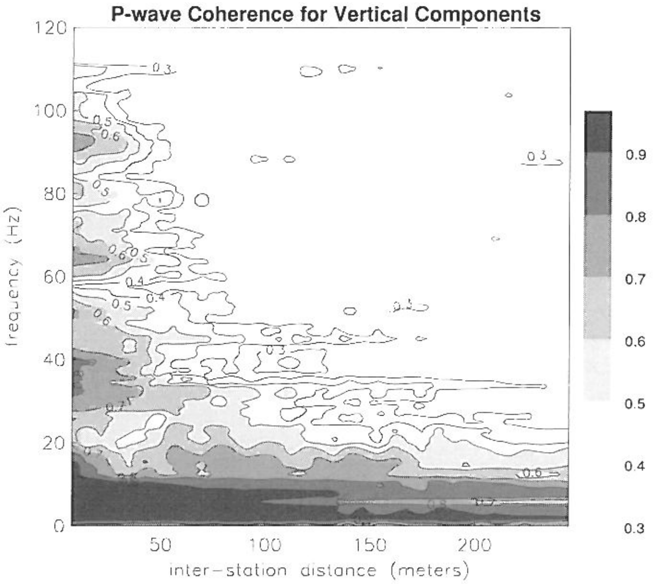
Changes in the elastic properties of a material over the scale of one wavelength mean that point measurements of displacement will show variations in displacement as the disturbance passes. This phenomenon is seen clearly in small-aperture, three-component array data through recently developed scientific visualization techniques (Anderson, 1993).

Resonances may contaminate seismic measurements at high-frequencies when a sensor is placed in the weathered layer. The accompanying figure provides evidence that consistent standing wave patterns are set up in the near-surface at hard rock sites. The figure summarizes the statistics of over 30,000 spectral estimates made from P waves recorded by a high-frequency array deployed in 1990 at Pinyon Flats in southern California using PASSCAL instruments. These results demonstrate that stable patterns of frequency dependent amplification occur on scale lengths of a few meters. My current interpretation is that these represent resonance modes of complicated structures in the near-surface weathered layer.

The data required to reach the above understanding of near-surface wave interaction did not exist before the advent of PASSCAL facilities. It is an excellent illustration of how arrays can be used to provide basic experimental data for fundamental research on wave-propagation. The understanding of these processes is important because most seismic experiments are forced to place their sensors in the weathered layer due to the overwhelming cost of deploying sensors in shallow boreholes.

Near-Surface Scattering Effects Observed with a High-Frequency Phased Array at Piñon Flats, California

Frank L. Vernon
University of California, San Diego
Gary L. Pavlis
Indiana University
Tom J. Owens, Dan E. McNamara, Paul N. Anderson
University of South Carolina



Contour plot of average magnitude squared coherence for the vertical component of the P wave plotted against distance and frequency. White signifies region where coherence has less than 95% confidence of being not equal to 0.

Analysis of data collected by a high-frequency array experiment conducted at Piñon Flat in southern California provides strong evidence that the high-frequency wavefields from local earthquakes at this hard rock site are strongly distorted by near-surface scattering. The seismic array we deployed consisted of 60, 2-Hz natural period, 3-component sensors deployed in a three-dimensional array. Two of the sensors were located in boreholes at 150 and 275m depth. The other 58 sensors were deployed in an areal array above these boreholes. 36 of these were deployed in a 6 by 6 element grid array with a nominal spacing of 7m centered over the borehole sensors. The remaining 22 seismometers were laid out in two 11 element linear arrays radiating outward from the grid. Coherence calculations reveal a rapid loss of coherence at frequencies over 15 Hz at all but the shortest lengths scales of this array. Three-dimensional visualization techniques were used to closely examine the spatial stability of particle motions of P and S waves. This reveals systematic variations of particle motion across the array in which the particle motion tracks tilt drastically away from the back-azimuth expected for an isotropic medium. These variations however, are frequency dependent. Below around 8 Hz the particle motions become virtually identical for all stations. At progressively higher frequencies the wavefield particle motion becomes increasingly chaotic. Frequency-wave number analysis of these data provides quantitative measures of the same phenomena. We find that direct wave f-k spectra are bathed in a background of signal-generated noise that varies from 10-30 dB down from the direct arrival signal. This signal-generated noise appears to be nearly white in wave number indicating that the wavelength of this “noise is on the scale of tens of meters and less. Refraction measurements we made on in two lines crisscrossing the array reveal the weathered layer velocities are highly variable and define a very strong waveguide. Measured surface velocities varied from 400 to 1300 m/s, and velocities at depth of approximately 15 m varied from 1600 to 2700 m/s. Previous measurements in the boreholes showed that the intact granite below about 65 m depth has a velocity of approximately 5400m/s. These results demonstrate the extreme velocity contrast and degree of velocity heterogeneity of the near-surface at this site.

The most logical model that can explain all these observations is that body waves propagating upward from earthquake sources are scattered in the near-surface into body-waves trapped in the surface waveguide and high-frequency surface wave modes associated with the same waveguide. The weathered layer is highly irregular on scale lengths that are a significant fraction of the wavelength of incoming body waves. Numerous numerical simulations of this type of geometry indicated this type of corrugated weathered surface can induce near-surface scattering. High-frequency seismograms are seriously distorted by near surface scattering at this site. The same phenomena almost certainly occurs to some degree at any hard rock site. We cannot yet, however, easily extrapolate these results to predict the degree of signal generated noise at a given site. It no doubt depends upon the depth of the weathering and the degree of heterogeneity in the near-surface.

Surface Wave Tomography of Eurasia

Anatoli L. Levshin and Michael H. Ritzwoller
University of Colorado, Boulder

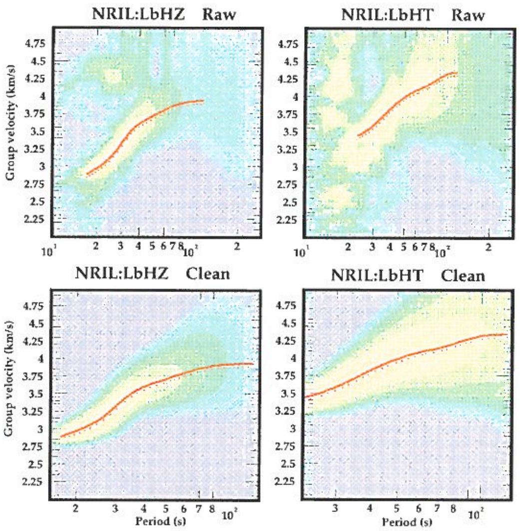


Figure 1a.

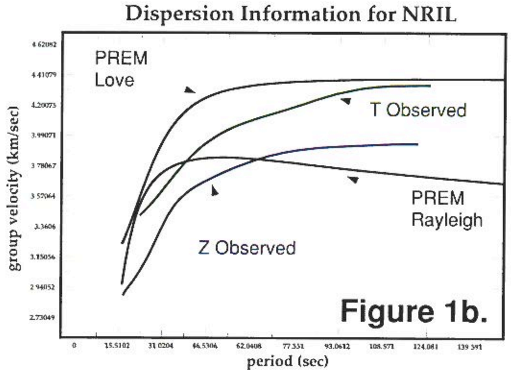


Figure 1b.

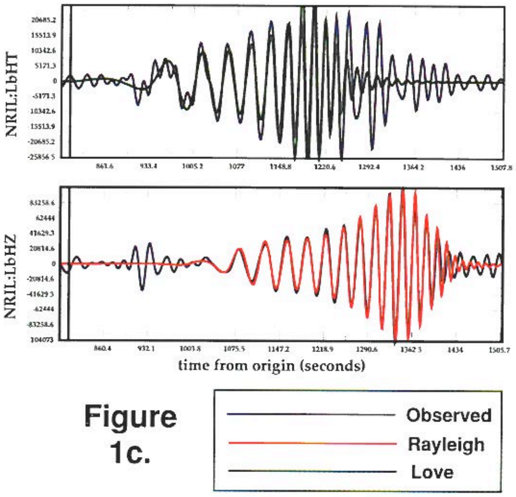


Figure 1c.

Deployment of three-component modern digital seismographic networks and arrays in Eurasia by IRIS and USGS has opened new opportunities for the study of surface wave propagation across this continent. Due to the high quality of the instrumentation and the reliability of their calibration, both Rayleigh and Love wave velocity and polarization measurements are proving to be reliable and highly accurate. The goal of the project described here is to obtain a detailed image of the lithospheric shear-velocity structure underlying Eurasia and to relate the observed variations to tectonic structures. Other FDSN networks, such as MEDNET and GEOSCOPE, complement the IRIS deployments. Data from these events since 1988 with Ms > 5.9 have been obtained from IRIS DMC. Phase and group velocity dispersion curves as well as frequency-dependent azimuthal particle-motion anomalies for fundamental Rayleigh and Love waves in the period range between 20 - 300 s are measured by means of frequency-time analysis and floating filtering. Figure a displays raw and filtered frequency-time images for an event in Kamchatka (11/13/93, Ms = 7.1) recorded at the IRIS/IDA receiver in Norilsk, Russia. Contamination from overtones and coda are eliminated from the resulting waveforms, as shown in Figure b where frequency-time filtered Rayleigh and Love waveforms are plotted over raw data. Dispersion and polarization measurements are made on the filtered waveforms. Group velocity measurements are shown and compared with predictions from PREM in Figure c. Such measurements from approximately 10,000 source-receiver paths will provide the data set for 3D-tomographic inversion. The expected spatial resolution of tomographic images will be 300-1000 km, depending on local ray coverage. Preliminary results of tomographic inversion for such regions as the Tibetan Plateau, the Tarim Basin, and the Sayan-Baykal zone have revealed some previously unknown lithospheric features.

Multiwavelet Spectral and Polarization Analysis of Seismic Records

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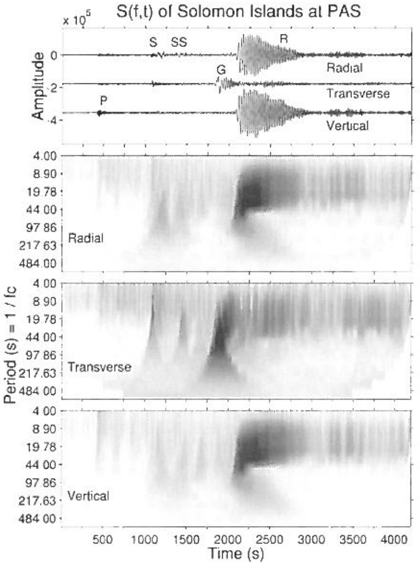
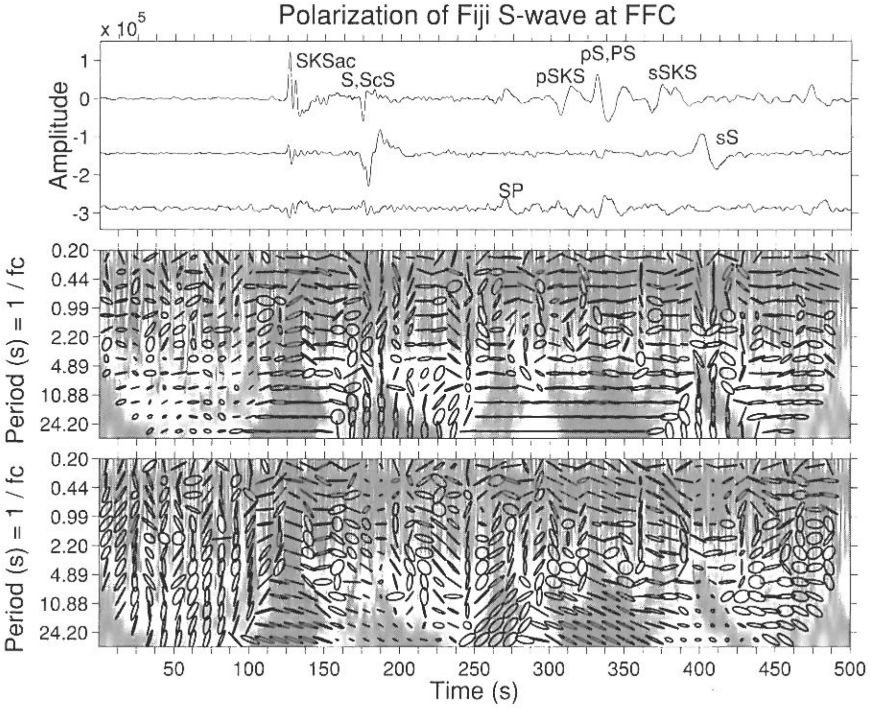
University of Washington
Jeffrey Park
Yale University

If one is interested in frequency-dependent, time-limited signals in a seismogram, an estimate of the time-varying spectrum is useful. One way to estimate the time-varying spectrum is by means of discrete Fourier transforms (DFTs) of overlapping time intervals that step through a longer time series. However, the choice of an ideal segment duration for a moving-window Fourier transform is often problematic. A moving-window DFT has the same time-resolution for all frequencies, or equivalently, has a uniform resolution in frequency space. This restriction is cumbersome when analyzing seismic records, which are a composite of signals of varying durations and frequency content: body waves, surface waves, scattered waves and local resonances. The wavelet transform offers an alternative time-frequency trade-off strategy for spectrum estimation, in which the analyzed time interval scales inversely with the frequency of interest. The wavelet transform decomposes a seismogram into a set of band limited pulses, a paradigm that most seismologists would find agreeable. We have adapted the wavelet transform to improve its spectral leakage properties and to make the trade-off between spectral variance and resolution more explicit, and therefore more susceptible to optimization.



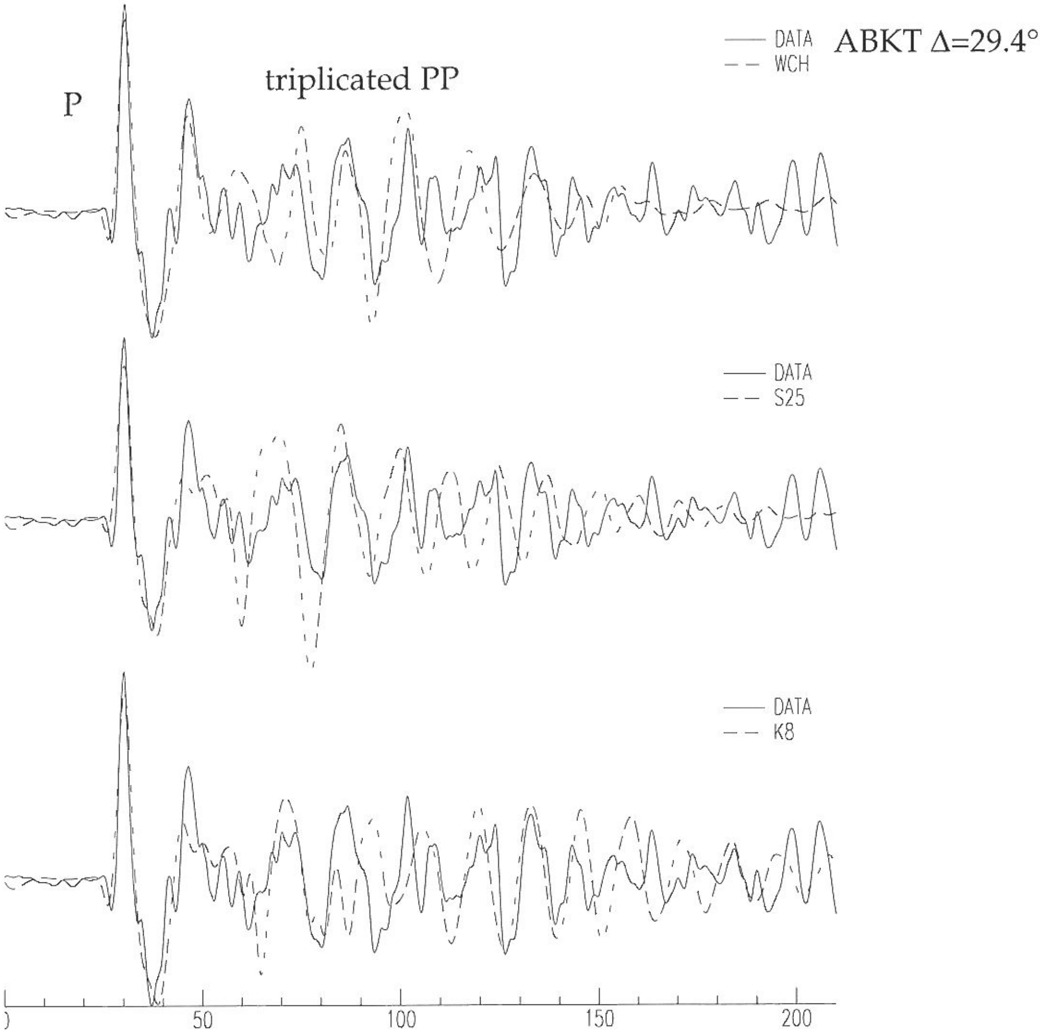
Multiwavelet spectral analysis of the 9 February 1991 Solomon Islands event (NEIC magnitude m_b=6.9, location 9.4°5, 159.1°E, depth 33km), recorded at PAS (Pasadena, California, =89.3 °). The lower panels show the wavelet spectrum estimates for each component of motion. Our analysis uses three complex Slepian wavelets with p=2.5,p_c=3.0. We set the spectrum estimates to zero wherever they are subject to bias from finite-record effects.



Multiwavelet polarization analysis of the broadband SKS wavetrain of the 9 March 1994 deep Fiji earthquake, recorded at FFC. Our analysis uses three complex Slepian wavelets with p=2.5, p_c=3.0. In the lower panels the normalized first singular value of the multiwavelet transform matrix is shaded where it exceeds 9% confidence for non-randomness. The center panel shows particle motion in the horizontal plane, with radial component oriented right-left, and the transverse component oriented up-down. The lower panel shows particle motion in the radial-vertical plane, with radial component oriented right-left, and the vertical component oriented up-down. The gradual increase of horizontal ellipticity with decreasing period is consistent with a fixed time shift associated with shear-wave splitting. This pattern breaks down at periods less than 0.75 sec, where the signal level is low. A shallow-incidence P phase appears to precede the SKS phase by roughly 10 seconds.

Asian Upper Mantle Structure from IRIS Waveform Data

Arthur Rodgers and Susan Schwartz
Institute of Tectonics, UC-Santa Cruz



We are modelling the waveforms of crustal events that occur and are recorded within the Asian continent in an attempt to constrain the upper mantle velocity structure of this region. Shown is the vertical displacement due to a magnitude 5.8 earthquake in Tibet recorded at station ABKT (Turkmenistan). Overlying the data trace are synthetic seismograms (dashed trace) for three models of the upper mantle. The top panel shows the best fit to the triplicated PP arrival. Such modelling allows us to infer the depth dependent velocity structure within this region in order to understand propagation effects for nuclear monitoring as well as address basic science questions regarding the tectonic evolution of Asia. Recent deployment of IRIS stations has made high-quality digital broadband data available for this effort.

SAMSON: The Onshore Broadband Array

John Nabelek, Guibiao Lin, and Anne Trehu
College of Oceanic and Atmospheric Sciences, Oregon State University

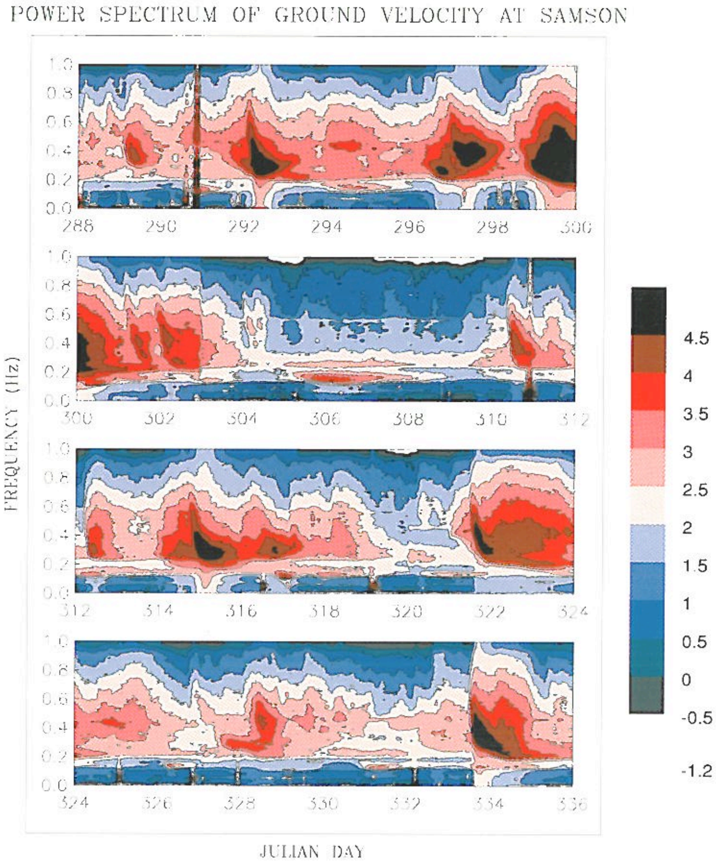


Figure 1. Power spectrogram of ground velocity from the center of the onshore array for the entire SAMSON experiment.

In Oct. and Nov., 1990, we collected data from an array of 37 three-component seismometers (16 broadband, 6 5-s, 15 1-s) deployed on the coastal plain of northeastern North Carolina and southeastern Virginia as part of the multidisciplinary SAMSON (Sources of Ambient MicroSeismic Oceanic Noise) experiment. This was first large-scale PASSCAL experiment involving broadband sensors. The array extended from a few hundred meters to 170 km from the coastline. The purpose of the experiment was to characterize the broadband frequency-wavenumber noise field and relate it to coastal processes, major deep-ocean storm systems, and the concurrent seafloor noise field measured by other participants in SAMSON.

Large variations in the broadband noise level are observed as a function of time (Fig. 1), with the power during the noisiest times being more than 100 times higher than during the quiet times. Some of these noise variations are related to large-scale regional environmental changes (e.g., a "nor-easter" on Julian Days 299-301), which resulted in large changes in sea-state, but many powerful noise peaks are not accompanied by such large regional disturbances.

We observe two microseisms types of that are generally unrelated to each other. Type A has peak power between 0.2 and 0.8 Hz. This type shows a characteristic temporal pattern, with an abrupt onset, a duration of about 12 hours and a frequency reddening with time (e.g., JD 292, 315, 322, 334, Fig. 1). Both the lack of coherence across the array and the decay of amplitude with distance from the coast clearly indicate that the Type A microseisms are generated locally along the Atlantic continental margin. We have found that these peaks occur at times of rapid change in the wind direction, as high-pressure fronts move from the continent to the ocean. These events are well explained by the Longuet-Higgins theory.

In contrast to the Type A events, Type B microseisms are relatively narrow band, with peaks centered around 0.15 Hz and less energetic peaks at a half of the frequency (Fig. 1). This type of microseism is coherent across the array, occurs at regular intervals, and does not decay measurably in amplitude across the array, indicating a distant origin. F-k analysis generally shows primary energy arriving from the north.

To identify the source region and understand the source mechanism of Type B microseisms, we used data from global broadband stations operating during SAMSON. In order to determine directional information from single stations, we developed a scheme to estimate the azimuth of approach of the microseismic noise from particle motion analysis of three-component recordings. The strongest Type B event occurring during SAMSON (JD 305-307, Fig. 1) can be observed simultaneously at all stations on the North American continent. Rayleigh-wave-type motion dominates the particle motion, and the azimuth of approach indicates that the most likely source regions for the noise peak centered around 0.15 Hz are in the vicinity of Hudson Bay and the Labrador Sea; for the less energetic peak centered around 0.07 Hz, the most likely source region is in the Labrador Sea. Type B microseisms are generally correlated with low-pressure weather systems in the Labrador Sea and Hudson Bay.

Seismology as a Cornerstone in Earth Science

Raymond Jeanloz
University of California at Berkeley

Seismology is revolutionizing our understanding of the Earth, the new generation of observations providing remarkable insights into the structure and processes of our home planet. A measure a discipline's import is its influence on neighboring disciplines. There is no doubt that the observations being made by seismologists are having a major impact on research across the Earth sciences.

The ability to image small variations in seismic wave velocities characterizes much of the new information about the Earth's interior. The analogy can be made with the impact that CAT scans, MRI and other techniques of imaging have had in medicine. The seismological variations represent heterogeneities in the material properties at depth, and it is these heterogeneities that drive global-scale processes such as the fluid-like convection of the Earth's rocky mantle. It is fair to say that the percent-variations in rock density and seismic wave velocities reflect the driving forces behind plate tectonics, and the associated phenomena of earthquakes, volcanism and ore formation; indeed, most of the geological processes of the Earth's crust.

One of the first surprises to emerge is that the detailed variations in seismic velocities deep in the Earth are not what was previously expected based on laboratory experiments carried out on rocks. Specifically, the magnitude of the lateral variations in shear-wave velocity, relative to those in compressional-wave velocity, are roughly 50-100% higher than was anticipated for the mantle. Could our understanding of how temperature, pressure and chemical composition influence the properties of rock be so far off?

The answer seems to be yes, at least in part. Motivated by the new seismological observations, mineral physicists have reexamined the factors that determine the wave velocities of rock, and have come up with two possible explanations. First, an old idea was revived, namely that temperatures in the mantle may be so close to the melting point that the rock at depth contains small pockets of magma. Since shear-wave velocity is especially sensitive to the presence of fluid, small variations in the quantity of melt at depth could easily explain the relatively large velocity-variations that are observed. Indeed, this idea is considered attractive for the shallow mantle of the Earth, since geological evidence shows that many volcanic eruptions at the surface originate from magmas that come from well within the upper mantle.

Although there is good reason to expect that a large fraction of the upper mantle is partially molten, this is considered much less plausible for the entire mantle. Put another way, it would be a dramatic shift in our understanding of the planetary interior if one could prove that the bulk of the mantle is so close to the melting point, because this varies greatly as a function of depth. An alternative explanation has been sought, leading to the discovery that significant new effects on wave velocities can come into play at high pressures and high temperatures; that is, at the conditions of the deep mantle. These phenomena, anharmonic effects, represent deviations from aharmonic potential describing the bonding energy between atoms. Anharmonicity is normally small in magnitude, but is highly interesting in its own right because it is the underlying cause of thermal expansion and therefore of convection. In short, the buoyancy forces driving mantle convection and plate tectonics originate in the anharmonic nature of chemical bonds, and the seismological observations have motivated a new level of understanding of these phenomena at an atomic scale.

The distribution and sizes of heterogeneities are themselves interesting, the continental crust being the most notable global-scale heterogeneity. In retrospect, it is perhaps not too surprising that the degree of heterogeneity is strongest near the two most significant boundaries of the Earth, the surface and the boundary between the mantle and core. After all, these boundaries are likely to be regions where heterogeneities produced by a variety of geological processes can accumulate.

The core-mantle boundary, for example, has been identified as being perhaps the most chemically active region of our planet. Experimental and theoretical investigations have shown that the rock of the mantle can react vigorously with the liquid metal alloy of the outer core, and the products of this chemical reaction can neatly explain the seismologically observed heterogeneity at the bottom of the mantle. Accepting this evidence leads to the remarkable conclusion that the rocky mantle has been effectively dissolving into the underlying liquid core over geological history. If this picture is correct, the seismological heterogeneity near the core-mantle boundary surely reflects one of the most spectacular ways in which the planetary interior has evolved over time.

In comparison, it is remarkable how "smooth" — free of heterogeneity — the bulk of the lower mantle is observed to be. Fortunately, laboratory experiments demonstrate that material with the perovskite lattice structure is predominantly stable throughout this single largest region of the Earth. One concludes that the lower mantle, containing more than 60 percent of the planet's matter, is predominantly made of dense perovskite-type crystals, structurally similar to a class of materials having wide-ranging technological applications. This result is enormously helpful in allowing the experimentalist and theoretician to focus on understanding the properties of this one type of material that dominates the bulk of the Earth's interior.

By imaging the heterogeneities within the transition zone, between 400 and 700 km depth, seismology is beginning to resolve the pattern of convective flow throughout the mantle. The overall distribution of seismic heterogeneities remains enigmatic, however. Why are large-scale heterogeneities so abundant ("red" spectrum), for example? Theories about complex mixing in fluids are being investigated in order to find clues about how the heterogeneities in the Earth's mantle might evolve over geological time. These theories are at the cutting edge of research in physics, chemical engineering and fluid dynamics, yet the pattern of heterogeneities inside our planet continues to elude a full understanding in geophysics and geochemistry.

In addition to identifying heterogeneities within the interior, the new seismological observations have revealed significant anisotropies: waves propagating with different orientations through a given region exhibit markedly different velocities. In many locations near the surface, the orientations of fast and slow velocities appear to be correlated with directions of tectonic deformation. This is especially true for the uppermost mantle under the ocean basins, where alignment of minerals due to plate-tectonic motions appears to be the cause of seismic anisotropy.

Whether mantle anisotropy always reflects present-day geological motions is uncertain. The effects of earlier tectonic deformations, perhaps far in the geological past, might remain frozen in the rocks at depth and expressed as an anisotropy in seismic waves. Observations of anisotropy in ancient continental lithosphere may offer an example of this phenomenon. If so, the seismological data would provide unique insights into geological processes that took place early in Earth history.

Given that the upper mantle shows such good evidence of tectonically-induced anisotropy, it is perhaps surprising that the bulk of the mantle appears isotropic. After all, convection is expected to impose a tectonic deformation on the entire mantle, and the minerals of the lower mantle are as elastically anisotropic as those of the uppermost mantle. The two sets of minerals deform in different ways, however, and the most recent laboratory experiments confirm that unlike the uppermost-mantle minerals, the perovskite minerals of the deep mantle actually do not exhibit a strong anisotropy even after substantial deformation. The laboratory data and seismological observations are therefore in good agreement with each other.

Possibly the most intriguing observation has been the discovery that the crystalline inner core of the Earth also exhibits anisotropy. The seismic waves travel a few percent faster in the polar (North-South) direction than in the equatorial directions. One suggestion has been that the planetary magnetic field, which originates in the core, may be the ultimate cause of this anisotropy. If so, it may be necessary to invoke novel magnetic processes taking place deep in the core. An alternative, but not contradictory explanation, is that the anisotropy of the inner core may be due to tectonic deformation, just as is the case for the anisotropy of the uppermost mantle. Indeed, estimates of the mechanical state of the inner core strongly suggest that this region is undergoing vigorous solid-state convection, like the mantle. The conclusion thus seems to be that tectonic motions take place throughout our entire planet, from the surface to the center.

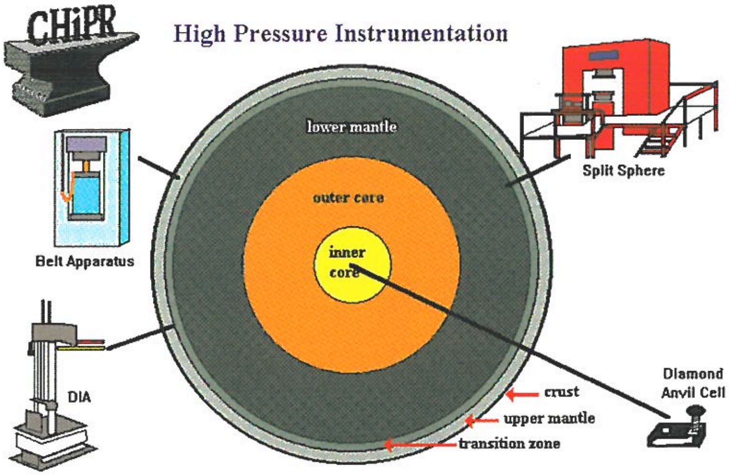
This brief tour of recent discoveries offers selected examples of the ways in which the new generation of seismological observations are unraveling the secrets of our planet's interior, from the crust to the innermost core.

Mineral Physics and Seismology

Donald J. Weidner
State University of New York at Stony Brook

Our greatest insights into the state and evolution of the Earth come from seismic studies. IRIS offers the state-of-the-art data base for these studies. As a mineral physicist, my research agenda is to gather and use laboratory data on the properties of earth materials in order to better understand the processes and properties of the earth. This task requires comparisons with information gathered about the earth directly. Seismology can provide the data for this comparison.

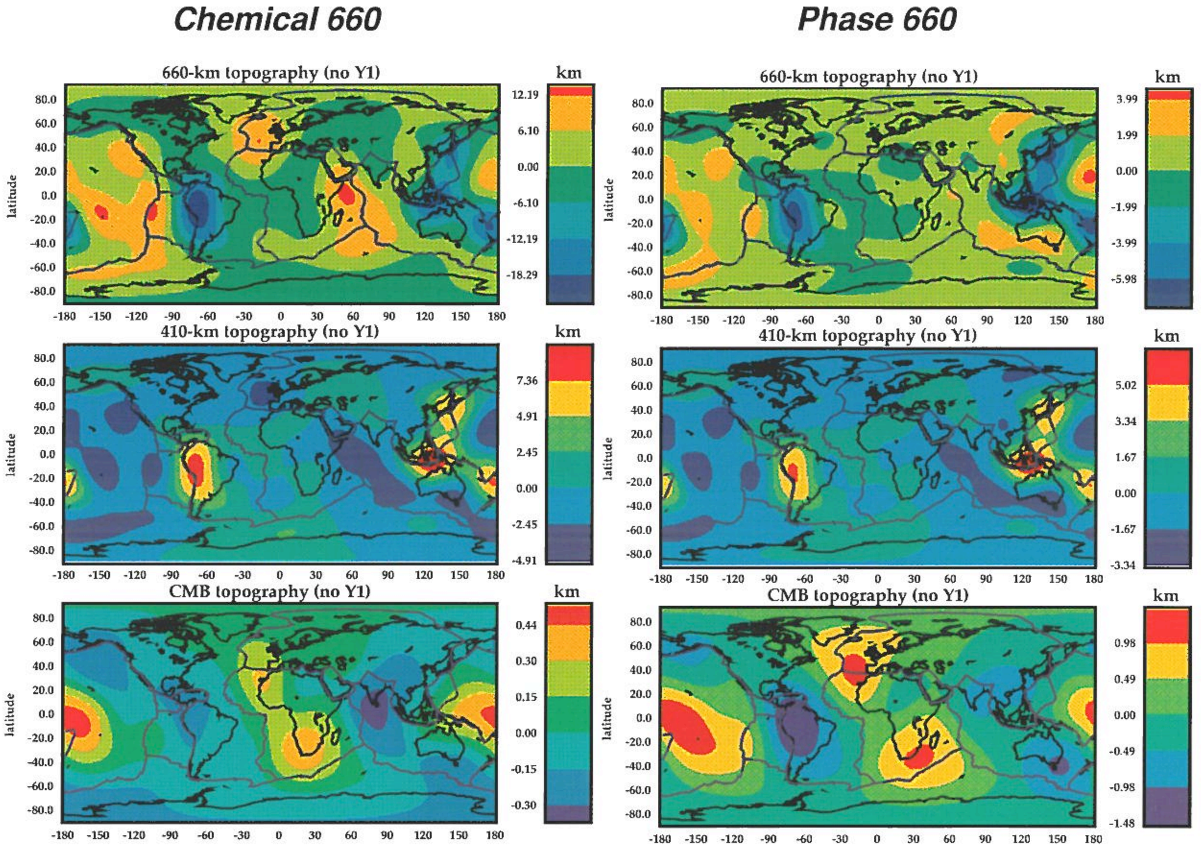
The radial variation of seismic velocity has been very fruitful in establishing chemical constraints for the mantle. The more recent information concerning lateral variations observed in tomographic studies, and anisotropy seen in shear wave splitting observations add a wealth of information about the Earth. As a high pressure scientist, I approach the Earth as a large volume, high pressure/temperature device with in situ measurements of a number of properties including acoustic velocity, density, stress. These informations, used in conjunction with laboratory high pressure systems, can define the properties of materials under extremes of pressure and temperature. For example, the radial variation of shear velocity in the lower mantle, combined with the laboratory measurements of perovskite shear velocities, demands that the temperature derivative of the shear modulus be relatively large. The deduced value, in turn, places constraints on the lateral temperature variations in the lower mantle that are revealed by tomography. These all then couple into dynamic models of convection. Central to these types of understandings are the data provided by IRIS.



Pressure and temperature of the Earth's interior can be replicated in the laboratory with a variety of apparatus. The belt device, representing the first apparatus to grow diamonds commercially reaches into the upper mantle. The DIA apparatus, capable of studying large volume samples with precisely controlled high temperature, reaches into the transition zone. Split sphere large volume systems are capable of creating large volumes of lower mantle phases. The diamond cell can simulate pressures throughout the Earth's interior.

Geodynamically Consistent Global Mantle Models

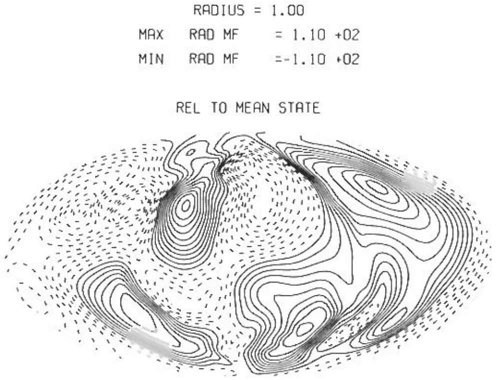
Michael H. Ritzwoller and John Wahr
University of Colorado, Boulder



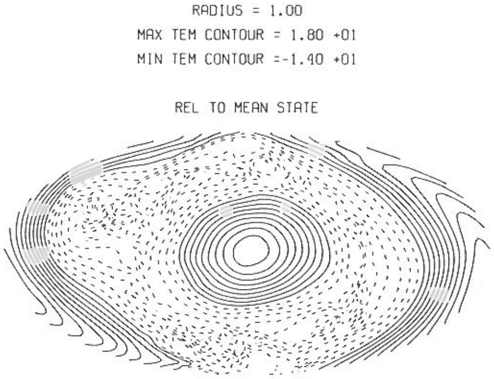
The growth of global seismic networks, in particular the IRIS GSN, as well as the historical accumulation of long period seismograms from many large earthquakes, have permitted the construction of increasingly more accurate models of the seismic structure of the mantle. These models, unlike the Earth, are typically static. The use of seismic models to reveal dynamical information about the Earth is a principal challenge of global geophysics. One route to infer aspects of mantle dynamics from seismic models has been to convert existing large-scale seismic models to density anomalies which are entered as body forces into the equations of motion for buoyantly-driven viscous flows. This same approach can be taken during the seismic inversion. The resultant models possess both volumetric structure and boundary topography that relate to one another through geodynamical kernels. These kernels are themselves dependent on the nature of each boundary (chemical or phase), the scaling between density and the estimated seismic velocities, the radial viscosity profile, the density jump across each boundary, whether an *a priori* slab model has been employed and its density, and the Clapeyron slope for a phase boundary. Seismic models constructed in such a way are said to be geodynamically consistent, but the price of this consistency is the production of a suite of models which results by varying each of these parameters within reasonable bounds. A question of particular interest is the impact of varying the nature of the 660-km discontinuity on the magnitude and geometry of topography on the mantle boundaries. The accompanying figure displays topography on the CMB, and the 410-km and 660-km boundaries resulting from two inversions that differ only in the nature of the 660-km discontinuity (chemical or phase). In each inversion, normal mode structure coefficients and the geoid were inverted for volumetric structure, boundary topography, and the radial dependence of the scaling between density and seismic velocity, but other free parameters were fixed. In the left column of the figure, the 660-km boundary is a chemical boundary and in the right column it is a phase boundary with a Clapeyron slope of -4.6 MPa/K. The geometry of topography on the transition zone boundaries is similar irrespective of the nature of the boundary, although there are differences that may be significant. In all cases the magnitude of topography differs substantially when the nature of the 660-km boundary is changed.

Deep-Earth Seismic Models as Constraints On Convection Models for the Earth's Core

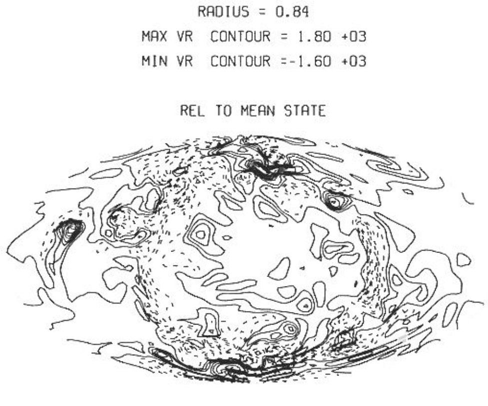
Peter Olson
Johns Hopkins University



Contours of radial magnetic field on the core-mantle boundary produced by the interaction of a toroidal magnetic field and the velocity pattern shown in the last figure. Solid contours are radially outward flux; broken contours are radially inward flux.



Temperature variations on the core-mantle boundary produced by applying lower mantle heat flow variations obtained from the Su et al (1994) lower mantle shear wave tomography model to a calculation of thermal convection in the core. Note that the solid (warm) contours are smooth, indicating conduction, whereas the broken contours (cold) are irregular, indicating enhanced core convection



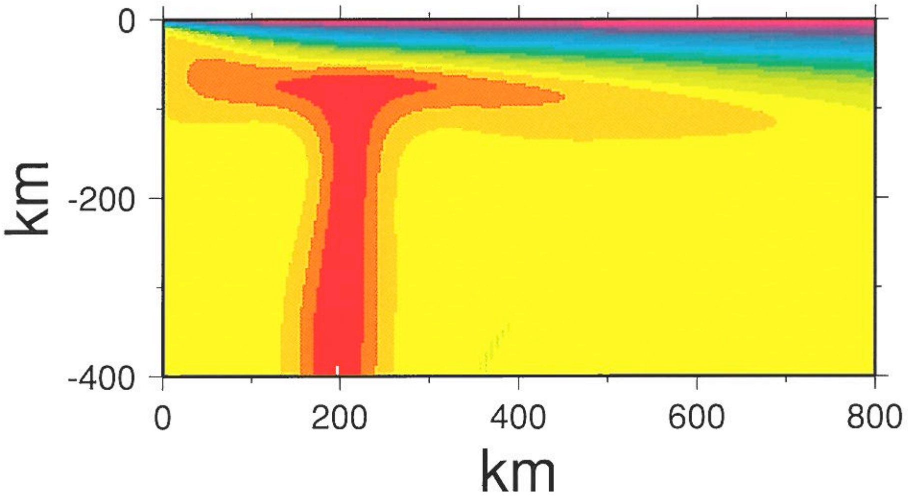
Radial velocity variations at radius r=0.84 in a calculation of thermal convection in the core. The convection is driven by the temperature variations shown in Figure 2 obtained from the Su et al (1994) model of lower mantle shear wave tomography, and shows a plausible form of thermal coupling between the core and lower mantle. Solid contours are upwellings; broken contours are downwellings.

Dynamical Models for Seismic Velocity Heterogeneity at Hotspots

N. M. Ribe
Yale University

Although the existence of mantle plumes is almost universally accepted, they are very difficult to observe directly. In recent years, however, the advent of seismic tomography has provided new ways of imaging the seismic velocity heterogeneities associated with mantle plumes. Nataf and VanDecar have detected seismic velocity anomalies at about 700 km depth west of Canada, which they interpret as being due to the mantle plume that feeds the Bowie hotspot. More detailed seismic imaging studies have been carried out at other hotspots,including Yellowstone [Humphreys and Dueker,] and Iceland [e.g., the ICEMELT experiment; Bjarnason et al., 1995].

In order to interpret properly the observed seismic velocity anomalies beneath a hotspot, we require a realistic 3-D dynamical model that can predict their distribution. I have recently developed such a model in collaboration with U. R. Christensen (University of Goettingen, Germany). The model domain is a rectangular box 400 km deep and of variable length and width, filled with fluid whose viscosity exhibits a strong Arrhenius-type dependence on temperature and pressure. Hot plume material ascends from a thermal anomaly on the lower surface of the box, and spreads out to form a broad "plume head" when it reaches the base of the lithosphere. The shape of the plume head depends critically on the lateral velocity $U(x)$ of the lithosphere, which is imposed as a boundary condition in our model. The velocity $U(x)$ can be chosen to represent either uniform translation, translation plus uniform extension, or spreading. This flexibility allows us to model hot spots in a variety of tectonicsettings, including old intraplate lithosphere, actively deforming continental lithosphere (e.g., Yellowstone), and mid-ocean ridges. Numerical solutions are obtained using a hybrid spectral/finite difference technique and yield the flow velocity and temperature at each grid point in the model box. An example of such a flow is shown in Figure 1, in which a plume rises 200 km away from a spreading ridge. The temperature anomalies associated with such a flow can easily be translated into corresponding anomalies in seismic velocity. The result is a 3-D "map" of lateral heterogeneity that can be compared with the results of seismic inversion or used as the basis for seismic ray tracing and forward modeling.

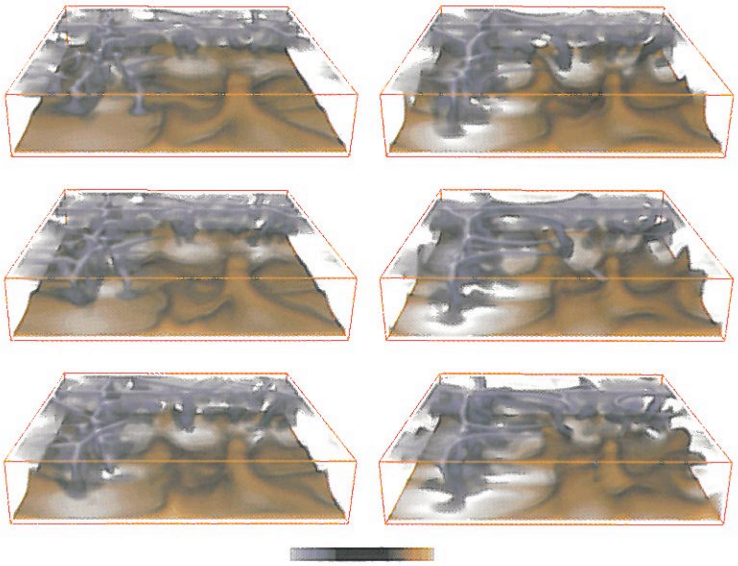


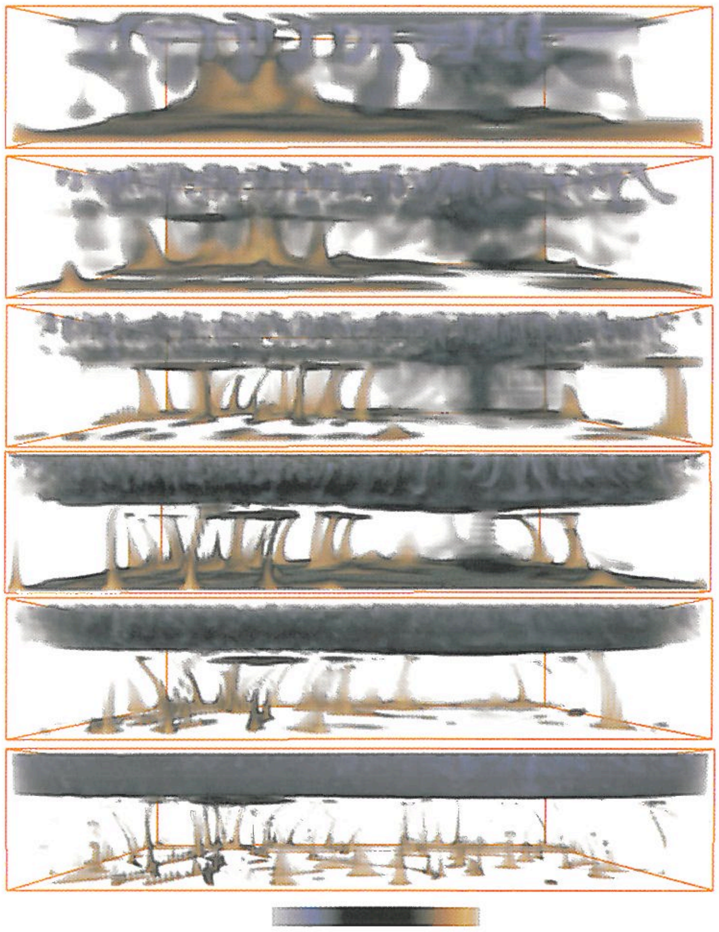
Temperature field (0 to 1600 degrees C) for a mantle plume rising 200 km away from a spreading ridge (left edge of figure). Shown is the vertical plane which is normal to the ridge and bisects the plume. The plume has buoyancy flux 920 kg/s, and the half spreading rate of the ridge is 0.85 cm/s. Note that some of the plume material is channeled to the ridge, producing a "hotspot" there.

3-D Convection in Cartesian Geometry

D.A. Yuen
University of Minnesota

Although the geometry of the mantle is spherical in nature, there are many facets in mantle convection which can be best studied with cartesian geometries. In issues of understanding nonlinear physical pheneomena, the use of cartesian geometry has shed much more light than using spherical geometry. The underlying reason is the issue of spatial resolution. Phenomena such as viscous heating and phase-transitions are best captured with the cartesian geometry, because of the presence of many short wavelength features. Unless one is really interested in long wavelength phenomenon, there seems to be no reason to employ spherical-shell geometry. Many phenomena for high Rayleigh number convection have been studied first with cartesian geometries (Malevskyand Yuen, 1993 ; Yuen et al. , 1994), well before they can be attempted with spherical-shell geometries. We can already exceed realistic Rayleigh numbers for the present-day Earth in cartesian geometries with aspect-ratio of five by five by one. Rayleigh numbers around 10**8 can easily be attained with the super-computers of the mid 1990's, whereas it would be a grand challenge problem to reach such Rayleign number in a spherical-shell geometry. In order for us to compare mantle circulation patterns with seismological data, it is necessary to employ spherical-shell geometry. Local problems in the upper-mantle such as slab-detachment can best be studied with the cartesian model. In fact, many of the 3-D visualization of tomographic data in the regional upper-mantle can be carried out in cartesian box geometries. Tackley (1995) recently has shown that many new effects of variable viscosity convection are captured with cartesian geometries. These results on viscous dissipation have been supported by similar 3-D efforts by Balachandar et al. (1995). We emphasize that to study the same phenomena in spherical-shell geometry would not be feasible with the current computational technology. We emphasize here that for understanding detailed physics the usage of cartesian geometry will shed far more light than using spherical-shell geometry.





IRIS

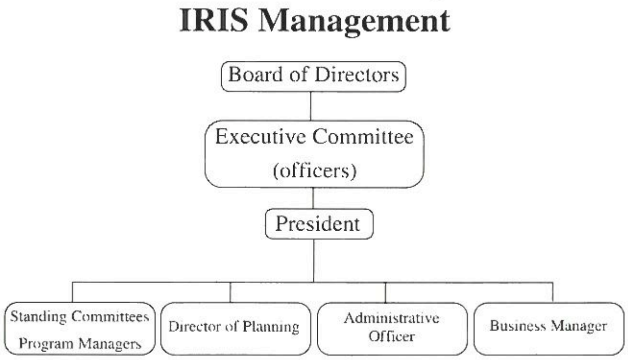
The Consortium

IRIS Governance

IRIS is a nonprofit consortium of research institutions founded in 1984 to develop scientific facilities, distribute data, and promote research. From a founding group of 22 universities, membership has now grown to 85 institutions, with 23 affiliate members.

Each member institution appoints a Director to the Board of IRIS. IRIS is governed by an Executive Committee, elected by the Board of Directors with two year rotations. The Executive Committee, in turn, appoints Standing Committees to provide oversight of the three facilities programs: the Global Seismographic Network (GSN), Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), and the Data Management System (DMS). In addition, the Executive Committee appoints members to special advisory committees such as the Joint Seismic Program (JSP) Committee and approves *ad hoc* working groups convened for special tasks.

It is the role of the standing committees and the advisory committees to develop recommendations for approval by the Executive Committee. The Executive Committee represents the IRIS Board of Directors.

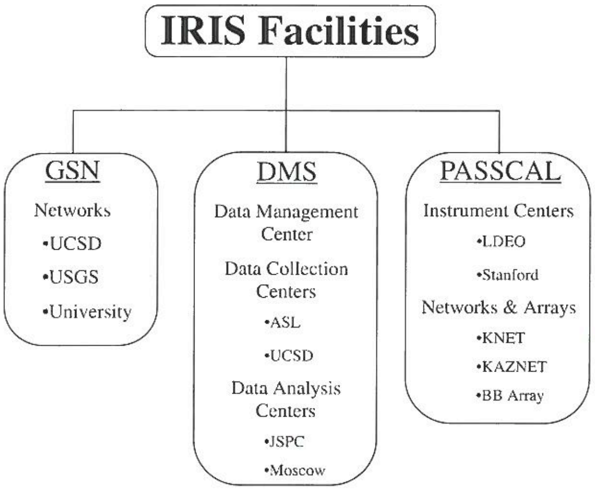


The IRIS management structure serves as an interface between the research community, funding agencies, and the programs of IRIS. The structure is designed to focus scientific talent on common objectives, to encourage broad participation across the university research community, and to provide for efficient management of IRIS programs.

IRIS Management

In addition to the Committee oversight described above, the IRIS management structure consists of a corporate office, program managers, and outlying facilities staffed either with IRIS employees or through subawards and contracts. The corporate office, with headquarters in Rosslyn, Virginia, works with the funding agencies and the IRIS program managers to allocate resources, to develop new initiatives, to create an overall scientific plan for the Consortium, and to represent the seismological community within the various professional and federal science planning forums. The corporate office consists of the following principals:

David Simpson, President
Gregory van der Vink, Director of Planning
Timothy Ahern, DMS Program Manager
Rhett Butler, GSN Program Manager
James Fowler,PASSCAL Program Manager
Shawn Boo, Business Manager
Elizabeth McDowell, Administrative Officer



IRIS Members

Full Members

University of Alabama
University of Alaska
University of Arizona
Arizona State University
Auburn University
Boise State University
Boston College
Brown University
California Institute of Technology
University of California, Berkeley
University of California, Los Angeles
University of California, San Diego
University of California, Santa Barbara
University of California, Santa Cruz
Carnegie Institution of Washington
University of Colorado, Boulder
Colorado School of Mines
Columbia University
University of Connecticut
Cornell University
University of Delaware
Duke University
Florida International University
University of Georgia
Georgia Institute of Technology
Harvard University
University of Hawaii at Manoa
IGPP/Lawrence Livermore National Lab.
IGPP/Los Alamos National Laboratory
University of Illinois at Urbana Champaign
Indiana University
Indiana University/Purdue University at Fort Wayne
University of Kansas
Lawrence Berkeley Laboratory
Lehigh University
Louisiana State University
Massachusetts Institute of Technology
Memphis State University
University of Michigan
Michigan State University
Michigan Technological University
University of Minnesota
University of Missouri
University of Nevada Reno
University of New Orleans
New Mexico Institute of Mining & Technology
New Mexico State University
SUNY, at Binghamton
SUNY, at Stony Brook
University of North Carolina
Northern Illinois University
Northwestern University
The University of Oklahoma
University of Oregon
Oregon State University
Pennsylvania State University
Princeton University
Purdue University
Rensselaer Polytechnic Institute
Rice University
Saint Louis University
San Diego State University
San Jose State University
Southeast Missouri State University
University of South Carolina
University of Southern California
Southern Methodist University
Stanford University
Syracuse University
University of Tennessee
Texas A&M University
University of Texas at Austin
University of Texas at Dallas
University of Texas at El Paso
University of Utah
Virginia Polytechnic Institute
University of Washington
Washington University, St. Louis
West Virginia University
University of Wisconsin, Madison
University of Wisconsin, Oshkosh
Woods Hole Oceanographic Institution
Wright State University
University of Wyoming
Yale University

Affiliate members

Naval Air Weapons Station, China Lake, CA
Academia Sinica, Institute of Earth Science, Taiwan
Academy of Sciences, Seismological Center, Albania
Australian National University
Universidade de Brasilia, Brazil
University of Bristol, England
University of Cambridge, England
Ecole Polytechnique, Canada
Geological Survey of Canada
Instituto Geofisico Del Peru
Geophysical Institute, Czech Republic
University of Hong Kong
International Inst. of Earthquake Engineering and Seismology, Iran
Istanbul Technical University
The University of Leeds, England
Masaryk University, Czech Republic
Universidad Nacional, Costa Rica
National Central University, Taiwan
Peking University
The University of Queensland, Australia
Tubitak-Marmara Research Centre, Turkey
Utrecht University, The Netherlands
Victoria University, New Zealand

IRIS Committees 1994-95

IRIS Executive Committee

Terry Wallace (Chair), University of Arizona
Alan Levander (V. Chair), Rice University
Shawn Boo (Treasurer), IRIS
Lind Gee (Secretary), University of California, Berkeley
Göran Ekström, Harvard University
Hiroo Kanamori, California Institute of Technology
Guust Nolet, Princeton University
Anne Trehu, Oregon State University
Doug Wiens, Washington University (St. Louis)

PASSCAL Standing Committee

Gary Pavlis (Chair), Indiana University
Fred Followill, Lawrence Livermore National Lab
Anne Meltzer, Lehigh University
John Nabelek, Oregon State University
Tom Pratt, U.S. Geological Survey, Seattle
Brian Stump, Los Alamos National Lab
Cliff Thurber, University of Wisconsin, Madison
Frank Vernon, University of California, San Diego
Rick Williams, University of Tennessee

Global Seismographic Network Standing Committee

Lane Johnson (Chair), University of California, Berkeley
Duncan Agnew, University of California, San Diego
Eric Bergman, U.S. Geological Survey, Denver
Kazuya Fujita, Michigan State University
Bob North, Geological Survey of Canada
Stuart Sipkin, U.S. Geological Survey, Golden

Holly Given (IDA Rep), University of California, San Diego
Bob Hutt (USGS Rep), Albuquerque Seismological Lab

Data Management System Standing Committee

Francis Wu (Chair), SUNY, Binghamton
Geoff Abers, University of Kansas
Harley Benz, U.S. Geological Survey, Denver
Karen Fischer, Brown University
David Okaya, University of Southern California
Tom Owens, University of South Carolina
Larry Ruff, University of Michigan
Susan Schwartz, University of California, Santa Cruz

J. Peter Davis (IDA Rep), University of California, San Diego
Bob Woodward (USGS Rep), Albuquerque Seismological Lab

Joint Seismic Program ad hoc Committee

Göran Ekström (Chair), Harvard University
Bernard Minster, University of California, San Diego
Keith Nakanishi, Lawrence Livermore National Lab
Jeffrey Park, Yale University
Robert Phinney, Princeton University
Paul Richards, Lamont Doherty Earth Observatory
Brian Stump, Los Alamos National Lab

Corporate Office Activities

• *Planning, New Initiatives, & Resource Allocation*

The major task of the corporate headquarters is to carry out the program activities of the Consortium. In consultation with the Standing Committees, the IRIS staff develops program plans and budgets for approval by the Board of Directors through the IRIS Executive Committee. The staff contributes both scientific and financial oversight to the programs and identifies new areas for advancement.

• *Financial Management, Accounting, & Inventory*

IRIS's Business and Administrative Departments are responsible for financial planning, contract administration, property management, financial accounting, and office administration.

• *Representation to Federal Agencies and Scientific Organizations*

As a large Consortium, IRIS also serves as a representative of the Earth science community. Members of the IRIS staff sit on many advisory and review panels, and frequently provide scientific advice upon request to policy makers through various forms including Congressional testimony, reports, and presentations.

IRIS has participated in an advisory role to the deliberations of the following organizations:

National Academy of Sciences
American Association for the Advancement of Science
American Geophysical Union
Federation of Digital Seismographic Networks (FDSN)
Joint Oceanographic Institutions (JOI)
University Navstar Consortium (UNAVCO)
Council of the National Seismic System
Society of Exploration Geophysicists
International Seismological Centre
International Science (Soros) Foundation
White House Office of Science and Technology Policy
National Science and Technology Council
Congressional Research Service
Congressional Office of Technology Assessment
Scientific and Policy Advisory Committee of the Arms Control and Disarmament Agency (Presidential Appointment)
Interagency Verification and Monitoring Task Force for a Comprehensive Test Ban Treaty
Interagency Review for Presidential Decision Directives for the verification of a Comprehensive Test Ban Treaty

• *Educational Initiatives*

IRIS data and the use of the IRIS Data Management System have become standard teaching tools in many graduate and undergraduate labs. The Princeton Earth Physics Program (PEPP) is developing inexpensive seismic stations as a stimulating entree to science in the high school classroom. In addition, IRIS has assisted in or supported museum exhibits, teacher workshops, and publications for high school education in Earth science.

• *The IRIS Newsletter & Special Publications*

The IRIS Newsletter, published quarterly with a distribution of 2000, contains announcements, schedules, and technical articles of interest to the IRIS community. In addition to the Newsletter, IRIS produces and distributes special publications ranging from programming guides, reference manuals, tutorials, the FDSN Station Book, to Congressionally requested assessments on *NuclearTesting and Nonproliferation,* and the National Science Foundation's *A National Program for Research in Continental Dynamics-CD/2020.*

The following publications are available through IRIS:

IRIS Newsletter Volumes VII through XI
PASSCAL Users Guide
PASSCAL Instrument Center Training Manual
Program for Research in Continental Dynamics - CD/2020
Nuclear Testing and Nonproliferation
1990 IRIS Proposal to the National Science Foundation
Technical Plan for a New Global Seismographic Network
PASSCAL- Program for Array Seismic Studies of the Continental Lithosphere
Science Plan for a New Global Seismographic Network
Strategies for the Design of a Data Management System
SEED Reference Manual
SEED Programmers Toolkit
Tutorial Guide - How to Use the IRIS DMC
SPROUT
POD-The IRIS SEED Writer
FDSN Station Book

• *The Annual IRIS Workshop*

Each year IRIS convenes a scientific workshop to assess the state of the science and to introduce new programs. The workshop, which in 1995 involved 200 participants, provides an ongoing forum for input to IRIS programs and new initiatives; and provides an opportunity for demonstrations and training sessions. Through a student grant program, young scientists may attend the workshop at little or no cost, and thus become introduced to the programs and services of the Consortium.

IRIS also helps organize and support special focused meetings such as the ILIAD (Investigations of Lithospheric Architecture and Dynamics) workshop in November 1994.

• *Oceanic Seismology*

IRIS together with the Joint Oceanographic Institution, supports the Ocean Seismic Network (OSN) Planning Office. The OSN Planning office is staffed by E. Kappel, and the OSN Steering Committee consists of Mike Purdy, Chair, J. Orcutt, D. Forsyth, B. Romanowicz, and A. Trehu.

Operations related to the use of undersea cables are carried out by IRIS Ocean Cable Inc.

IRIS Staff

In addition to the principals listed on page 1, the staff of the IRIS headquarters in Rosslyn, Virginia are:

Anne D. Miller, Administrative Assistant, Production Editor
Chau Tran, Business Analyst
Jamie Understein, Business Analyst

IRIS staff located at the Data Management Center in Seattle, Washington are:

Deborah Barnes, Interface Specialist
Rick Benson, Director of Operations
Rick Braman, Unix Administrator
Robert Casey, Data Control Technician
Chris Laughbon, Senior Software Engineer
Anh Thi Ngo, Data Control Technician
Sue Schoch, Senior Software Engineer
Kris Skjellerup, Administrative Assistant
Raoul Titus, Data Control Technician

IRIS Facilities

In addition to IRIS-staffed facilities, most operations are managed through subawards.

- The GSN is operated through two main network operators, and through the direct support of individual University stations. The two main networks are:

Project IDA
Scripps Institution of Oceanography, IGPP
University of California, San Diego

Network managers: *Jon Berger and Holly Given*
IDA Data Collection Center Director: *Peter Davis*
Obninsk Data Collection Center Directors: *Oleg Staravoit and Igor Chernobye*

Albuquerque Seismological Laboratory
U.S. Geological Survey

Network managers: *Bob Hutt and John Derr*
ASL Data Collection Center Director: *Bob Woodward*

- The PASSCAL program is operated through two instrument centers:

PASSCAL Instrument Center
Lamont Doherty Earth Observatory

Doug Johnson
Carl Ebeling
Paul Friberg
Sid Hellman
Tom Jackson
Gennady Pratusvich
John Webber

PASSCAL Instrument Center
Stanford University

Simon Klemperer
Marcos Alvarez
Bill Koperwhatts
Steve Michnick
Anthony Wei

- The Data Management System supports software development and data assessment through:

Joint Seismic Program Center
University of Colorado, Boulder

Danny Harvey
Dan Quinlan
Luda Ratnikova
Greg Wagner

- IRIS also supports various research groups to operate facilities as part of their ongoing research projects:

Data Management Center Host
University of Washington
PI's - *Steve Malone and Ken Creager*

Waveform Quality Control Center
Harvard University
PI- *Göran Ekström*

Kyrghyz Network
University of California, San Diego
PI - *Frank Vernon*

Kazakh Network
Lamont Doherty Earth Observatory
PI's - *Won-Young Kim and Arthur Lerner-Lam*

Moscow Data Analysis Center
Moscow, Russia
PI - *Mikhail Rozhkov*

Participation

Since 1984, the following members of the community have served as officers or committee members.

Geoffrey Abers, University of Kansas	DMS
Duncan Agnew, University of California, San Deigo	GSN
Keiiti Aki, University of Southern California	PAS
Shelton Alexander, Pennsylvania State University	EXE*; DMS**
Don Anderson, California Institute of Technology	EXE
Charles Archambeau, University of Colorado, Boulder	JSP
Milo Backus, University of Texas, Austin	DMS
Harley Benz, US Geological Survey, Denver	DMS
Jon Berger, University of California, San Diego	JSP; GSN
Eric Bergman, US Geological Survey, Denver	GSN
Greg Beroza, Stanford University	GSN
Gilbert Bollinger, Virginia Polytechnic Institute	SEC; PAS
Shawn Boo, IRIS	TRES
Tom Boyd, Colorado School of Mines	SEC
Larry Braile, Purdue University	EXE; PAS**
Tom Brocher, US Geological Survey, Menlo Park	PAS
Rhett Butler, University of Hawaii	GSN
Robert Crosson, University of Washington	DMS
F.A. Dahlen, Princeton University	GSN
Paul Davis, University of California, Los Angeles	PAS
Diane Doser, University of Texas, El Paso	PAS
Adam Dziewonski, Harvard University	EXE; GSN
Göran Ekström, Harvard University	DMS; JSP; EXE
William Ellsworth, US Geological Survey, Menlo Park	PAS
Robert Engdahl, US Geological Survey, Denver	DMS**
John Filson, US Geological Survey, Reston	JSP
Karen Fischer, Brown University	DMS
Fred Followill, Lawrence Livermore National Laboratory	PAS
Don Forsyth, Brown University	GSN**
Clifford Frohlich, University of Rhode Island	DMS
Kazuya Fujita, Michigan State University	GSN
Lind Gee, University of California, Berkeley	SEC
Freeman Gilbert, University of California, San Diego	EXE
Stephen Grand, University of Texas, Austin	GSN
Don Helmberger, California Institute of Technology	GSN
Tom Henyey, University of Southern California	PAS
Eugene Herrin, Southern Methodist University	GSN
Heidi Houston, University of California, Santa Cruz	GSN
Gene Humphreys, University of Oregon	PAS
David James, Carnegie Institute of Washington	PAS
Lane Johnson, University of California, Berkeley	DMS**; GSN**
Arch Johnston, Memphis State University	EXE
Hiroo Kanamori, California Institute of Technology	GSN; EXE
Charles Langston, Pennsylvania State University	GSN; JSP
Thorne Lay, University of California, Santa Cruz	EXE; GSN
Art Lerner-Lam, Lamont-Doherty Earth Observatory	JSP; GSN
Alan Levander, Rice University	DMS; EXE*
Peter Malin, Duke University	PAS; DMS
Stephen Malone, University of Washington	DMS
Robert Massé, US Geological Survey, Denver	GSN
Guy Masters, University of California, San Diego	EXE
Tom McEvilly, University of California, Berkeley	EXE**; GSN
Sue McGeary, University of Delaware	SEC; EXE
George McMechan, University of Texas, Dallas	PAS
Anne Meltzer, Lehigh University	PAS
William Menke, Lamont-Doherty Earth Observatory	PAS; DMS
Robert Meyer, University of Wisconsin	PAS
Bernard Minster, University of California, San Diego	JSP; DMS
Brian Mitchell, St. Louis University	TRES; GSN
Walter Mooney, US Geological Survey, Menlo Park	PAS
John Nabelek, Oregon State University	DMS; PAS
Keith Nakanishi, Lawrence Livermore National Lab.	JSP; DMS
Guust Nolet, Princeton University	EXE
Bob North, Geological Survey of Canada	GSN
Emile Okal, Northwestern University	GSN
David Okaya, University of Southern California	PAS; DMS
John Orcutt, Universityof California, San Diego	EXE**; DMS
Tom Owens, University of South Carolina	PAS; EXE; DMS
Jeffrey Park, Yale University	EXE**; SEC; JSP
Gary Pavlis, Indiana University	TRES; DMS; EXE; PAS**
Robert Phinney, Princeton University	PRES; EXE**; PAS**; JSP
Tom Pratt, U.S. Geological Survey	PAS
Paul Richards, Lamont-Doherty Earth Observatory	JSP**; EXE*
Barbara Romanowicz, University of California, Berkeley	GSN
Larry Ruff, University of Michigan	DMS
Selwyn Sacks, Carnegie Institute of Washington	PAS
Martha Savage, University of Nevada, Reno	DMS
Susan Schwartz, University of California, Santa Cruz	DMS
Paul Silver, Carnegie Institute of Washington	EXE**; PAS; JSP
David Simpson, Lamont Doherty Earth Observatory	PRES; PAS; JSP
Stuart Sipkin, US Geological Survey, Golden	GSN
Robert Smith, University of Utah	EXE; PAS
Stewart Smith, University of Washington	PRES; JSP**
Sean Solomon, Carnegie Institute of Washington	GSN**
Seth Stein, Northwestern University	EXE
Brian Stump, Los Alamos National Laboratory	PAS; JSP
Fumiko Tajima, University of Texas, Austin	DMS
Toshiro Tanimoto, California Institute of Technology	DMS
Ta-liang Teng, University of Southern California	EXE; GSN
George Thompson, Stanford University	EXE
Clifford Thurber, University of Wisconsin, Madison	EXE; SEC; PAS
Anne Trehu, Oregon State University	PAS**; EXE
Frank Vernon, University of California, San Diego	PAS; JSP
Terry Wallace, University of Arizona	GSN**; EXE**; JSP
Doug Wiens, Washington University (St. Louis)	EXE; GSN
Richard Williams, University of Tennessee	TRES; PAS
John Woodhouse, Oxford University	DMS
Francis Wu, SUNY, Binghamton	DMS**
George Zandt, Lawrence Livermore National Lab	PAS

EXE = Executive Committee
GSN = Global Seismographic Network Committee
DMS = Data Management System Committee
PAS = Program for Array Seismic Studies of the Continental Lithospere Committee

JSP = Joint Seismic Program Committee
TRES= Corporate Treasurer
SEC = Corporate Secretary
PRES = President
** = Chair
* = Vice Chair

Completing Global Coverage

Origins of the GSN

In July, 1983 an ad hoc group of seismologists met at Harvard University to discuss the future of global seismology. At that time, the existing analog and digital global networks had been in decline for many years. These older networks were either analog (recorded on paper) such as the USGS-sponsored World-Wide Standardized Seismographic Network (WWSSN) dating from the 1960's, or else early generation digital (with limited dynamic range and bandwidth) such as the USGS- and ARPA-sponsored Seismic Research Observatories (SRO) and the UCSD International Deployment of Accelerometers (IDA). Modern seismometers with feedback electronics were becoming available with very-broad bandwidth (from tidal frequencies to ten Hertz), high-dynamic range and linearity for recording large earthquake signals, and instrumental noise below the lowest natural seismic background noise. Analog-to-digital encoders (digitizers) were being developed with superior dynamic range — more than 140 dB — at 24-bit resolution. Computer processing speed and recording capacities were expanding exponentially as the costs decreased. Global communication by telephone was a reality; satellite communication technology was in place and improving; fiber optic cables were being developed; computer networking was becoming the standard form of communication for geophysicists.

This strong technological foundation came at a time when the science of seismology had advanced theoretically beyond its observational capacity. The questions being posed by the science could not be answered with the limited data available. Furthermore, existing seismic stations were unevenly distributed about the planet and strongly biased in coverage — enormous areas of the oceans and large sections of continents were not instrumented at all. The southern hemisphere was particularly poorly monitored. At the same time, the synergy of the Earth as a system was coming into focus. Seismology with its unique vantage into the planet was called to image the Earth's interior and provide fundamental physical data for other branches of the geosciences. Finally, the deaths of several hundred thousand people in a single earthquake in Tangshan, China, in the prior decade and billions of dollars lost world-wide in earthquake damage accentuated the need to understand better the dynamics of earthquakes in order to mitigate their hazards.

At the Harvard meeting, the ad hoc group developed the rationale and objectives for a new initiative whose cornerstone would be a Global Seismographic Network of some 100 stations of wide bandwidth and dynamic range transmitting data in real time to a central data collection and distribution system. In October of that same year, a workshop at the Scripps Institution of Oceanography was attended by some 90 participants from the academic community, government agencies and national labs to solicit community-wide input and gain broader support for this initiative.

From these meetings evolved the plan whose scientific justification, rationale, design, and implementation were clearly elucidated in the 1984 proposal from IRIS to the NSF as a collective request from the US seismological community. That proposal called for a new Global Seismographic Network of approximately 100 stations equipped with modern high-quality digital instrumentation:

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

To implement this ambitious program, IRIS drew from the established capabilities of network operators in both the US Government and university community: the USGS Albuquerque Seismological Laboratory and the IDA group at the University of California, San Diego. With direction and support from IRIS, they began the task of integrating new technology and developing new techniques to create the GSN as a union and expansion of their existing network infrastructures.

Initially, site development concentrated on existing stations of the two networks but gradually the GSN siting plan for 128 stations worldwide led to the task of finding suitable new sites and operating partners. Today (June 1995), less than 10 years after the first stations were installed, there are 80 new broadband stations in operation around the world. By the end of the century, when the GSN is completed, there will be more than 130 GSN stations in over 80 countries and ocean islands, completing the vision of the 1984 IRIS founders.

What is the GSN?

The Global Seismographic Network is a successful, cooperative partnership of U.S. universities and government agencies, coordinated with the international community, to install and operate a global multi-use scientific facility as a societal resource for environmental monitoring, research, and education.

The GSN is an efficient, state-of-the-art, digital network of scientific instrumentation and inheritor of a century-long tradition in seismology of global cooperation in the study of the Earth. GSN instrumentation is capable of measuring and recording with high fidelity all of the Earth's vibrations from high-frequency, strong ground motions near an earthquake to the longest free oscillations of the Earth. Sensors are accurately calibrated, and timing is based on satellite clocks. The primary focus in creating the GSN has been seismology, but the infrastructure is inherently multi-use and can be extended to other disciplines of the Earth science.

The concept of the GSN is founded upon global, uniform, unbiased coverage of the Earth by a permanent network of over 100 stations with rapid data access. The equipment is modular and extensible to evolve with technology and the science. Standardization of equipment and data formats create efficiencies for use and maintenance.

A cornerstone of the GSN is free exchange of data with the international community. The stations are open for data access by anyone with a telephone modem, either directly from the stations or through the Data Management System.

The GSN is both benefactor and beneficiary of government-university cooperation through the National Science Foundation, US Geological Survey, Department of Defense, NASA, and NOAA. As a core US facility, IRIS is a member of the international Federation of Digital Seismographic Networks and data from GSN stations are being used in technical tests for an international monitoring network for a future Comprehensive Test Ban Treaty.

The GSN is an educational tool for the study of Earth. With the ease of access to data and blossoming computer technology, GSN data are now routinely used in introductory college courses and high school use is approaching. The GSN stations themselves are focal points for international training in seismology.

The GSN is a fundamental resource in the compilation of catalogs and bulletins of earthquake locations. Rapid access to GSN data has led to rapid analysis of earthquake mechanisms, bringing public awareness of earthquakes as scientific events, not just news events. GSN data are critical to the public and government agency response to earthquakes, tsunamis, and volcanoes and as a resource in mitigating earthquake hazards.

International Cooperation

International cooperation is the sine qua non of any global undertaking, and the success of the GSN has only been possible with widespread international cooperation. The establishment of the Federation of Digital Seismographic Networks (FDSN) with IRIS as one of the founding members has facilitated coordination in global siting of seismic stations and led to the adoption of a standard exchange format for seismic data (SEED). Beyond the individual cooperation that is required for the establishment of any station in a foreign country, the GSN has been able to develop many stations as joint international sites in cooperation with non-U.S. network operators. Each of the joint sites results from the collaboration and contribution of seismic equipment or other support by the international partners who include:

GEOSCOPE Program, University of Paris, France
MEDiterranean NETwork (MEDNET), Istituto Nazionale di Geofisica, Italy
POSEIDON Program, Japan
GEOFOrschungsNetz (GEOFON), Germany
Bundesanstalt fur Geowissenschaften und Rohstaffe (Geological Survey), Germany
Alfred Wegner Institute for Polar Research, Germany
University of Addis Ababa, Ethiopia
Instituto Geografico Nacional, Spain
Mexican National Seismic Network, Mexico
State Seismological Bureau, China
The Institute of Physics of the Earth, Russian Academy of Sciences
The Institute of Seismology of the Turkmen Academy of Sciences
The National Survey for Seismic Protection, Armenia
The Institute of Seismology of the Kyrghyz Academy of Sciences
The National Nuclear Center of Kazakhstan
The Academy of Sciences of Tadjikistan
The King Abdulaziz City of Science and Technology, Saudi Arabia
The Geological Survey of Canada

Beyond cooperation in the installation of stations, IRIS, USGS, and GEOFON have agreed to explore sharing maintenance responsibilities, wherein the GSN would maintain IRIS/USGS/GEOFON global stations and GEOFON would maintain IRIS/USGS European stations. In response to interest from Kuwait and Singapore in establishing GSN-class stations in their countries, IRIS has provided instrument specifications and offered with the USGS the services (at cost to the countries) of its network operations and maintenance teams to install stations and coordinate international data exchange. IRIS has continued its active involvement in the FDSN, which serves as a forum for the international networks to meet together and discuss mutual interests. In connection with the verification community, IRIS has encouraged the use of GSN stations as contributors to the auxiliary network in an International Monitoring System in support of treaty verification. Many countries are using their GSN stations in the ongoing GSETT-3 (Group of Scientific Experts Technical Test-3) verification monitoring experiment being conducted by the United Nations Conference on Disarmament.

GSN PROGRESS

1985-1990

Instrumentation

One of the first activities of the IRIS GSN program was to establish equipment standards and goals which have subsequently been adopted both nationally and internationally by other seismic networks. The GSN IRIS-2 station processor was developed by the private sector, while the IRIS-3, based on PASSCAL hardware, was developed by the University of California, San Diego. The very-broadband Streckeisen STS-1 sensor was chosen for deployments in seismic vaults, and the Teledyne KS36000 borehole seismometer was modified to provide broadband response for borehole sites. High frequency and low-gain seismometers were selected for sites with high-frequency signals and local strong-ground motion, respectively, in order to record the whole seismic spectrum on scale.

Station Deployments

During the first five years, GSN site development focused mainly on upgrading existing global seismic stations of the USGS and IDA networks. A University Network in the United States was established using matching funds to foster university involvement in the new GSN both for education and as a testbed for the new technology. Data Collection Centers (DCCs) were established at both network operations centers to manage and monitor the quality of data flowing from the GSN stations. With the development of the IRIS Data Management System, the oversight of DCC functions was moved from GSN to the DMS.

In 1986, a unique collaborative project in seismology began between the Academy of Sciences of the USSR and the Natural Resources Defense Council (a private environmental group interested in a comprehensive ban on the testing of nuclear weapons). It led to the establishment of seismic stations around the Soviet nuclear test site in Kazakhstan by UCSD. This collaboration provided a framework for the expansion of the GSN into the USSR with the establishment of five new stations in 1988. In 1989 the IRIS and the USGS signed an agreement with the Academy of Sciences of the USSR for a joint program of seismological studies and data exchange. The stations and open data exchange established under this Joint Seismic Program, as it came to be known, provided the first readily available digital seismic data from the vast stretches of the Soviet Union that had previously been a seismological terra incognita and provided a new IRIS funding source through the Department of Defense for seismic nuclear monitoring.

By the end of this first period, twenty-five GSN stations were installed and telephone dial-up for access to data had been tested and implemented at some sites. Long-range needs for oceanic coverage were recognized and were met through focusing on oceanic islands, cooperation with the Japanese on re-use of undersea telephone cables, and establishment of an Ocean Seismic Network planning effort.

1991-1996

Instrumentation

During the current funding period, GSN has continued to be a pioneer in the development and use of seismic instrumentation and technology. The goal of recording all seismic signals above the Earth's background noise (Figure 1) is achieved through a combination of seismometers with extremely low "instrumental-noise" and low-noise deployment modes. Working with Teledyne, the very-broadband KS54000-IRIS sensor for borehole installations was brought into production at half the cost of the original KS54000 with no compromise in capability. Streckeisen STS-2 and Guralp CMG-3 broadband sensors were adopted for use as auxiliary high-frequency sensors at GSN sites. These sensors have excellent high-frequency response, comparable to the standard Teledyne GS-13 and overlapping the response of the standard STS- 1, giving the high-frequency data user a wider usable frequency response without the need of patching together two separate data streams. A borehole version of the Guralp CMG-3

IRIS GSN SYSTEM

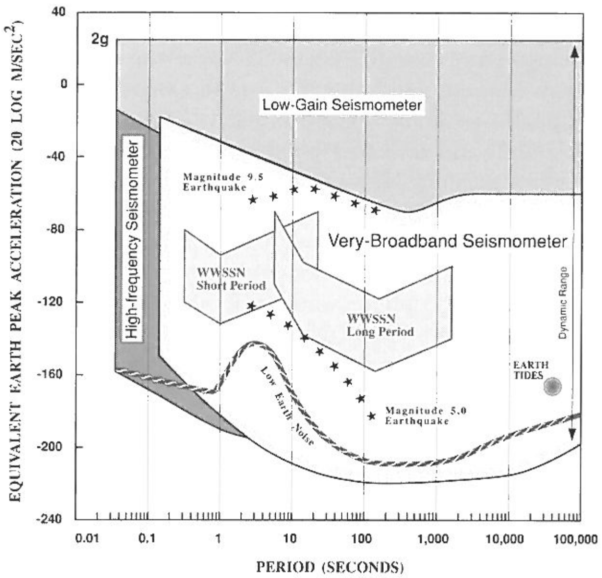


Figure 1. The seismic instrumentation for the IRIS GSN system has tremendous bandwidth and dynamic range compared to its predecessor, the World Wide Standardized Seismographic Network. Using two seismometers, the WWSSN was able to record only a limited period and amplitude range. The stars indicatethe approximate acceleration of Magnitude (Mw) 5.0 and 9.5 earthquakes recorded at 30°. The very-broadband seismometer of the GSN system is capable of recording the full range of earthquake motions on scale, and has a long-period response well beyond the Earth tides. To record the strong ground motions low-gain seismometers are used with clipping levels set at 2g's acceleration. High-frequency seismometers extend the bandwidth and noise floor of the GSN system to 40 Hz. The GSN system is capable of resolving the Earth's quietest seismic background noise. (Earthquake amplitudes and instrument ranges provided by Hiroo Kanamori and Bob Hutt, respectively.)

has been tested for deployment in the same borehole as a KS54000-IRIS. This would eliminate the need for drilling two holes at a borehole site where high-frequency data are to be recorded.

In response to the nuclear verification community, IRIS has updated the sample rate on its high-frequency sensors to include 40 sps continuous data, in addition to higher speed triggered channels. The low-gain FBA-23 accelerometers, which are sampled at 80-100 sps in a triggered mode to capture strong ground motion from local earthquakes on scale, have been augmented with a 1 sps stream to record on scale the long-period motions of great earthquakes (Mw > 8) which can clip the STS-1 seismometers at distances less than 30 degrees. Comparisons conducted by the IDA group indicate that the LaCoste-Romberg gravimeters used by the GSN supported IDA Network have a better response than the STS-1 vertical sensor at periods greater than 1000 seconds.

The IRIS GSN station processor continues to evolve and serve as a world standard. The GSN system was selected, after a rigorous evaluation, for use in the Air Force Global Telemetered Seismic Network of 9 stations in South America, Africa, and Antarctica. The GSN equipment was also selected by the Advanced Research Projects Agency (ARPA) for the upgrade of three Chinese Digital Seismographic Network (CDSN) sites for use in the GSETT-3 experiments.

The basic IRIS-2 GSN station processor, manufactured by Quanterra, follows upon the line of GSN equipment developed from the IRIS 1986 GSN RFP through Gould, Martin Marietta, and Quanterra. The Quanterra line of equipment of GSN lineage is used internationally by MEDNET and GEOFON and nationally by the US National Seismic Network, the Caltech TERRAscope Network in southern California, the Berkeley Digital Seismic Network in northern California, and by St. Louis University in the central US. To foster cooperation and coordination of common software for these systems, IRIS has encouraged a GSN- Quanterra Users' Group which meets twice annually and has garnered increasing foreign interest and participation.

The IRIS-3 GSN station processor, manufactured by REFTEK, follows upon the line of PASSCAL equipment developed from the IRIS 1986 PASSCAL RFP through REFTEK and modified for GSN application by the UCSD IDA group. A near-real-time system (NRTS) has been developed for the IRIS-3 station processor to provide Internet and dial-up access to IRIS/IDA GSN sites. Data Request Manager software written by the IDA group links the NRTS system with the IRIS DMS SPYDERTM data retrieval system.

Workstations or PC's have been installed at many GSN sites to provide additional seismic processing capabilities for local host organizations with an active interest in the GSN data. All GSN systems are fully capable of supporting a wide range of telemetry possibilities from telephone dial-up to direct satellite links. All GSN station processors produce state-of-the-art 24-bit digital data streams. All GSN data are available at the DMC in SEED format and are indistinguishable between the GSN IRIS-2 and IRIS-3 station processors.

While telemetry has always been one of the two cornerstones of the GSN program, along with global coverage, global real-time telemetry is not yet feasible, primarily due to cost. However, a number of approaches for providing near-real-time access to GSN data have been tested and implemented. The greatest success has been in the use of Internet and telephone dial-up links to retrieve GSN data. The exponential growth of the Internet now permits direct access to many sites or Internet links to a computer near a GSN site where a low-cost, local telephone call can dial-up the GSN station.

To provide connectivity to stations where adequate telephone service is not available, several satellite approaches to telemetry have been tried: two have been discontinued, two have been successful, and one is under test at this time.

A system to send continuous VLP (0.1 sps) data on an hourly basis using GOES satellites was successfully tested, but abandoned due to the limited hemispheric coverage of the GOES satellites coupled with the availability of telephone lines to most sites under the GOES satellite "footprint".

Working with NASA personnel at the Goddard Space Flight Center, IRIS GSN proposed a Wide Band Data Collection System (WBDCS) to uplink data from all GSN stations to the Earth Observing System (EOS) satellites scheduled for flight at the beginning of the next decade. Although the proposal was accepted by NASA for inclusion in EOS, the cost (>$150K) of the ground stations at each GSN site (to have been funded by IRIS and NSF) exceeded the seismic equipment costs at each site. Given the high costs, the delays of the EOS program into the next century, and the limited lifetime of the EOS satellite compared to GSN station expectations (10 yr versus 30 yr), the WBDCS program was abandoned in favor of waiting for emerging technologies being developed by the global telecommunications markets, such as global digital cellular systems.

Through the NSF Office of Polar Programs (OPP) the GSN has made successful use of a satellite in skewed geosynchronous orbit to forward files of long period data from the South Pole Station — especially important during the austral winter when data shipments are not available from the Pole. GSN continues to work with OPP to increase telemetry bandwidth available from the Pole for the GSN data.

As part of the Joint Seismic Program funded by the Air Force, the GSN through the IRIS/IDA group established a 128 kbps satellite link between Obninsk, Russia and the Center for Seismic Studies (CSS) in Virginia (jointly funded by CSS) with a 56 kbps domestic circuit to the IDA Data

Collection Center at UCSD to provide connectivity from GSN stations in Western Russia through the Obninsk data center. This link has been very successful in providing near-real-time access to GSN data for the DMS SPYDER™ system, as well as for the ongoing international GSETT-3 experiment. To lower the operating costs for this link, IRIS is currently working to convert this satellite connection into an Internet link.

At the cutting edge of satellite technology, IRIS is currently planning a test of the new INMARSAT B system at a remote GSN location without local telephone access. Although the capital costs (~$50K/each) and transmission costs (~$15/minute at 64 kbps) are coming down, it still would cost about $250/day to download the 7 Mbyte compressed data from one standard GSN site and therefore near-real-time access only to selected segments of the waveform data (SPYDER™ access) is practical at this time.

GSN sites are selected to have as low seismic noise as possible to meet its scientific goals. However, logistical considerations sometimes offer limited choices. GSN systems can be separable, wherein a telemetry link can connect a remote, quiet location to a recording site at a host institution. Long-period horizontal noise is exacerbated by wind and near- surface thermal effects, which are reduced by siting underground. In many cases a cave or mine has been used, but often a tunnel must be excavated into a hillside.

The installation of seismometers in boreholes at about 100 m depth has been used since the SRO deployments in the early 1970's to reduce long period noise and this approach has been adopted by the GSN for some continental sites. On small islands where there are few siting options, the efficacy of a borehole installation was uncertain. To test the hypothesis, the GSN drilled a 100 m borehole on the island of Rarotonga to compare the relative noise level of a seismometer in a borehole with an adjacent surface vault and verified that the borehole sensor emplacement yielded noise improvements comparable to the continental case. Subsequently, the GSN has embarked upon an extensive island drilling campaign for the installation of borehole seismic systems (see Figure 2).

To further improve the performance of borehole installations, the Albuquerque Seismological Laboratory has successfully tested a method to reduce long-period horizontal noise caused by thermal air convection in the borehole by filling sand around the sensor to eliminate the air gap. The UCSD IDA group has been testing seismometer installations in shallow borehole and vault configurations to find new methods for low-noise seismic deployments in logistically difficult parts of the world.

Station Deployments

The goal of 128 uniformly distributed GSN stations proposed by IRIS in its last five-year proposal is attainable in the next five years. During the current NSF Cooperative Agreement about 75 new GSN stations will have been installed, bringing the GSN to about 100 stations. This remarkable achievement has been aided by the strong interest of the seismic nuclear verification community and accelerated funding of the GSN for these verification goals by the Air Force. The focused interest by the verification community in high-frequency, regional wave propagation has led to densification of GSN sites in some continental

GLOBAL SEISMOGRAPHIC NETWORK

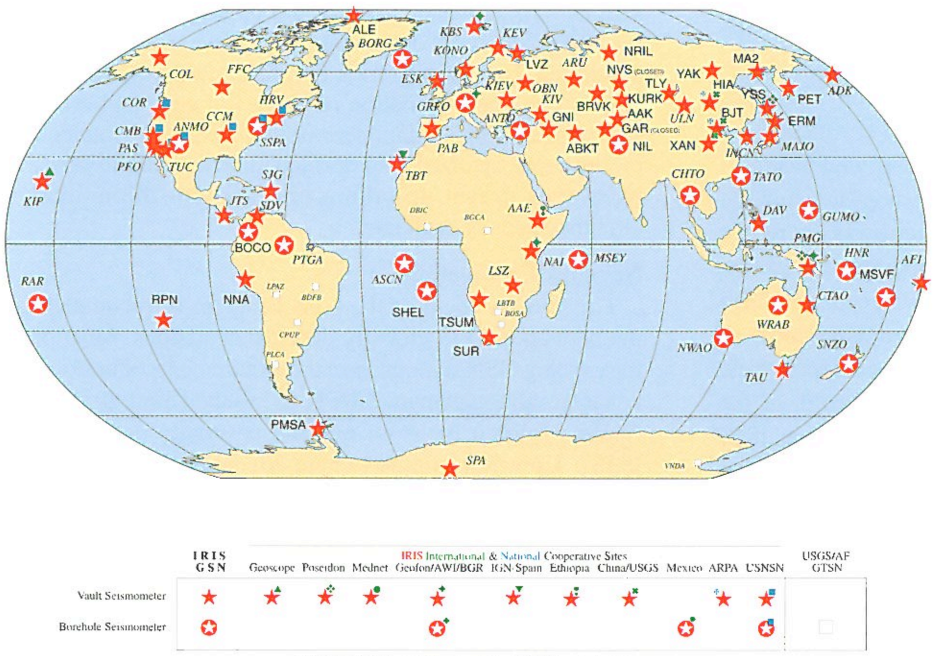


Figure 2. Current GSN stations (June 1995) are plotted in red with station code names. Seismometers are installed either in seismic vaults or 100 meter-deep boreholes. International and national cooperative sites with other networks and organizations are noted. Global Telemetered Seismic Network (GTSN) stations which are operated by the USGS complement GSN coverage and provide data to the IRIS Data Management Center.

regions, with inter-station spacing of about 1000 km compared to the original 2000 km spacing implied by a 128 station uniformly distributed network. The upgrade of the China Digital Seismographic Network to GSN design goals with Air Force funding will yield both global and regional benefits. Balancing the continental focus of the Air Force funds, IRIS has focused its NSF funding resources toward the larger scientific goal of uniform global coverage, emphasizing island and Antarctic sites.

The IRIS University Network component of the GSN has been a great success for graduate school education in the United States and the focus for universities to raise funds for their own GSN stations matched by modest IRIS funding. The total IRIS matching funds for the five GSN sites installed as part of the University Network were less than half the cost of a single GSN station. The IRIS University Network forms an essential core of the US National Seismic Network, which has contributed equipment to some of the sites.

The success of the GSN instrumentation and plans are best reflected in the extraordinary use of its data - users in the thousands have requested several million waveform segments of GSN data totaling over a trillion bytes.

PLAN FOR 1996-2001

Operation and Maintenance

During the next five years the GSN will make the transition from a mode of operation that has been primarily development and deployment to one which will be primarily operation and maintenance. Past experience with other seismographic networks (the WWSSN in the 1960's and the GDSN in the 1980's) has shown that this is a critical period when the enthusiasm and momentum mobilized in establishing the network can be easily lost. IRIS is well aware of this potential problem and is taking steps to avoid the difficulties encountered by past networks. A recent study (Peterson, J., Global Seismographic Network Operation and Maintenance, July, 1995), commissioned by the GSN, provides an experienced assessment of the critical operation and maintenance tasks, their estimated costs, and keys to long-term health of the network. Building upon information such as this, IRIS is developing a strategy that will allow the GSN to continually evolve and provide observational data which maintain the highest standards of relevancy and quality.

This strategy involves several different elements, some of which have already been initiated and some of which will depend upon experience gained over the next few years of network operation. The first element is that of monitoring network performance, a task which is currently being shared by the DMS and the GSN. The present standard is for at least 90% of all potential data to reach the DMC archive, which appears to be quite feasible. As experience is acquired concerning the most common causes of downtime and methods of improving mean-time-to-repair, an improvement in this standard may be possible. Here the critical elements are likely to be the type and amount of spare parts to stock, the number and positioning of support personnel, and the quality of station operators. This is an area where the IRIS philosophy of providing local scientists access to seismic data will hopefully have long term benefits in terms of reduced maintenance costs, as local interest in seismology is likely to lead to more involved and better trained station operators.

Other methods of reducing operation and maintenance costs without reducing data quality are likely to emerge by taking advantage of accumulating experience and developing technology. The inclusion of more real-time telemetry in the network will lead to reduced maintenance costs, as it removes one of the last moving parts from the system, the data recorder at the station. An important element of this general strategy for operation and maintenance of the GSN will be the concept of a dynamic network that is continually being improved and adapted to new uses, as this type of vitality is necessary for the continued enthusiastic support of the network. The plan to extend the GSN to a general global science data collection network, discussed below, should provide considerable impetus in this direction during the next five years.

The GSN budget includes the projected costs for each site, as well as planned equipment upgrades. Equipment for many sites are on inventory or have already been purchased, but not delivered. For these sites, only the site preparation and installation remains. For each and every site on the GSN site plan, permissions have been obtained (or are being finalized) and detailed implementations plans have been drawn up taking into account the unique circumstances of each site.

Network Completion

The primary focus of the GSN Program is to complete the network of 128 globally distributed stations. Most of the existing GSN stations meet the requirements of uniform coverage, although many have been installed through DOD funding (with a focus on regional coverage) or through IRIS / University funds (where educational use by the University program is paramount). Coverage in some parts of the world is already provided by other international networks (GEOSCOPE being foremost), but most non-US networks focus their coverage on a regional or national scale. The GSN has coordinated its own global siting plan to take best advantage of other networks in the Federation

IRIS GSN & FDSN

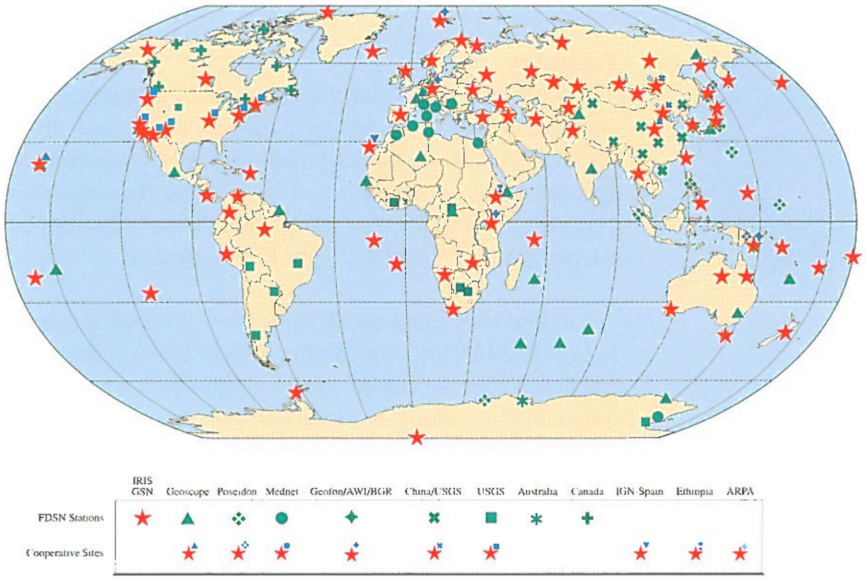


Figure 3. Seismic stations of IRIS GSN and other networks participating in the Federation of Digital Seismographic Network (FDSN) are shown for June 1995. GSN stations which are cooperative sites with other networks and organizations are noted. Some FDSN stations do not meet GSN design goals for seismometer bandwidth and continuous 20 sps sampling.

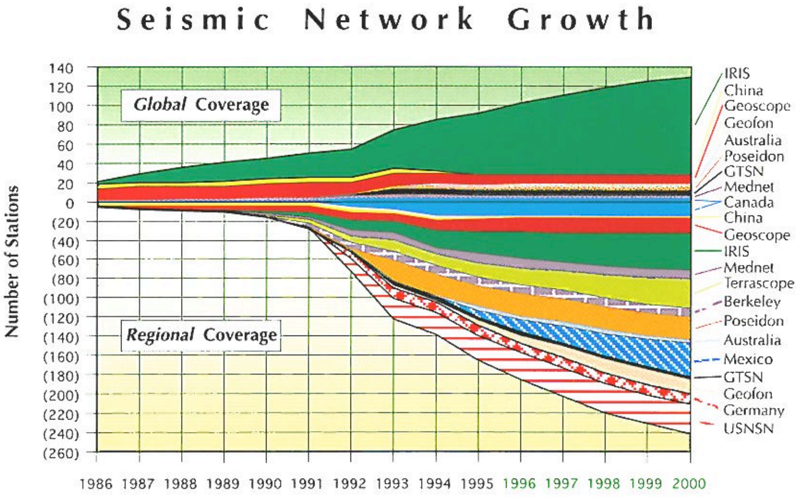
of Digital Seismographic Networks (Figure 3). Figure 4 illustrates the growth of global and regional broadband stations and shows how uniform global coverage is still wanting. The growth of other networks will improve regional coverage, but only the GSN will complete the required uniform global coverage.

The GSN network as it is anticipated in mid-1996 is shown in two maps (Figures 5 and 6, next page), as cartographic projections tend to bias toward either a continental or oceanic perspective of the Earth. The figures also plot locations for proposed new GSN sites, which are listed in the table at the end of this section.

Although the network as of mid-1996 will be impressive, there remain 25 new sites in the GSN siting plan to fill crucial gaps in coverage, as shown in the two maps. Many of these gaps are in oceanic areas. Short of ocean bottom deployments, the island sites selected for new stations represent the only global siting opportunities amidst even vaster ocean regions devoid of islands. Important holes in continental coverage still exist in Nigeria, southern India, southern Egypt, Mali, Gabon, and Florida.

Each of these sites is crucial for global tomographic studies of the Earth's three-dimensional structure for the simple reason that spatial aliasing due to gaps in coverage cannot be mitigated. With few exceptions, there have never been seismometers at these remaining sites, and hence the scientific opportunity for new discoveries is great. The new, broader coverage will provide additional seismic

Figure 4. The growth of broadband digital seismic networks is shown. The figure is divided into two parts. The upper section plots the growth of seismic stations which provide global coverage at station spacing of about 2000 km. The lower section shows the rapid growth of regional networks and other seismic stations where the inter-station spacing is less than 2000 km. The IRIS Global Seismographic Network is the only network whose growth is focused on achieving uniform global coverage. The explosive growth of broadband regional networks is a result, in part, of the success of the IRIS and French Geoscope programs. Many of the networks shown use data acquisition equipment developed in response to the IRIS program, including Geofon, GTSN, Mednet, Terrascope, Berkeley, Mexico, Germany, and US National Seismic Network (NSN). The Chinese network is being upgraded with GSN equipment under IRIS/USGS sponsorship, and is included within IRIS GSN.



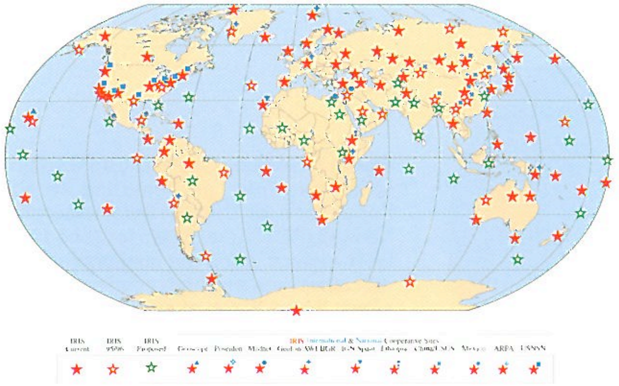


Figure 5. Current GSN stations (June 1995) and stations to be installed through the summer of 1996 are plotted in red. Open green stars show locations of proposed new GSN stations (see Table). International and national cooperative sites with other networks and organizations are noted.

raypaths from earthquake to stations, sampling parts of the lithosphere, upper mantle, lower mantle, core-mantle boundary, and inner and outer core of the Earth which have heretofore been unexamined. Studies of seismic wave propagation in the oceanic lithosphere will make data available from a wide range of tectonic provinces and seafloor ages. Valuable insights into the nature of inter- and intra-plate earthquakes in the region of the new stations will broaden our understanding of the distribution of stress and the dynamics of the earthquake source. The improvement in the global distribution of stations will yield better earthquake mechanisms.

Several new sites in the GSN siting plan provide regional coverage in areas of interest to the seismic verification community. These include Uganda and Tajikistan; the additional sites in Saudi Arabia, Egypt, Argentina, Brazil, Pakistan, and India; and the completion of upgrades to the China Digital Seismic Network. Studies of regional seismic wave propagation and improved earthquake catalogs of low-magnitude sources are of particular interest to this community. All GSN sites have been offered to the verification monitoring community as part of an International Seismic Monitoring System

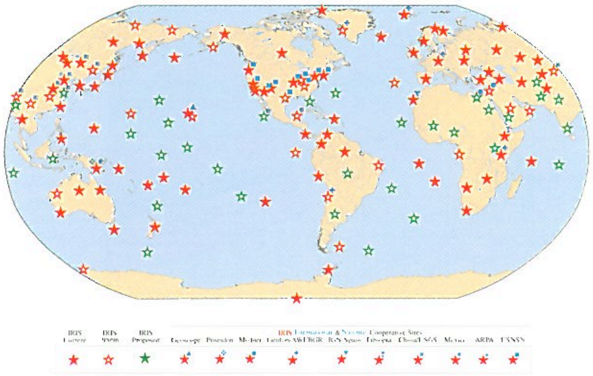


Figure 6. Same as Figure 5 but using a map projection which emphasizes oceanic coverage.

New Initiatives

Telemetry

Recent and projected advances in communications technology will have enormous impact throughout IRIS over the next five years. A separate section in the document describes the opportunities which these developments provide and indicates some of the applications of advanced telemetry in GSN and the other IRIS programs.

Satellite telecommunications systems are available now such as INMARSAT which offer global coverage for voice and data. While the cost for use is slightly lower than regular international telephone and the systems can be used anywhere, independent of ground-based telephone lines, the cost of equipment is high (~$50K). As a result, except in a few special cases, the retrieval of data from the GSN stations via near real-time telemetry has been confined to signal segments from moderate and large seismic events via SPYDER^{TM}.

On the horizon are proposals for "global digital cellular telephones" using constellations of low-Earth-orbiting (LEO) satellites. These developments are being driven by global markets with resources well beyond those of the Earth sciences. Within the next decade, it is evident that global digital telemetry will become as commonplace as an international phone call is today. It is important for IRIS to stay abreast of these developments and be prepared to take advantage of them as soon as price and availability permit.

In terms of the coming five years, we propose to deploy a modest number (10) of INMARSAT B terminals at remote GSN sites without regular telephone access, and plan for extensive use of "global digital cellular" systems if and when they become available near the end of this five year program. A important consideration in the selection of sites for the deployment of INMARSAT systems will be their importance for use by the NEIC and the international nuclear monitoring community.

Transportable GSN Stations

Many seismological investigations require seismic coverage at a finer scale than the 2000 GSN spacing. The IRIS PASSCAL program complements the GSN program in providing the means for temporary fine-scale seismic investigations using portable equipment. Many PASSCAL experiments conclude with excellent scientific reasons for continued operation of one station for additional years. In tectonically active regions, the GSN 2000 km spacing may be viewed as a lowermost bound on acceptable coverage. The scientific results from TERRAscope, Anza, the Berkeley Digital Seismic Network and Italy's MEDNET illustrate the obvious value of dense broadband stations spaced more closely than GSN goals. Nonetheless, completing the 128-station uniformly distributed network remains the GSN's paramount goal.

To balance the needs of the scientific community for additional seismic coverage in places where GSN stations already exist, IRIS proposes semi-permanent or portable GSN stations to bridge the gap between the GSN and PASSCAL programs. Such a station would be compatible with current GSN equipment but intended for more rugged installations, as opposed to classic seismic observatories. Broadband seismometers such as the STS-2 and CMG-3 may be used, instead of the very-broadband (but not very portable) STS-1. A standardization of the telemetry interface and GSN data cartridge format would permit straightforward incorporation of the site into the IRIS DMS. Unlike the GSN sites which are permanent observatories, these portable GSN sites would be implicitly temporary, with their length of deployment justified by the science. Five sets of portable GSN equipment are proposed with concomitant installation funds.

Although no specific sites are being considered at this time, some discussions of possibilities helps to focus the intent for the program. Several recent PASSCAL experiments have found excellent sites where longer-term seismic monitoring — Fiji above the Tonga-Kermadec subduction zone, Tanzania in the East African Rift Zone, Bolivia on the Altiplano plateau above the Andean subduction zone — would result in a continuing harvest of scientific benefits from the experiments. With the adoption of antipodal XAN, Xi'an, China as a permanent GSN station, a "podal" station could be installed in Chile to form a two-element "diameter array" with the unique property that both stations would be on the same great circle path from every earthquake globally.

GSN Station Software

GSN software will evolve in the coming years and will benefit from existing cooperation among IRIS GSN, the USGS National Network, University Network partners, and instrument manufacturers. Two specific enhancements are discussed among a number of ongoing developments:

(1) the GSN system as a hub of a network of outlying sensors; and

(2) Event detectors to pro-actively respond to events and send out data and information.

Network Hub - The concept of a separable GSN system, where remote data acquisition (DA) functions are linked by telemetry to the data processing functions (DP) at a host institution, has been a successful approach for the GSN, as it balances the need for low-noise, remote sites with easy data access and operation by the local host organization. In designing this capability into the IRIS-2 system, the possibility for supporting multiple DAs linked to a single DP was specifically not precluded in the design. Working with Quanterra, the manufacturer of GSN IRIS-2 systems, the Berkeley Digital Seismic Network has brought this concept into reality — the hydra (many headed) system. In the past year the GSN has funded the hydra development for the GSN system, coordinating with Berkeley and Quanterra to standardize the software. A similar development for the UCSD IRIS-3 systems can draw upon the experience of the telemetered K-NET array in Kyrghyzistan.

The option of expanding a single GSN site into the hub of a local or regional array is a valuable extension to the GSN. Local hosts and countries can make use of the existing GSN infrastructure to add additional outlying sites to the GSN hub site to create regional networks or augment existing ones. Obvious examples of developing nations with high seismic risk include Zambia, Kenya, and Kyrghyzstan.

Event Detectors - The current operating mode for collecting near real time data from a GSN site is to respond to data requests by the DMC SPYDER system. The SPYDER system itself is triggered by earthquake alert bulletins from the USGS National Earthquake Information Center (NEIC), which in turn depends primarily on real-time data from the US National Seismic Network. Many GSN stations are sufficiently remote that they would be the dominant source of information on the occurrence of a regional earthquake if the news of the earthquake could be rapidly made known by the station. Software triggers and protocols developed for the US National Network can be ported to GSN stations to give the GSN site the ability to provide NEIC automatically with both trigger and waveform information. The IDA group has initiated an experiment with the USGS to use similar software (a "virtual data logger") to provide access to data from those IRIS/IDA stations that are available on Internet (see Telemetry section elsewhere in this document). Especially for stations outside North America, this ability for remote GSN stations to initiate contact with the NEIC, rather than waiting for a request, would greatly enhance the timeliness of NEIC response and the uniformity of global detection levels. Although these protocols will be initially developed for sites connected via Internet, later applications will include dial-up or satellite linked sites.

Observatories

The leap from a Global Seismographic Network to a Global Geoscience Network is a natural extension. The GSN provides an existing global scientific infrastructure. Most sites have digital channels for recording additional data streams and adding digital channels is straightforward at sites currently operating at full capacity. Agreements with host organizations are based upon scientific cooperation, and extending seismology to more general geoscience is within the scope of existing arrangements. Collocation of other geophysical sensors at GSN sites has been discussed for several years, and the concept has been endorsed in two National Academy reports ("International Global Network of Fiducial Stations: Scientific and Implementation Issues", National Research Council, Committee on Geodesy, 1991; "The National Geomagnetic Initiative", National Research Council, U.S. Geodynamics Committee, 1993).

The concept of expanding selected GSN sites to become geophysical observatories was initiated in the last IRIS proposal and several concrete steps were taken.

- The IDA network of LaCoste-Romberg gravimeters, which are collocated with many IRIS/IDA GSN stations and are supported by IRIS, has been a significant geophysical component of the GSN since 1987.

- Atmospheric events such as volcanic explosions produce infrasonic vibrations which may be recorded on a microbarograph. IRIS has tested a number of excellent, low-cost (<$4K) microbarographs at the Albuquerque Seismological Lab, and units are operating at the GSN station in Albuquerque and at University Network stations in Tucson and Pasadena. Microbarographs are also of interest to the nuclear verification community in the detection of clandestine atmospheric tests. The GSN has begun to install microbarographs at all network stations, a process which will continue into the next NSF Cooperative Agreement.

- IRIS has been encouraging the installation of Global Positioning Satellite (GPS) location equipment at GSN stations (GPS clocks for timing are in widespread use in the GSN). A joint IRIS/UNAVCO (University NAVSTAR Consortium) workshop on GPS-seismic co-location was held at UCSD in April, 1994. IRIS has proposed to integrate a GPS receiver into the GSN station processor, but needs guidance from the GPS community with respect to sensor and data format standards. Two GSN stations now have co-located GPS geodetic receivers — Pinon Flat, California (PFO) as part of the Permanent GPS Geodetic Array of Southern California, and Mahe, Seychelle Islands (MSEY) in collaboration with JPL's global network. On Easter Island an Internet connection has been jointly funded by NASA and IRIS to access the GPS and GSN data. Cooperation with the NASA FLINN (Fiducial Laboratories for an International Natural sciences Network) is building — FLINN will soon be installing a collocated GPS sensor at the GSN Guam station, and agreements are in place for cooperation in the Seychelles, Diego Garcia, Kwajalein, Nigeria, and Tristan da Cunha. Interest by the Defense Mapping Agency (DMA) in GPS data from GSN sites shows some promise.

These last two items alone show the synergy of combining sensors and data streams. As the UNAVCO MetGPS project has shown, if precise measurements of surface pressure (provided by the barometer) are available from the site of a GPS receiver, the data collected by that receiver can be used to map the total amount of water vapor in the atmosphere overhead: a quantity of great interest to meteorological and climate studies, and one not generally available except through the laborious process of launching sounding balloons. We can expect more of this kind of fruitful interaction as more sensors are added — but there is, in any case, much to be gained merely from sharing the costs of the capital investment (in both equipment and people) needed to collect data routinely all over the world.

IRIS has discussed collocation of geomagnetic instruments at GSN stations with the geomagnetics community and with NASA and the USGS. There is substantial interest in the concept of collocation, which the geomagnetics community endorsed in a 1994 report to the National Research Council, "An Enhanced Geomagnetic Observatory Network". Two INTERMAGNET observatories operated by the USGS are already collocated with GSN stations — Guam and Puerto Rico — and two other sites are within 10 km — Oahu and Tucson. Collocation of seismometers with geomagnetic equipment requires some care, as the instruments have different noise concerns: for seismometers, it is extraneous vibrations; for geomagnetometers, it is nearby electrical currents and magnetic materials.

During the next 5 years IRIS intends to take a lead in developing ways to combine sensors at common sites, perhaps using local telecommunications technology to build an "observatory without walls" to overcome some of the siting problems just discussed. IRIS proposes in the next five years to fund several prototype geophysical observatories at GSN sites. Instrumentation would include GPS, meteorological, and geomagnetic sensors, for all of which standard equipment is readily available; in addition, air pressure and temperature would be monitored at all GSN sites. Data exchange would be internationally coordinated with the International GPS Service (IGS) with NASA/FLINN and DMA, and with the INTERMAGNET program.

GSN stations on islands provide an other example of a unique kind of observatory. For the RIDGE Oceanographic community, the continuous monitoring of ridge crest seismic activity by existing GSN sites on Ascension Island, Easter Island, and Iceland; and planned sites on Tristan da Cunha, the Azores, Galapagos, Diego Garcia, Isla Socorro, and Macquarie Island provides crucial seismic coverage of the major mid-ocean ridge systems throughout the world's oceans. The de-classification and conversion to civilian use of the Navy's global hydrophone arrays offer unique opportunities at Ascension Island and Wake Island. On Ascension Island, the network of hydrophones can be used in conjunction with the seismic data from the GSN station, ASCN, to locate local and regional earthquakes along the mid-Atlantic ridge crest (Figure 7). The Wake Hydrophone Array operated by the University of Hawaii can be used with the GSN station being installed at Wake for the study of seismic wave propagation in the old western Pacific lithosphere. In both cases it is only a small step to use the GSN data acquisition system to acquire the hydrophone data directly (as in a local seismic array), turning these stations into ocean observatories.

Ocean Seismic Stations

The completion of the land-based (continents and islands) GSN with adequate operations and maintenance support is the foremost goal of the GSN program. However, with a world that is more than two-thirds ocean, the ultimate scientific goal for the global study of the Earth system must include coverage in the deep ocean as well. IRIS has been a leader in the establishment of an Ocean Seismic Network (OSN) through its efforts in undersea telephone cable re-use, funding support of the OSN planning office with its international coordination, scientific support of the OSN instrumentation development and the pilot experiments, and modest funding support of broadband ocean bottom seismometer development in conjunction with the NSF Ocean-Science division.

In its last proposal, IRIS initiated a modest effort toward tackling the problems of oceanic coverage, recognizing that many years of research and development lay ahead. IRIS has been active in two areas of strong interest to the GSN community — telecommunications to the seafloor via cables for data access, and determining the best method for emplacing broadband seismometers at the bottom of the ocean. There have been substantial successes.

IRIS and the Earthquake Research Institute (ERI) of the University of Tokyo successfully transferred a section of the Trans-Pacific Cable-1 (TPC-1) undersea telephone cable between Guam and Japan from AT&T and Japan's KDD to ERI and IRIS for scientific re-use.

The Ocean Drilling Program drilled a scientific borehole (OSN-1) 200 km SSW of Oahu, Hawaii, in response to a proposal by the Ocean Seismic Network (OSN) Steering Committee (co- sponsored by IRIS and Joint Oceanographic Institutions, JOI) for a test hole for pilot experiments to compare the performance of borehole sensors with that of seafloor and surficially buried sensors.

In addition to these major successes, there have been many smaller ones which are building to a promising ocean initiative.

- In the cable re-use arena, IRIS successfully raised funds for re-engineering the Guam terminus of TPC-1, and funded research at the University of Hawaii (UH) and Woods Hole Oceanographic Institution (WHOI) on developing inductive coupling to undersea cables, to promote the re-use of cables without expensive cutting and splicing methods.
- Through the IRIS-JOI Cable Steering Committee, IRIS has served as liaison with AT&T for the academic community and has aided Japanese efforts to re-use the Guam-Philippines and TPC- 2 cables near Japan.

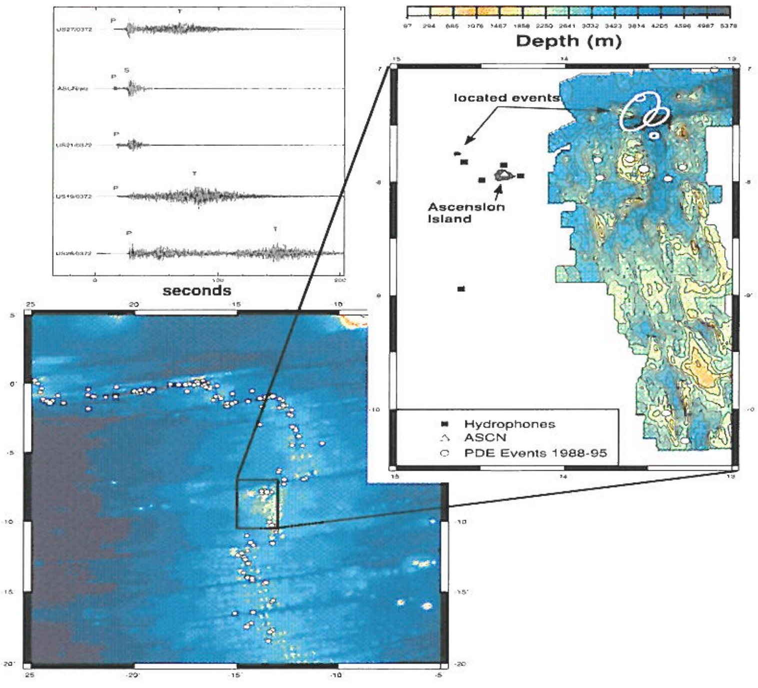


Figure 7. Mid-Atlantic bathymetry near Ascension Island, where the GSN station ASCN and a hydrophone network are located. The expanded map shows high resolution SEABEAM bathmetry and the locations of small magnitude events located using data from ASCN and the hydrophone array. Hydrophone and ASCN data are shown for one event with magnitude 3.7 (Figure provided by J. Hanson, H. Given and J. Berger, USCD)

Japanese ocean bottom seismometer instrumentation has been developed for installation on TPC-1 in mid-1996 and is planned for TPC-2.

- With the University of Hawaii (UH), WHOI, and Scripps Institution of Oceanography (SIO), IRIS has proposed to the NSF to install a broadband seismometer on a junction box with underwater-mateable connectors on the Hawaii-2 cable between Hawaii and California.

- IRIS has been an advocate of the opportunities for re-use of Navy SOSUS hydrophone arrays.

- In support of the concept of an Ocean Seismic Network, IRIS has funded an OSN planning office at JOI to coordinate the national efforts toward the OSN pilot experiments at the OSN-1 hole (scheduled for late 1996) as well as international liaison with Ocean Initiatives in France and Japan. For the latter, the planning office has held an international OSN workshop in conjunction with the IRIS workshop on Hawaii in 1993. The meeting brought together technical experts from US, Japan and France to forge closer ties between engineering groups at institutions around the world that are involved in developing ocean floor seismometers and to make some real progress in identifying successful strategies to solve the technical problems. OSN was a major presence at the other national and international workshops which mainly discussed ocean floor observatories. A follow up to the 1993 meeting was held in Marseilles in early 1995 to develop a detailed plan for Ocean observatories, the International Ocean Network (ION).

Summary

The completion of the Global Seismographic Network and the continuing operation and maintenance of this unique global facility for the scientific community are the foremost tasks in the next five years. So important is this goal that over 90% of the GSN budget is committed to network station installations, and operations and maintenance. The vision which IRIS set forth for global seismology ten years ago is now within reach. As this foundation is being completed, IRIS looks to the future. New initiatives will begin to broaden the GSN into geophysical observatories. Data access and maintenance efficiency will be improved through increasing the use of telemetry. GSN coverage will be augmented with portable GSN stations, and continent and island coverage will be completed with deep ocean observatories.

Proposed New GSN Stations

Site	Country	Lat °N	Lon °E	Network Operator
Central	Argentina	-35.00	-65.00	IRIS/USGS
Macquarie Island	Australia	-54.50	158.96	IRIS/USGS
South Keeling Islands	Australia	-12.20	96.80	IRIS/IDA
Bermuda	Bermuda	32.38	-64.68	IRIS/USGS
Trindade Island	Brazil	-29.50	-29.30	IRIS/USGS
Western	Brazil	-9.00	-65.00	IRIS/USGS
Praia	Cape Verde Islands	15.00	-23.60	IRIS/IDA
Sheshan	China	31.10	121.19	IRIS/USGS — China
Abu Simbel	Egypt	22.19	31.38	IRIS/USGS
Siwa	Egypt	29.11	25.31	IRIS/USGS — Mednet
Furi (replaces Addis Ababa)	Ethiopia	8.90	38.68	IRIS/USGS
Nukuhiva, Marquesas	French Polynesia	-8.36	-140.00	IRIS/IDA
Kodaikanal	India	10.23	77.47	IRIS/USGS
New Delhi	India	28.68	77.22	IRIS/USGS
Shillong	India	25.57	91.88	IRIS/USGS
Sulawesi	Indonesia	-4.00	120.00	IRIS/IDA
Kanton	Kiribati	-2.50	-171.40	IRIS/USGS
Kiritimati	Kiribati	2.00	-157.30	IRIS/USGS
Tarawa	Kiribati	1.30	173.00	IRIS/USGS
Kowa	Mali	14.50	-4.02	IRIS/USGS
Kwajalein Atoll	Marshall Islands	9.15	167.30	IRIS/IDA
Isla Socorro	Mexico	18.73	-110.95	IRIS/USGS — Mexico
Raoul Island, Kermadec	New Zealand	-29.15	-177.52	IRIS/USGS
Jos	Nigeria	9.50	8.50	IRIS/IDA
Quetta	Pakistan	30.19	66.95	IRIS/USGS
Ab'ha	Saudi Arabia	18.30	42.50	IRIS/IDA
Gissar	Tadjikistan	38.38	68.51	IRIS/IDA
Funafuti	Tuvalu	-8.30	179.12	IRIS/USGS
Diego Garcia, Chagos Archipelago	U.K.	-7.30	72.40	IRIS/IDA
Pitcairn Island	U.K.	-25.04	-130.06	IRIS/USGS
South Georgia Island	U.K.	-54.00	-36.00	IRIS/IDA
Tristan da Cunha Island	U.K.	-37.00	-12.50	IRIS/USGS
Disney Wilderness Reserve, Florida	U.S.A.	28.33	-81.21	IRIS/USGS
Johnston Atoll	U.S.A.	16.45	-169.42	IRIS/USGS
Midway	U.S.A.	28.21	-177.33	IRIS/USGS
Kampala	Uganda	0.19	32.35	IRIS/IDA

PASSCAL

Facilities to Support Experimental Seismology

Introduction

The familiar example of Galileo and the telescope teaches that major advances in science are triggered whenever fundamentally new data become available. In this century, space probes have revolutionized the field pioneered by Galileo by providing images of the planets far beyond the resolution of Earth-based telescopes. Spacecraft have provided new information that was invisible to optical telescopes (e.g. radar images of Venus). The development of PASSCAL finds analogy in these programs. PASSCAL has made it possible to conduct seismic experiments now that would have been impossible as recently as five years ago. The data provided by PASSCAL lead to new discoveries about the internal workings of the Earth, the nature of earthquakes, and how seismic waves propagate within the Earth.

What was planned

The goal of the IRIS Program of Array Seismic Studies of the ContinentAl Lithosphere (PASSCAL) is to provide IRIS member institutions access to state-of-the-art instrumentation to support experimental seismology. PASSCAL was born in 1983 and 1984 as an outgrowth of several key studies by the National Academy of Sciences. These studies helped launch the workshops that defined the requirements for a new generation of standardized, portable seismic instruments for studying the continental lithosphere. It was originally conceived as a pool of 1000 instruments, providing the university community the ability to image the Earth using two-dimensional areal arrays. The PASSCAL program would enable the research community to apply techniques to crustal problems similar to those used by the oil companies in exploration of sedimentary basins.

What has emerged

PASSCAL currently has a stable of more than 400 portable, digital seismic recording systems with a total capacity of more than 1,500 channels. These facilities are supported by two instrument centers that provide hardware and software support to scientists in the design and execution of their experiments.

Since its conception a decade ago, PASSCAL has profoundly changed the science of seismology. Before PASSCAL existed, American academic institutions engaged in seismological research fell into two distinct groups: (1) a few large groups with active experimental programs that supported a staff of technical and field personnel and a collection of instrumentation; and (2) smaller groups who either did theoretical work or utilized openly available data sources like the WWSSN. This led to a scientific social structure in which virtually all of the experimental activity was in a handful of larger institutions. Those that did have experimental programs often struggled to support their technical staff. Data collected in experiments rarely made it outside the institution that collected the data other than in the form of published papers.

PASSCAL has changed the social structure of seismology. There are numerous examples in the past decade of young scientists who have, through PASSCAL facilities, been able to design experiments to test a well posed hypothesis, execute the experimental program, analyze the data, and publish the results. A decade ago few of these projects could have been completed. The benefits this has provided to the science of seismology, and implicitly to the nation as a whole, are significant:

- PASSCAL dramatically improved the quality of instrumentation available to do experimental seismology.
- PASSCAL greatly expanded the number of instruments available for field programs. The number of seismic channels in an experiment and its total data volume have increased steadily for the past five years.
- PASSCAL has a demonstrated capability in supporting both large-scale and small-scale experiments Thus the facility supports both "big science" and "little science".
- PASSCAL has dramatically improved the basic infrastructure of seismology by expanding the pool of people experienced in collecting field data. Many of these people come from smaller institutions that would previously been unable to consider mounting major field projects.
- PASSCAL management of this shared pool of instrumentation provides higher efficiency in equipment acquisition and operations than would be possible with a number of independent institutions.
- PASSCAL works with NSF to provide an unbiased forum for equitable distribution of scarce resources (i.e. available instruments).
- The shared resources of PASSCAL are standardized. This greatly simplifies data collection and analysis by reducing the number of instrument parameters and data formats that must be tracked.

PASSCAL's Impact

The advances induced by PASSCAL are driven by technology. The real measure of success of the program, however, lies in the science that has been supported. This is covered in more detail elsewhere in this proposal (Section II), but it is useful to highlight a few examples. The items discussed here are not intended to be exhaustive. Instead the intent is to illustrate the breadth of experimental efforts spawned by these new facilities.

Tibet

The Tibetan plateau is one of the most unusual geologic provinces on the planet. It is bounded by the highest mountains on Earth resulting from the collision of the Indian and Eurasian plates. A decade ago, very little was known about the internal structure of the crust and upper mantle beneath Tibet. A profoundly new picture is emerging through data obtained in multifaceted investigations in this remote area, including the use of PASSCAL facilities. Tibet was the site of one of the first modern broadband array experiments. Furthermore, new insight into the nature of the southern boundary of the plateau (the Himalayas) is emerging through INDEPTH, a multi-technique experiment in which PASSCAL instruments play a major role.

Bolivia and Fiji

In 1994 two of the largest deep earthquakes since modern seismic instruments existed occurred in remote area in Bolivia and the South Pacific. Although mainly fortuitous, broadband array experiments happened to be in operation near the epicenters of both earthquakes. These earthquakes are providing new data about one of the fundamental unsolved problems in Earth science — the processes responsible for deep earthquakes — and on seismic sources in general. Recording these events was only partly a matter of luck, however. The exisence of PASSCAL facilities made these experiments possible, which illustrates that one of the side benefits of an active experimental seismology program is the chance of catching unusual, large earthquakes at close range and recording them on scale.

Western US

The past five years have witnessed a remarkable range of experiments directed at a wide variety of geologic targets within the western United States. Examples include: Basin and Range wide aperture recording, PACE/RISC, Rocky Mountain Front, BARGE, Cascadia, Snake River Plain, the Mendocino Triple Junction, Southern Sierras, Southwest Washington, Valles Caldera, N.M., and the planned 1995 Deep Probe experiment. These experiments provide a wealth of new information that has not yet been fully assimilated. We are on the edge of a grand new understanding of the overall structure of the crust and upper mantle beneath the western United States and how these structures relate to larger scale tectonic processes.

S-wave splitting

With the availability of the new generation of portable, broadband instruments a new technique has emerged - teleseismic S-wave splitting. S-wave splitting exploits the fact that rocks in the upper mantle acquire a fabric (preferred orientation of minerals) controlled by deformation. This technique is now used to interpret flow directions of material in the upper mantle, based on observations of distant earthquakes with broadband seismometers. PASSCAL instrumentation has been the backbone of focused experiments to utilize this technique beginning with the 1989 experiment by Carnegie Institution and the University of Wisconsin. Continued experiments of this type will revolutionize our understanding of the dynamics of the upper mantle by allowing us to map flow patterns within the Earth.

Brooks Range

The Brooks Range, Alaska experiment and subsequent similar experiments illustrate the great improvement in resolution made possible by a unified acquisition and processing scheme that merges narrow offset seismic reflection data with wide offset reflection/refraction data from many closely spaced receivers and shots. The geometry allows simultaneous estimation of seismic velocity structure using wide-aperture travel-time data and construction of near-vertical-incidence and wide-aperture stacks resulting in high resolution images of the crust and upper mantle. The Brooks Range seismic section shows crustal scale duplexing and a complex lower crust / Moho transition zone.

RAMP

PASSCAL has helped the university community coordinate the Rapid Array Mobilization Plan (RAMP). This program sets aside a group of instruments (currently 10) to be used in a scientific response to a major earthquake. The concept emerged with an unplanned deployment following the Loma Prieta earthquake. Since then PASSCAL has taken a leadership role in organizing this effort. Scientists from the Southern California Earthquake Center (SCEC) used PASSCAL's RAMP instruments and other equipment in major RAMP responses following the Landers and Northridge earthquakes. Smaller scale efforts were mounted following other earthquakes by a number of IRIS institutions.

KYRGnet

Through funding from the DOD-supported Joint Seismic Program, an integrated hardware-software system was developed that added a new level of functionality to the PASSCAL instruments that was not envisioned in the birth of the program in 1983. A functional system now exists that allows PASSCAL instruments to serve in telemetered regional seismic networks. Systems of this type are presently operational in the newly independent country of Kyrghyzstan and in the southern California Anza network.

The First Five Years

Instrument design and procurement

By the early 1980s many different recording systems existed within the research community. However, because of the difficulty in getting the funds necessary to maintain and operate large numbers of instruments, most institutions had only small numbers of instruments. The state of digital electronics was such that the instruments could record only small amounts of data, therefore, they had to be optimized for specific research goals. It was very difficult to field an experiment with even a moderate number of instruments. Each set of instruments had its own response characteristics and required its own personnel to handle them in the field and to convert the data into a common usable format. The community recognized that a new approach was needed if there were to be a significant improvement in observational capability in crustal and lithospheric seismology. The PASSCAL program was launched to develop, acquire, and maintain this new generation of standardized equipment.

The initial efforts of the program were directed at designing and acquiring a single instrument that could be used to image the crust and lithosphere. The ideal instrument was one that could record seismic reflection profiles and also operate unattended for long periods of time recording local or teleseismic events.

This initial goal was to design an instrument that could be upgraded, be capable of doing a full range of experiments, would last a long time and be versatile so the hardware would not limit the type of science done in the future.

TABLE I PASSCAL Field Recorders

	Three Channel Systems		**Six Channel Systems**
Configuration	**72A-06**	**72A-07**	**72A-08**
Input Channels	3 with 16 bit resolution	3 with 24 bit resolution	3 with 24 bit resolution 3 with 16 bit resolution
Output Channels	6 (two gains per channel)	3	6
Data Streams	8	8	8
Sample Rates	Same for all Data Streams 50, 100,125, 200, 250, or 500 sps	Same for all Data Streams 20, 50, 100, 125, 150, 200, 250, 500, or 1000 sps	Variable across Data Streams: from 1 to 1000 sps
Gain	Dual gain. Low gain fixed at 18 dB; high gain programmable per channel30, 42, 54, 66, or 78 dB	Programmable per channel 0 or 30 dB	Programmable per channel;
Primary Data Storage	Internal SCSI 230 MB disk	Internal SCSI 540 MB disk	External SCSI 540 MB disk
Timekeeping	Internal oscillator (VCXO), or Optional external GPS clock	Internal oscillator (VCXO), or Optional external GPS clock	GPS clock or OMEGA clock
Passband	90% Nyquist with -86 dB minimum stopband.	85% Nyquist with -130 dB minimum stopband	80% Nyquist with -100 dB minimum stopband

The REFTEK instrument delivered in the spring of 1988 represented a significant step forward in portable recording systems. It successfully operated over the wide range of experiments for which it was designed, and proved adaptable to new classes of experiments (e.g., broadband seismic arrays).

During the initial three years of the program, PASSCAL assembled principal investigator teams and fielded focused experiments. As part of this effort large scale reflection/refraction profiles were conducted in the Ouachita Mountains of Arkansas and in the Basin and Range of Nevada. Passive experiments were conducted in the Basin and Range of Nevada and along a line from South Dakota to western Ontario, Canada. PASSCAL also funded a prototype experiment along the line shot in the Brooks Range in 1990. As the facility developed, and more people in the community saw the possibilities of these new facilities, PASSCAL shifted into the current mode of providing basic infrastructure to maintain and operate the facility while support for experiments came from the normal peer review process at NSF or other funding agencies.

6-channel: The basic PASSCAL instrument (Figure 1) consists of a six-channel acquisition system with external clock, 12-volt power source, and SCSI recording device. One unique feature of this system is the ability to record different data streams. The six input channels can be grouped into eight different data streams. Each steam can access any or all of the input channels and can record at any of 13 sample rates between 1000 sps and 1 sps. This flexibility allows an investigator to simultaneously record high-sample-rate event triggered data streams and low-sample-rate continuous data. Table I shows a list of the characteristics of the current six-channel instrument (72A-08).

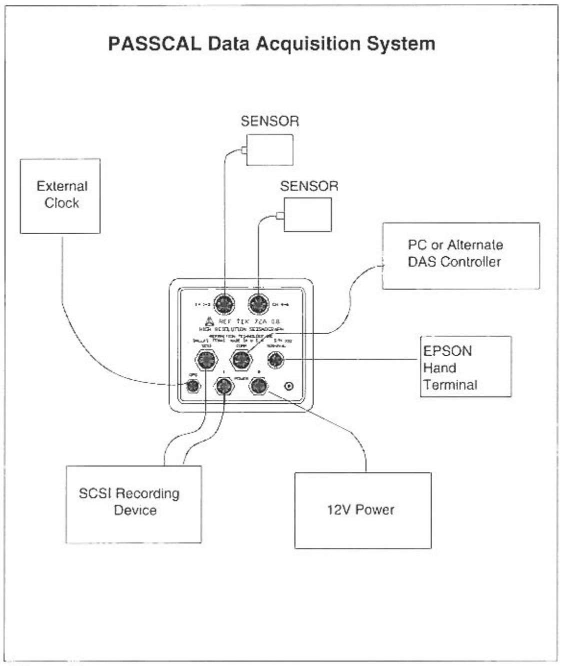


Figure 1

3-channel: After the completion of the original six-channel instrument, we entered a short development phase for an instrument more easily used in reflection/refraction profiling. This development was driven by two concerns. First, the six-channel unit had the wrong "granularity" for this type of experiment. It could support either six vertical sensors, or two sets of three-component sensors. Either way, cables had to be strung to use fully the channel capacity, which significantly increased field costs and deployment effort. Second, a three-channel unit would reduce the cost per instrument and at the same time not give up much in the way of overall performance. The three-channel instrument developed toward the end of the first five years fulfilled these goals. The instrument was simpler to deploy, it could be used in active as well as passive source experiments, and it could record large amounts of high quality seismic data. Finally, it utilized the same support equipment and field computers as the original system. Table I shows the characteristics of the two types of three-channel instruments now in use.

SGR: In addition to the support of the PASSCAL equipment described above, PASSCAL has helped support the Seismic Group Recorder Facility at Stanford University. The facility is a joint project of PASSCAL, Stanford and the USGS. In 1988 AMOCO gave 185 seismic group recorders (SGR) instruments to Stanford. The SGR is a single-channel recording instrument designed for radio turn-on. These instruments were used extensively in the oil industry for seismic exploration. Since they were accepted by Stanford, the units have been modified to turn on at preset times. This makes them useful to the reflection/refraction community. As part of the requirement for receiving maintenance support from PASSCAL, the instruments are made available to the entire PASSCAL community. This facility has added greatly to the capability to conduct large refraction surveys.

Instrument Centers

PASSCAL operates as a facility for the research community. In order to provide the needed assistance to the PI to conduct field work, PASSCAL established an instrument center at Lamont-Doherty Earth Observatory. This center provides the staff to maintain and upgrade the equipment. It takes care of shipping and inventory problems, provides assistance to the PI in the field and provides development support for the field processing software. The center at Lamont was established in 1989 when we received the first delivery of production instruments. A second center was established at Stanford in 1991 to house the three-channel instruments.

The Second Five Years

Growth of the inventory

While the first five years involved the initial development of recording hardware, the second five years focused on acquisition of recorders and multiple types of sensors and development of processing capability to keep up with ever-increasing amounts of data.

By the end of the first five years, 90 instruments were available. Since that time we have acquired more six-channel instruments, 100 broadband sensors and a significant number of three-channel instruments. By the end of 1995 we will have approximately 125 six-channel instruments, 290 three-channel instruments and 10 instruments devoted to the Rapid Array Mobilization Program (RAMP). Supported experiments have ranged in size from a few instruments to 250 instruments. Figure 2 shows the growth of the pool of PASSCAL instruments.

The growth of the instrument inventory and a balanced development of the facility are major challenges under the constraints of budgets available to the program. The emphasis over the past five years was to acquire as many instruments as possible while keeping the support infrastructure at the facilities as small as possible without compromising the quality of service. In instrument acquisition there has been a long-standing struggle in budget priorities between facilities to support active source experiments and broadband experiments. It is strong testimony to the success of the committee structure of IRIS that these conflicts have been worked out with a reasonable balance to move the program forward.

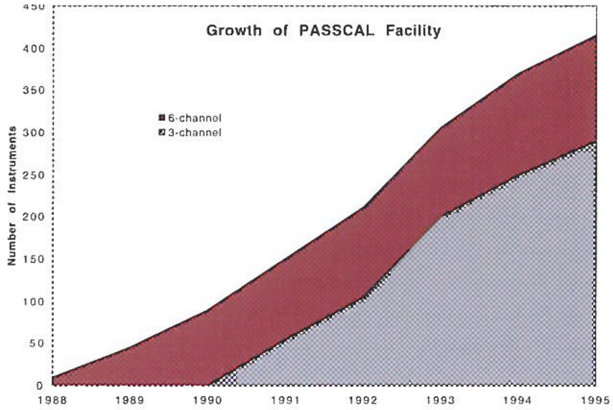


Figure 2

Hardware developments

The primary focus in hardware development in the second five years of the program was to maintain standardization of the instrument pool and to adopt new recording and timing technologies. Significant efforts were directed also at testing the new generation of broadband sensors that emerged during this period. These are discussed in detail below.

24-bit and disk upgrades

Several major equipment upgrades took place during the second five years of the program.

- Conversion of all of the six-channel units to 24-bit systems. This entailed replacement of three 16-bit channels with three 24-bit channels in approximately 110 units.
- Conversion of older clocks based on OMEGA (a low-frequency RF signal used in navigation) to newer, more reliable GPS satellite-based clocks.
- Upgrading 190-Mbyte disks with lower power units with at least 540 Mbytes capacity.
- Replacing all original Exabyte tape units used for copying disks with more reliable DAT drives.
- Upgrading battery units for the three-channel systems to provide more than twice the capacity of the original units.

We sacrificed the purchase of recorders to accomplish these upgrades, but the upgrades enabled us to keep all of the equipment at a standardized level.

Telemetry developments

The original PASSCAL instrument was conceived as a stand-alone system, primarily because in active source experiments the time an instrument occupies a particular spot on the ground tends to be limited. Furthermore, at the time of prototype construction most passive experiments utilized very large station spacing. The emergence of passive array experiments with closer station spacing, however, quickly demonstrated the need for some form of communication between instruments. The earliest example of this was a high frequency array experiment conducted at Pinyon Flat Observatory in southern California in 1990 where 60 stations were deployed using wireline telemetry in an array with an aperture of only 250 m.

A completely different scheme implemented more recently is low data rate communication via the ARGOS system which provides daily state-of-health information such as the number of events recorded, the disk and memory capacity used, the status of the clock, the battery voltage and temperature of the system. The initial trials of the system took place on remote islands in the South Pacific. The data allowed the PI to keep much better track of the systems and do a more efficient job of planning service runs.

Another telemetry system utilizes a two-way dial-up interface via standard telephone lines or cellular phone to provide access to both status and data. The speed of the modems (normally 9600 baud or less) limits the amount of data that can be uploaded. However, data from significant events, or regular viewing of noise data, gives the PI a much better understanding of station operation. The two-way aspects of the system allow the PI to change operating parameters over the phone line.

The final, and most sophisticated, form of telemetry, has been developed through the DOD-supported Joint Seismic Program. This is a fully digital telemetry system that transmits data continuously to a central array concentrator (see Section III - Arrays). There data are time aligned and handled in one of two ways: (1) continuous data are written directly onto DAT tape, and (2) a triggered data stream is processed by a second computer that makes decisions about whether to "trigger" and record data. This system utilizes the same standard data acquisition uint used in other PASSCAL experiments. The only significant difference is the EPROM that contains the software run by the system is replaced by another EPROM containing a different program. With this software change, and the communication and data concentrator hardware, the "standard" instrument can be used in a radically different operational mode.

The first versions of this system were tested in early 1991 with a prototype array experiment at Pinyon Flat in southern California. This system was then deployed in the then-Soviet Union in the republic of Kyrghystan in the summer of 1991. It was also used in a JSP experimental array deployed in Turkmenistan from August 1993 to December 1994. The Anza seismic network in southern California has utilized the same technology since 1993.

Instrument Centers

The PASSCAL Instrument Centers were conceived as the place where instruments would be housed and maintained. The center would provide training for the PI but generally would not provide field support. It soon became obvious the instrument centers would have to provide at least some support, especially for larger experiments and those conducted in remote areas of the world. For most passive experiments PASSCAL provides a field engineer to assist in the inital deployment. In addition to the in-field support, the instrument center is available by phone and e-mail to provide continuous support during the experiment.

Active source experiments are of shorter duration and are much more time-critical. PASSCAL usually provides one to four engineers during large active source experiments. These field support personnel provide the skills to maintain the equipment, oversee training of field personnel, and help with the problems associated with handling large numbers of instruments. The PASSCAL personnel in the field do not conduct the experiment. They are there to make sure the equipment works, provide training to field personnel and provide assistance to maximize the quality of the data.

In addition to assistance in the field, the Instrument Center at Lamont also provides software for field computers to enable the PI to conduct the experiment effectively and to perform quality control on the data. This effort, like the field support, has been larger than originally anticipated. However, there are only ten full-time people in both instrument centers combined.

RAMP

As originally conceived, PASSCAL did not have a charter to support aftershock studies. It was assumed the equipment would have the capability to do this, but it was never specifically stated as a requirement. One week after the completion of the first PASSCAL experiment, the Loma Prieta earthquake occurred. The equipment was shipped to California and a team of scientists from Lamont-Doherty initiated an aftershock response. The effort demonstrated prior planning was essential to achieving equally successful results. During the second five years of IRIS, the Rapid Array Mobilization Program (RAMP) became part of the PASSCAL responsibility.

PASSCAL has committed ten of the six-channel instruments to RAMP. These instruments are set aside and can be dispatched to anywhere in the world in less than 24 hours. The instruments can be used for studies of aftershocks of important earthquakes or other opportunities where a small number of instruments for a short period of time will provide a unique data set. As part of RAMP, PASSCAL is working with groups around the country to provide initial pre-planning for significant earthquakes. PASSCAL and the Southern California Earthquake Center (SCEC) have established a memo of understanding that describes the types of earthquakes that will be responded to and establishes lines of communications to use in a significant earthquake. Responses to the Landers, Big Bear and Northridge earthquakes were undertaken by SCEC under this MOU. We are currently working with a group of institutions in the central United States to establish a similar agreement.

Software support

Significant effort was directed at development of software to handle the immense volumes of data collected within the PASSCAL program. The original 1984 prototype systems had the capability of recording to 5 Mbytes of

RAM. With changes in the technology, the normal system can now record to a disk as large as 2.0-Gbyte. Since all of the units can now record compressed data, they each now have a storage capability equivalent to 1.5 to 6 Gbytes compared to the original 5 Mbytes. To handle the large data volumes from the field, PASSCAL provides the PI with one or more field computers. These computers usually consist of a SUN workstation with several GBytes of disk space and extra SCSI ports so the field disks can be downloaded directly to the workstation. In addition to the hardware, PASSCAL has developed software that can convert the data from field format, view the data, apply timing corrections, provide a temporary archive and produce output volumes in standardized formats including SEED for the PI and for permanent archive at the DMC.

Experiment Data Processing Flow

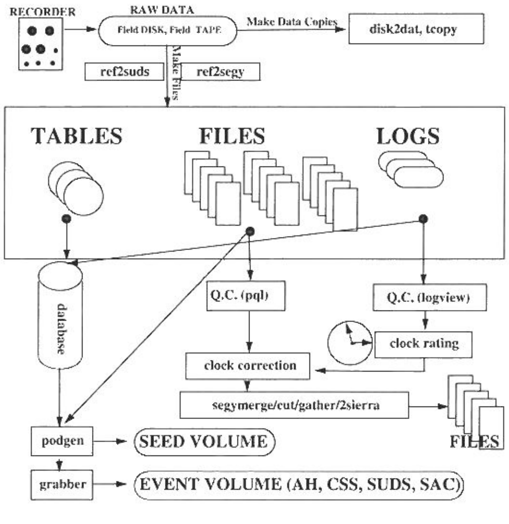


Figure 3

Figure 3 shows the basic flow of processing now available for the PI of a broadband experiment. The data come in from the field on field disks or on DAT tapes copied from the field disk. These data are converted from the field format to the PASSCAL SEGY format by the program ref2segy. In addition to saving the waveform data in a series of segy files, the program creates a series of tables with the information necessary to build a database and a series of log files that contain all of the state-of-health information from the recorder. Once any problems reading tapes and disks are solved and the data are converted, the information from the tables is entered into the database. The database provides the PI with the tools to keep track of an experiment. It has all of the information regarding instrument and sensor placement, data retrieval, instrument and sensor characteristics and data archive. The next steps involve data quality control. The software has the necessary routines to look at the waveform data, calculate the necessary timing corrections, and apply the corrections. Once this is done the PI is in the position to write a SEED volume which can be archived at the DMC. In addition to SEED the system can output data in a series of formats that can be used in analysis, including the ability to directly import the data into the database system developed by the JSP Center at the University of Colorado.

For most active source experiments, data are sorted into shot gathers and written to tape in conventional SEGY format for input into conventional seismic processing systems.

Why has the PASSCAL instrument been successful?

The success of the PASSCAL instrumentation can be traced to a handful of design features.

- *Standardization.* One may argue any instrument IRIS might have chosen for the PASSCAL instrument would have succeeded because of its application in a shared facility. The centralization of hardware and software maintenance assures a consistent, reliable instrument will be available for field deployment.
- *Use of industry standards.* The resources available to seismology pale in comparison to the resources devoted to the development of modern computer hardware. PASSCAL has ridden the wave of modern technology and benefitted from it in three major areas: (1) The SCSI interface on the instrument allowed constant upgrades in recording technology as disk drive technology advanced at a staggering pace in the past five years. (2) We are taking computers and associated peripherals into the field today that we would have called supercomputers slightly over a decade ago. (3) The auxiliary communication devices we use to communicate with the digitizer are commercial palmtop PC devices or small touch screen portable computers used in various commercial applications.
- *Low power = portability.* The best sites for seismic data collection are usually at remote locations where AC power is not necessarily available. For this reason, a key design feature of the original instrument was that it be low enough power to be deployed without AC power.
- *Modularity.* A modular instrument design allowed major upgrades to these instruments including: (1) conversion from 16-bit to 24-bit digitizers, (2) adaptability to new disk drive technology as it evolved, and (3) changes in clocks from GOES to Omega to GPS.
- *Flexibility.* The PASSCAL instrument was to be the ultimate portable instrument that could record any type of seismic data anyone could conceive. Reality has limited the scope, yet these instruments have repeatedly demonstrated remarkable flexibility. The same instruments have been used for experiments ranging from broadband teleseismic array experiments with sensors spaced at 100 km to active source experiments with sensors spaced on the scale of tens of meters. The range of options from sample rate, to triggering method, record length, etc. is remarkable. The present instrument is truly close to that ultimate instrument that was originally envisioned. In fact, it has exceeded the original concepts in a number of ways (e.g. adaptability to telemetry).

Pressures on the facility

PASSCAL currently maintains a stable of more than 400 instruments providing more than 1500 channels of portable, digital seismic recording systems. Use of the instruments is predicated on a two-step process: (1) securing funding for the experimental program, and (2) scheduling the instruments. The first is achieved through the standard peer review system of the National Science Foundation and other funding agencies. The second is accomplished by IRIS through a scheduling committee that resolves conflicts of experiment schedules and allocates instrumentation.

In the past seven years more than 80 PIs have conducted major PASSCAL experiments. Figure 4 shows the institutions represented by these PIs. Over 50 percent of the PIs conducted more than one experiment and 10 were involved in four or more experiments.

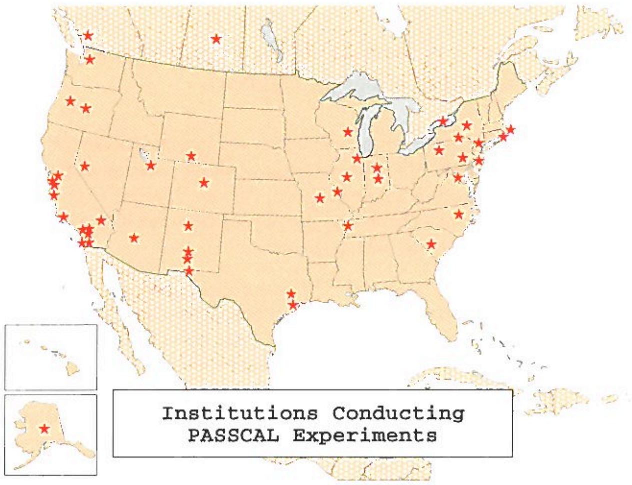


Figure 4

Clear evidence of the continuous, strong pressure on the availability of instrumentation can be seen in Figures 5 and 6. Instruments are nearly always in the field recording data; in transit between experiments; or in the lab for maintenance or repair. This is especially true for the broadband instruments (Figure 5) The only significant period when these instruments were not in almost 100 percent usage was early 1994 when all were cycled through the instrument center for upgrade from 16- to 24-bit digitizers.

The usage shown in the figure beyond the current date (5/1/95) is based on experiments already funded by NSF alone. Note that in the summer of 1997 there are only about 20 instruments available for experiments submitted for the June 1, 1995 NSF deadline. It is highly likely there will be none available until 1998 after that round of proposals is processed. For the past several years, the waiting time before a PI can take a broadband experiment to the field has been between 1.5 and 2 years from the time funding was received. Since NSF funded projects have first priority in the instrument allocation process, it has now become almost impossible for experiments not funded by NSF to obtain broadband sensors.

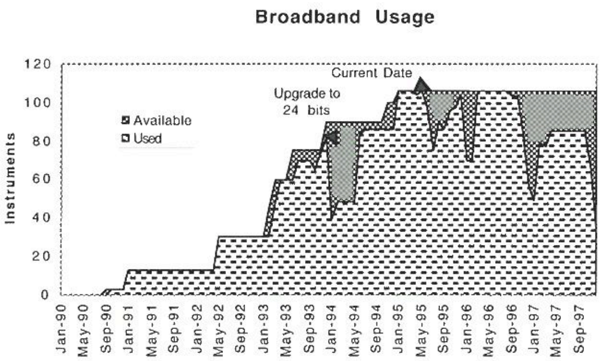


Figure 5

One of the biggest challenges to PASSCAL in the past five years resulted from the rapid evolution of the broadband array experiment. At the beginning of the current NSF-IRIS Cooperative Agreement, Guralp and Streckeisen had only recently introduced prototype sensors that seemed promising for portable, broadband deployments. The 1991 IRIS proposal requested funds for approximately 100 of these sensors. The exciting ideas emerging from this experimental field puts extreme pressures on the facility. There are similar demands from active source experiments for an increasing number of channels. This parallels the historical development of seismic data acquisition methodologies in the oil industry, most easily seen in multichannel reflection data. Standard numbers of channels in data acquisition grew from 24 channels in the early 1960s, to 120-plus channels in the 1970s, to 1000-plus in the 1980s.

How many instruments are needed?

Figures 5 and 6 make it clear that usage of the current facility is saturated. Discussions with IRIS members (especially PI's involved in field experiments) and NSF Program Managers, along with input from Standing Committees and Workshops have made it abundantly clear that more instruments are required. High quality proposals, especially for broadband deployments, are turned down or significantly delayed because of insufficient instruments. Most active source experiments and some broadband experiments are deployed with significantly fewer instruments than considered optimal.

While it is clear that more instruments are required, questions remain as to how many additional instruments can be used effectively and what types' of instruments should be acquired. The answers to these questions lie in a mixture of delicate and complex issues, some of which are appropriate for IRIS input, some of which require consideration by science programs at NSF. Among the more crucial issues are the balance between facilities for passive

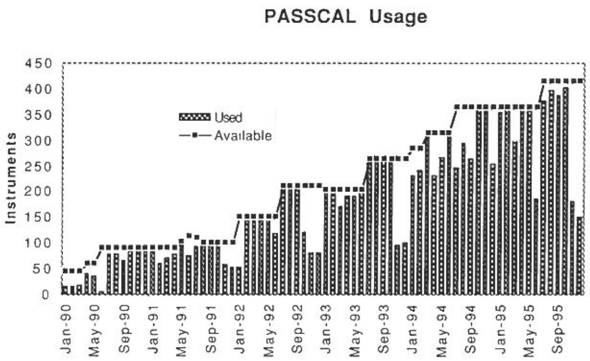


Figure 6

and active source experiments and the balance of resource allocation at NSF between acquisition of hardware and support of experiments.

Over the past year, IRIS has used a number of forums (Standing Committee discussions, annual IRIS Workshops, the ILIAD meeting, the JSP array studies group) to involve the research community in discussion of the range of experiments that PASSCAL should be prepared to support and the instrument complement required. We present the following summary of these discussions:

Long-term passive deployments

These experiments, for studies of deep Earth structure and earthquake sources, typically consist of 10's of instruments with broadband sensors, deployed in stationary configurations for periods of a few months up to 2 years. The current REFTEK instruments are well-suited for this type of experiment. Most experiments would prefer more instruments than can be provided from the current inventory. Communications capability to provide remote access to data will greatly improve the efficiency and utility of these deployments.

Proposed inventory - Upwards of 250 instruments, consisting of a mix of current design 6-channel and 3-channel REFTEKs with broadband or intermediate period sensors, could be continuously utilized in an average of 5 - 10 concurrent long-term deployments of 10 to 50 instruments each. Currently there are 120 of these systems available.

Active source experiments

There is a critical need for additional channels, in instruments that are easy to deploy and move, for crustal and lithospheric imaging using active sources. These controlled source experiments combine a variety of techniques, including common-depth-point (CDP), near vertical reflections; wide angle refections; and refraction. In large scale experiments, commercial multi-channel recording systems are sometimes contracted for CDP acquisition, and we anticipate that this mode of data collection will continue to be supported by NSF. The primary use for PASSCAL instruments is to augment the multi-channel systems in large scale experiments; as the primary data acquisition system in moderate scale reflection experiments; and especially for the acquisition of wide angle reflection and refraction data. The total number of channels that PASSCAL now has available (>1500), when used in conjunction with the 350 additional channels provided the SGR and Canadian recorders, would satisfy all but the largest active source experiments. However, because of scheduling conflicts with long-term passive experiments, the full complement on instruments is unlikely to ever be available at the same time. In addition, experience with the use of the current REFTEK instruments has shown that their complexity and size presents problems in active source deployments. The data characteristics of the current 3-channel PASSCAL instruments satisfy the technical requirement for all modes of deployment and are well-suited for the collection of 3-component data. However, they are difficult to use in configurations that require frequent re-positioning of sensors and the laying of long cables in roll-along deployments. A simple, single-channel instrument would be much better suited for most active source applications.

Proposed inventory - One thousand channels, based on simple, highly mobile, single channel data loggers, should form the core of a facility to support active source reflection and refraction studies. A few moderate size experiments each year would make use of all of these instruments, plus a number of 3-channel instruments, in deployments lasting more than a month. Additional smaller scale, shorter term experiments could use subsets of this inventory. Infrequent, very large scale experiments would use all of these instruments, plus multi-channel data acquisition systems contracted from industry sources, in integrated multi-disciplinary, multi-institutional (and often international) experiments of the type supported by the NSF Continental Dynamics Program. Only with this number of instruments will it be possible, for the first time, to support true 3-D investigations of the lithosphere using dense, 2-dimensional grids of sensors - a long standing goal of the active source community. While it is unlikely that the year-round utilization of these instruments in short-term experiments will be as high as for the broadband instruments in long-term deployments, issues of scheduling and efficiency require a dedicated core of instruments for active source applications.

Array studies

We foresee an increasing application of advanced array techniques in studies of seismicity, regional wave propagation and deep Earth structure, either as independent experiments or as adjuncts to long-term broadband deployments. The optimal number of elements in a multi-dimensional, broadband phased array is on the order of 20-30 (see Array section in Part III this proposal). We also see the opportunity for PASSCAL developments in array technology to be incorporated in regional networks, in the US or elsewhere, for studies of seismicity.

Proposed inventory - The development of an array capability for PASSCAL requires only the acquisition of radio equipment and central recording systems (data concentrators). Existing sensors and standard REFTEK data acquisition systems can be utilized as independent stations or array elements, depending on experimental requirements. With the development of a new specialized instrument for short-term active experiments, increasing numbers of existing 3-channel instruments could be made available for use in up to 6 arrays of 20 elements each.

Shallow Imaging

Reflection surveys over shallow geologic targets will play an increasingly important role in seismology in support of research directed at a variety of environmental geophysics and active tectonics problems. These experiments may become especially important in training graduate students, especially at the master's level, for careers in environmental geophysics. A section on Shallow Imaging in Part III describes some of these applications in more detail and outlines an extended PASSCAL facility for multi-channel reflection equipment

Proposed Inventory - IRIS has recently received an award from the DOE program in Basic Energy Sciences for the acquisition of two 60-channel data acquisition systems and associated sensors and cables. These will form the initial core of a PASSCAL facility for shallow imaging. These instruments will be available for both focused studies of the shallow crust and as augmentation for experiments in active source lithospheric imaging. We do not propose that PASSCAL acquire sufficient instrumentation to satisfy all of the demands by the university community for shallow imaging, but rather that we act to stimulate interest in this field, encourage acquisition of multi-channel systems by individual universities and coordinate the use and exchange of this equipment throughout the research community. After 1-2 years of experience with the use of the DOE-initiated facility, in both shallow imaging and deep crustal studies, there should be an evaluation of the use of this type of equipment and, within the flexibility of the PASSCAL instrument budget, a decision made on the relative balance of acquisition of multi-channel systems and the new single-channel PASSCAL instruments.

RAMP

PASSCAL now has ten 6-channel instruments dedicated for rapid response to record aftershocks of significant large earthquakes. Experience in numerous deployments, especially the Loma Prieta, Landers and Northridge events, has confirmed the value of this investment and has clearly shown how the facility could be improved if telemetry were available. The development path we are taking in array development is especially appropriate for the RAMP application. Instruments can be quickly deployed in stand-alone mode immediately following an earthquake and then simply upgraded to telemetry mode with the addition of radio transmitters or modems for more stable and efficient observations, after the initial pressures of immediate post earthquake deployment have subsided.

Proposed inventory - Highest priority should be given to acquiring the array components necessary to upgrade the existing 10 RAMP instruments to telemetry status. If funds permit, an additional 10 instruments should be acquired to provide a full 20-element array configuration.

Priorities for Acquisition and Development

Based on experience in operations over the past 5 years and projections for future usage, we therefore identify the following priorities for PASSCAL instrument acquisition and development over the next five years:

Additional channels - The original IRIS proposal called for a PASSCAL array of 1000 general-purpose, multi-channel instruments. In the second 5-year plan, this goal was specified as 6000 channels. The current inventory provides less than one half of these goals in terms of numbers of instruments and one quarter in terms of channel capacity. With the unanticipated growth of long-term broadband deployments, there is intense pressure to provide additional channels, especially for active source experiments.

Simple instruments - The flexibility of the current generation of instruments has served well in longer-term deployments and has been key in the development of innovative new techniques and experimental designs. It has become clear, however, that a new instrument design, acquired in significant quantities, is needed to meet the specific requirements of rapid mobility and simplicity in controlled source experiments.

Enhanced telemetry - The efficiency and utility of long-term deployments of broadband instruments will be greatly improved with remote communications to provide access to data and state-of-health information. Radio telemetry in local arrays and networks greatly simplifies data management and provides enhanced opportunities in studies of the seismic wavefield and seismicity.

New generation instrument - By the end of the five year period covered by this proposal, the current REFTEK instruments will be based on technology more than 15 years old. To insure the long term health of the program, it is essential that an investment be made in the development of a new generation of instruments.

In the next section we present a plan which, through evolution of the current facility and development and incorporation of new instrumentation, responds to these priorities.

The Next Five Years

Overview

We propose a natural evolution of the PASSCAL facility that we believe is a cost-effective strategy to fill existing and future demands and to begin the process of moving toward a new generation of instrumentation. The overall plan has four fundamental elements:

- Maintaining and improving the current facility.
- A modest development effort directed at a specialized instrument for active source experiments significantly reducing the cost per channel. Because of the envisioned size of this instrument, we refer to it as the "Walkman Seismograph".
- Development of array systems and other telemetry hardware with the expectation that existing three-channel PASSCAL instruments will evolve to be used mainly in passive array experiments. This transition will occur as lower cost Walkman Seismographs become available as a replacement in active source studies.
- A focused instrument development is proposed in the fourth and fifth years of this program to create a new-generation PASSCAL instrument.

Operation and Maintenance

Given the remarkable success of the existing pool of instruments from PASSCAL, the first order of business for the next five years is the continued operation, maintenance, and upgrading of the current instrument pool. The cost is not negligible, however, because this requires funds to support existing instrument centers at approximately the current levels.

As noted above, the modularity of existing instruments allowed us to extend their lifetimes because we were able to upgrade the instrument as new technologies became available. Furthermore, inventory-wide upgrades are necessary to keep the instruments in a standard configuration. This makes it possible to field large numbers of instruments without serious worries about whether all the instruments have the same configuration. We need to continue these upgrades. This will ensure the PIs will record data of the highest quality. The cost of upgrades, however, is not negligible. A simple modification to a unit that costs only $500.00 and takes three hours may seem trivial. But when 400 instruments are involved this becomes a $200,000.00 job that takes 30 person weeks to complete and has a strong impact on operations at the instrument centers. We do not anticipate any major upgrades such as the upgrade to 24 bit digitizers, but there will probably be several minor upgrades necessary to keep units current. These are budgeted as part of the Operations and Maintenance costs.

The software development effort within PASSCAL will continue. The effort will be directed toward improving the experiment control, field QC and initial archive of the data. PASSCAL will work with the DMS to ensure data can flow seamlessly from the field computer to the data archive at the DMC.

New Instrumentation

The Walkman seismograph

The current three-channel instrument was designed as a simple tool that could be used in reflection/refraction experiments as well as in passive experiments. As such it has performed very well. It has been used in traditional refraction experiments, on-shore/off-shore experiments and passive experiments. However, the active source community has continually advocated the need for a smaller, simpler instrument that is functionally similar to the SGR instruments presently maintained at the Stanford instrument center. The "Walkman seismograph" is conceived as a modern-day SGR. It would be capable of sitting on the ground for several days, being activated by radio command or at a preset time and recording a set time window. The instrument should weigh no more than a few pounds. While there are many additional features that would make this more versatile and usable for other types of operations, the goal is to keep the system cheap, holding the total cost for sensor and recorder down to about $1,000 per channel.

There are several groups presently building prototypes of this instrument. The motivation for these developments is the oil and gas industry, which has a need for this type of instrumentation for land 3D seismic reflection data acquisition. We plan to evaluate something similar to the "Walkman" as early as the summer of 1995. We believe it will be possible to begin acquiring this type of instrument during the first year of the new cooperative agreement. Because other market forces are driving this development, however, the proposed budget contains development money in the first two years to modify the instrument for the increased functionality that may be necessary in PASSCAL applications. In particular, 3D reflection arrays are usually small enough that radio rather than time turn ons are used. We anticipate a possible need to develop a timed turn-on module for this new instrument.

Shallow imaging

A second example of simpler instruments with a lower cost-per-channel is the new generation of multi-channel instruments developed by a number of companies primarily for shallow reflection surveys. Seismic reflection instrumentation has traditionally been a low priority for PASSCAL, because reflection acquisition at conventional scales is done more efficiently by industrial contractors. Shallow, high-resolution seismic reflection is, however, a different story. Because of the small scale and the fact that shallow seismic sources are not expensive to operate, high-resolution experiments are possible on low budgets, with small numbers of personnel.

With recent DOE funding of two, 60-channel, high-resolution, multichannel systems, PASSCAL will soon have some capability in this area.. This will strengthen the overall PASSCAL program in several ways.

These facilities will increase the number of channels available to the active source community. The same systems can be used for larger scale experiments by using cables with much wider sensor spacings than those used for shallow investigations.

High-resolution equipment has strong potential for reducing costs of basic physics experiments designed to understand fundamentals of wave propagation in a three-dimensional, heterogeneous Earth. Shallow experiments can utilize real, natural laboratories to test hypotheses related to seismic wave phenomena while working on a scale that is far cheaper and easier to deal with than crustal scale phenomena.

Experiments in shallow imaging are important as a basic training tool for earth scientists in a range of disciplines. In particular, students pursuing careers in environmental science will profit greatly from access to state-of-the-art seismic instrumentation of this type.

For these reasons, we believe that the maintenance of these instruments and development of a core facility of multi-channel shallow reflection equipment is justified as part of the NSF support of PASSCAL. The relative mix of acquisition of multi-channel recorders and simple single-channel instruments will develop based on experience with the DOE equipment and the proposed "Walkman seismograph".

Telemetry and Arrays

Developments over the past five years put the PASSCAL program in a strong position to change the communications capabilities of the instruments. A clear lesson from the past five years with passive array deployments is that some level of communications with individual instruments is necessary.

Communication with a remote site allows the PI to optimize the number of service trips. The large disk capacity possible today make it possible to visit the sites very seldom. However, without feedback on station performance the PI is usually inclined to schedule service runs more often than necessary.

Real-time telemetry within closely spaced arrays would make it possible to eliminate two of the most time-consumming processes in data quality control. First, timing would be broadcast from the central facility, so all data have the same relative time. Second, the data wsould be transmitted to the central facility in real-time and stored on the disk in time sort order. Therefore, it would not be necessary to perform the large sorts necessary to go from station order to time sort order.

As noted above, we now have functional communications capabilities with instruments of three levels of sophistication:

- ARGOS global, low-data-rate state-of-health telemetry
- Dialup communication
- Continuous, digital telemetry through wire or radio links to a central data concentrator

A major goal of PASSCAL is that by the year 2000 every three-channel and six-channel digitizer will be able to communicate by some mechanism with the field computer(s) associated with that experiment. We expect this to be achieved by one of the above three capabilities, but it could encompass a range of new emerging technologies like global cellular phone communications.

We stress that solutions for all three of the above communications options already exist. They are not, however, all at the same level of completeness. Known development efforts we foresee at this time are:

- A second generation of ARGOS satellites will allow expanded state-of-health information and two-way communications. We will continue to upgrade our capabilities to take advantages of these new systems.
- Dial-up has yet to be tested using cellular telephone circuits, a fundamental concern for applications within the United States. We will continue to expand the capabilities of this form of communications to take advantage of cellular phones and the new proposed world-wide satellite base systems.
- A complete digital telemetry exists, but it currently has one serious weakness: radio telemetry requires an FCC license. As noted above the wireless computer network communications market is pushing the development of a new generation of spread-spectrum radios that do not require an FCC license. This technology is in the process of being integrated into the array telemetry system through the 1995 DOD-supported Joint Seismic Program.

We expect that by the start of the new cooperative agreement the above functionality will be close to completion. Nonetheless, because of the complexity of some of these developments we have budgeted some funds for incremental developments of these systems over the first two years. This and the "walkman seismograph" development cost are lumped together in the proposed budget under the "Instrument Development" line of the subcontract section at a combined cost of $100,000 for each of the first two years.

The proposed budget would upgrade the communications capabilities of the present instrument pool as follows:

- Acquire 170 single station telemetry systems composed of a mix of ARGOS Stage I or II and phone dialup systems. The actual mix of systems will be driven by requirements of experiments that PASSCAL will need to support over the next five years and by the speed at which these services come on-line. This appears in the proposed budget under "Telemetry". Acquiring 170 such systems would allow all six-channel instruments to be equipped with this type of telemetry.

- Acquire hardware for six 20-element array systems. This involves purchase of the following hardware:
  - Radio communications equipment for each array station
  - Data concentrator hardware for each array system
  - Field computers to run real-time processing at the central site for each of the six array systems

The acquisition systems to be used for these array systems would come from the current pool of three-channel instruments. Thus, under the proposed budget by the year 2000 we would have 120 instruments (360 channels) of instruments that would be capable of being deployed as full-blown array systems. These could be deployed in a range of actual configurations. Each concentrator is presently capable of handling at least 50 stations at 250 sps. Thus, a given experiment could use a varied mix of array configurations from only three or four stations per concentrator to as many as 50.

The new technology that makes extensive use of telemetry along with a projected growth in the pool of instruments will necessitate staging a new instrument center early in the next five-year agreement. This is reflected in the proposed budget by a fraction of one year of support for this center in 1996 with full support each year after that. This is necessary for two reasons. First, the current instrument centers are close to capacity. Second, special expertise in communications will be important for the new center. To reduce the overall operational costs the expertise is best concentrated in one location to reduce duplication of highly paid specialists.

Under the base budget we plan to acquire the hardware to support six different array systems. Recognizing the potential demand we may find for operating both active and passive experiments in this mode, we are submitting two "add-on" budgets labeled "Array Expansion" and "RAMP expansion". The former would double the number of array systems from the base budget. The latter would add one array system for use in RAMP deployments.

A RAMP array could prove valuable in recording seismic data following a major earthquake. Real-time telemetry capabilities would be invaluable in refining array geometry to understand an aftershock sequence as it evolved. We envision a use of arrays in a RAMP deployment were stations would be initially brought up as standalone stations to begin acquiring data as quickly as possible. Once the central recording hardware was in place, stations could be converted to real-time telemetry capabilities. We emphasize again that because of the flexibility of the PASSCAL instrument, this is only a software change, and can be accomplished quickly.

New generation PASSCAL instrument - the Seismic Wide Area Network (SWAN)

The PASSCAL instruments have served us well, and we expect them to continue to be a central component of the PASSCAL facilities well into the next century. However, any instrument, no matter how modular and flexible it is, will eventually become technologically obsolete. By the year 2000 the current instrument will be nearly 15 years old. Given the staggering rate of change of computer hardware, and the fact the instrument is fundamentally a small computer, by 2000 this instrument will be technologically obsolescent. To continue to acquire these instruments beyond that date is clearly ill advised.

Recognizing this inevitability, we are proposing a three-fold evolution into a new technology. The first two were noted above: (1) acquisition of a new generation of SGR-type instruments (the "Walkman seismograph"); and (2) extensive conversion of existing instrumentation to utilize a range of telemetry options. The third is development of a new generation, flexible, modular instrument to serve as a replacement for the existing instrument.

It is important to stage the evolution of the facilities in this way for several reasons:

- Acquiring inexpensive "Walkman" seismograph systems will provide a cost-effective way to build the pool of instruments for active-source experiments and simultaneously move that part of the facility into a more up-to-date technology.

- The development of this communication technology within the existing instrumentation will help us refine the functional requirements of such a system in real-life applications.

- The seismological community needs time to adapt its experimental plans to this emerging technology. Plans and budgets will change with changes in communications technology.

- The evolutionary change to the existing equipment will make it compatible with our vision of future instruments.

Digital communications technology is developing extremely rapidly. More cost-effective communications technologies may evolve in the next two years that could have a huge impact on the next generation PASSCAL instrument.

Given the rate of change of computer technology, we cannot present detailed technical specifications of what the next generation instrument might be. We can, however, describe major functional capabilities we conceive in this new instrument and how these relate to the existing facilities:

- The instrument must be able to operate in a standalone station mode;
- It must support dialup communications;
- It must be able to operate with real-time, digital telemetry;
- The new instrument should have technical specifications (i.e. power consumption, bandwidth, noise level, etc.) comparable to or superior to existing instrumentation; and
- A new instrument should run a standard, commercial operating system to reduce software development costs.

The vision we have of where the new generation instrument will take us is encapsulated in the new acronym SWAN (Seismic Wide Area Network). The SWAN concept has these basic elements:

- Every station possible has an appropriate communication link to the PI's central field computer.
- The PI's view of an experiment will be as a network of remote computers. It will be possible to interact with each station by methods comparable to those we are now all familiar with through the Internet.
- Stations would interact with the central field computer site by standard protocols based on the well defined IEEE computer network model.

Current-generation instruments will be capable of performing these functions after the telemetry and arrays developments discussed above are complete. Thus SWAN will begin with these developments. We expect to develop the software on field computers that perform the kinds of automated experimental status functions above that are independent of the type of actual data logger. Thus, when a new instrument is developed the changeover would not induce a huge software revision. We note this development will need to be done in collaboration with the GSN and DMS programs and possibly with regional seismic network operators as well. All share a need to reduce operational costs that involve a common theme: site visits cost money in travel and personnel costs, and automated, remote monitoring of station state-of-health is an obvious way to reduce these costs.

We have budgeted $500,000 in each of the last two years of this proposal to develop the new generation PASSCAL instrument. This is comparable to the costs accrued in development of the current instrument. The expectation is that by the end of this five-year agreement, we would have tested a set of prototypes and would be prepared to begin acquiring these new instruments under the following five-year agreement.

Sensors

The new generation of broadband seismometers is revolutionizing seismology, and we are having difficulty supplying instrumentation for NSF-sponsored broadband experiments. A high priority is to acquire as many new broadband systems as we can afford. The fundamental problem we face, however, is the relatively high cost of the sensors themselves: $12,000 to $16,000 per station.

One solution may lie in recently developed, low-cost intermediate period sensors. Existing broadband sensors in the facility can resolve ground noise at the quietest sites down to 30 to 100 s periods. Guralp recently introduced a new, cheaper sensor (CMG-40T) that resolves ground noise from 0.1 to 50 Hz. This sensor could resolve larger signals below 0.1 Hz, but it would not be capable of resolving ground noise at quiet sites and thus would only record lower frequencies from events large enough to exceed the instrument noise floor.

The importance of this development to PASSCAL is that these new sensors are roughly half the cost of current broadband sensors (approximately $7,000 a set). We intend to focus sensor purchases on this new class of sensors for three reasons.

Many experiments currently utilizing broadband sensors could achieve the same objectives with these new intermediate period sensors. Most experiments utilizing teleseismic body waves focus on the 0.1 to 1 Hz band.

Some sites in portable deployments are of necessity stuck at relatively noisy locations. For these sites, the higher system noise levels of these less expensive sensors are not an issue.

As the community makes more effective use of arrays, intermediate sensors can span the range of scales between existing broadband sensors and existing high-frequency sensors.

Summary of specific activities proposed

With the intense pressure on the existing facilities, we must go as far as possible in adding new instrumentation to relieve these pressures. As noted above, after development is completed we expect to acquire a significant number (1050 channels) of "Walkman" seismograph systems (See Figure 7). These expand the pool of available instruments significantly at one-third the cost of three-channel PASSCAL instruments. However, we reiterate these simple instruments are specialized, and will not replace the three-channel or six-channel PASSCAL instruments for most experiments. Therefore, we also plan a modest growth of the three-channel and six-channel instrument pool along with an appropriate mix of new sensors.

The basic PASSCAL budget as submitted here calls for the following breakdown in terms of categories:

Category	Percentage of Budget
Operations and Maintenance	55%
Short Period Equipment	15%
Broadband Equipment	14%
Array Hardware	6%
Development	5%
Management and Committees	4%
RAMP	1%

Under the proposed budget we plan to acquire 10 new six-channel instruments each year for the next five years. This would produce a total pool of 170 six-channel instruments by 2001. Three-channel instruments would be acquired at a different rate because of the emergence of the new simple (Walkman-type) instrument. We plan to acquire 50 new three-channel units in 1996, and a total of 50 more in the succeeding four years. This would yield a total pool of 390 three-channel instruments in 2001. This would roughly double the total number of recording channels from 1590 at present to 3360. At the end of this five-year period a broad and flexible instrument pool consisting of approximately 150 broadband instruments, 150 intermediate period instruments, 390 3-channel instruments that can be used for both passive and active source experiments and over 1,000 "Walkman" systems. The facility will have the capability of fielding six real-time arrays and telemetry for individual stations will be possible where communications exists. The community will also have a second-generation data acquisition system and will be poised to take advantage of this new technology during the next five-year cycle.

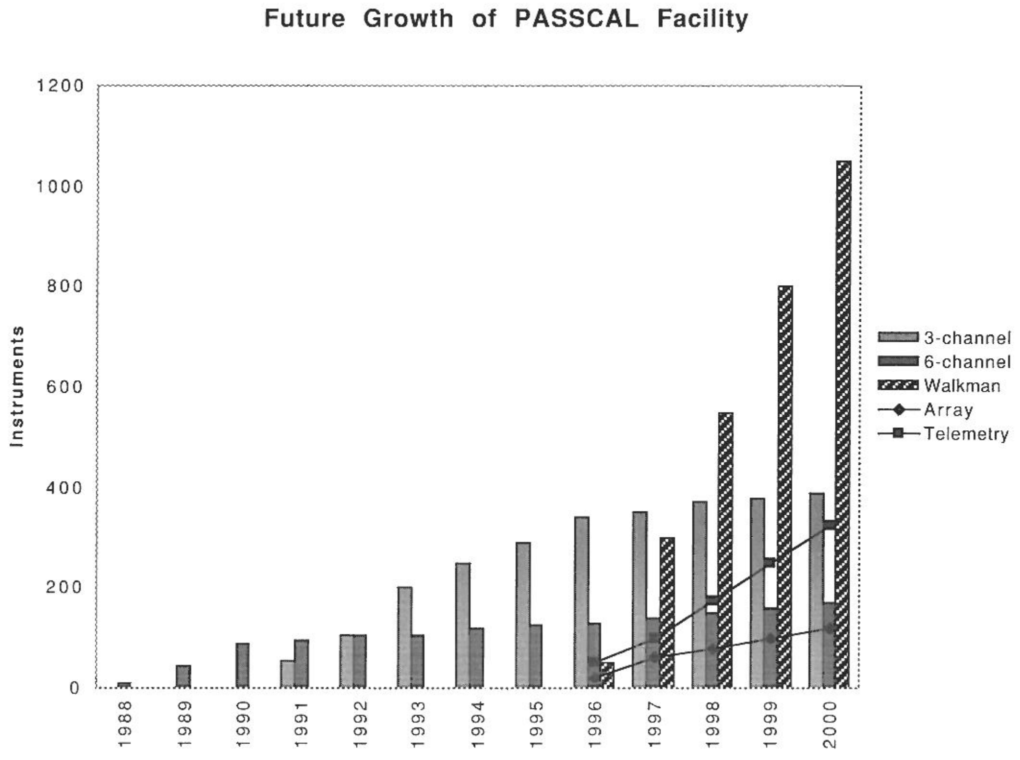


Figure 7

The IRIS Data Management System

Its Evolution, Present Status, and Proposed Direction

Introduction

Over the past seven years, the IRIS archive at the Data Management Center in Seattle has become the resource of choice for seismologists wishing to collect seismic data for studies of the Earth's deep interior and earthquake sources. The archive provides access to information gathered during temporary deployments of the IRIS PASSCAL program, by the permanent stations of the IRIS Global Seismographic Network and cooperating members of the Federation of Digital Seismographic Networks, as well as important data from earlier digital networks operated by the United States Geological Survey. Equipped with efficient access methods, it is the largest collection of seismic waveform data of its type in the world.

Within hours, seismologists can retrieve full waveforms from significant earthquakes recorded at dozens of sites around the globe. Users can query the archive interactively to provide information on earthquakes and stations and to develop customized collections of waveform data to support individual research projects. Collaborative efforts between the DMC, its data suppliers and its data requesters have led to standards for the exchange of data and for quality control procedures. The IRIS Data Management System also coordinates distribution and sometimes development of software to ease routine processes of calibrating and displaying waveforms.

With a well-exercised archive now in place, the DMS is poised to support the research community by providing enhanced information services and broadening the types of data it provides. We propose the following:

- To maintain the current archival facility, receiving data from our present sources and servicing requests from users worldwide. If the past can be taken as a guide, both inward and outward dataflow will continue to increase, as will the size of the archive.
- To work closely with other groups, such as the National Earthquake Information Center, U.S. regional networks and international bodies, to provide improved access to waveforms and derived data such as catalogs and moment tensor solutions to aid in the research and monitoring of national and global earthquake hazards.
- To enhance support of data collected in field experiments by the IRIS PASSCAL program. Considerable progress is necessary to make these data as accessible to researchers as are data from permanent stations.
- To apply modern telemetry techniques, as they become economically feasible, to provide rapid access to data from both permanent and temporary stations.
- To coordinate the development, distribution and support of software so large modern digital data sets can be used more efficiently.

The best way to become acquainted with DMS services is to log in and browse the data base. There are two ways to do this, either via the WWW home page (http://dmc.iris.washington.edu/) or through a bulletin board interface (rlogin to dmc.iris.washington.edu as user bulletin using password board).

The Past 10 Years of the IRIS DMS

A key component in the initial IRIS proposal to NSF, was a Data Management Center responsible for long-term archival and distribution of IRIS-generated seismic data. Although some elements of the seismological community possessed the capability to manage large data sets locally, the IRIS founders realized that the amount of data produced by the GSN and PASSCAL programs would far exceed the capacity of most, if not all, IRIS universities. In the mid 1980s, the projected data volumes exceeded the capacity of all economically viable mass storage systems. At the birth of IRIS, the need for a Data Management System was clear, but its precise form was forced to await advances in technology.

In 1986 the IRIS Data Management Center was created and the first program manager hired. Under the direction of the DMS Standing Committee, two significant design studies of the key elements for a successful DMC were initiated. A number of recommendations emerged from these studies. Because seismologists typically require data related to particular events (a time sort) or particular stations or regions (station sort) the studies recommended storing every sample of seismic data twice, in both time-sorted and station-sorted orders to ensure most requests could be serviced efficiently. Because large quantities of data were involved, the second recommendation was to establish a network Data Base Management System (DBMS) that would be more efficient than the more popular relational DBMS model. The initial design studies also reviewed the anticipated rates of data ingestion at the DMC and the number and characteristics of typical data requests by the scientific community. While the data ingestion estimates proved accurate, the data requests were greatly underestimated. Data shipments currently exceed 1987 estimates by a factor of 200.

In many ways, the DMS has evolved and expanded more than other IRIS programs. The initial concept for the DMC specified a limited and essentially passive data archive. There was skepticism that a single center could archive and process the amounts of data generated by IRIS programs and whether managing a data center was an appropriate IRIS task. Controversy over the appropriate role for the DMC continued until the archive became functional in 1988 and customized user requests became possible in the following year.

The Data Management System that evolved over the past seven years proves that maintenance of a full data archive is not only possible, but essential. With close cooperation from national and international partners, the DMS has expanded to become the dominant source of broadband seismic waveform data in the world. Strongly encouraged by the user community, the DMS is evolving towards a "full service" data facility, with emphasis on user support, development of software and hardware tools for data access and processing and collection of additional types of seismic and non-seismic data.

Much of the success of the DMS resulted from our ability to take advantage of recent developments in computer and communications technology, especially in mass storage devices and Internet services. As an IRIS facility separate from its data-collection programs, the DMS is able to concentrate on the best ways of providing documented digital data to a wide spectrum of users, unencumbered by the conflicts of interest that can inhibit institutions with overriding research and/or mission responsibilities. By both example and exhortation, the DMS persuaded many diverse producers of seismic data of the importance and benefits of open scientific exchange. The adoption of common standards and open data exchange are indirect results of DMS activities, but they contributed greatly to the vigor of seismological research.

The IRIS Archive in Seattle, Washington

In a successful data management system, the activities surrounding the maintenance of the archive, while crucial to the integrity of the entire system, should be largely invisible to the user. To populate and maintain the archive, one must apply quality control procedures to the incoming data stream, maintain a parameter database of stations and events, evaluate the structural form of the database itself and maintain the hardware components necessary to store and manipulate data. Most of these background activities take place at the two Data Collection Centers or at the DMC. Surrounding the archive, and more visible to the outside world, are the software tools to access data. The final measure of success is whether these tools are appropriate for the types of requests users make and whether they can evolve in response to changes in both data and user needs. This requires close feedback between the user and the system operator. The advice and input of the IRIS community, through the DMS Standing Committee, has played a significant role in the development of the DMS. By drawing upon the broad knowledge of the seismological community, rather than relying solely on the efforts of its professional staff, DMS services strive to be both efficient and user-friendly.

The heart of the IRIS Data Management System is the Data Management Center in Seattle. Since the Seattle DMC became operational in 1992, the facility has developed a professional staff of nine that operates an array of hardware for data archival, responds to user requests, and develops user services. As it grew, the DMC endeavored to become stable and efficient. Through a phased growth in hardware and personnel in response to growing demands, the DMS increased input and output data flow rates with a minimal increase in funding. For example, in 1991 the IRIS DMC had two data technicians who were responsible for receiving data (at an approximate rate of 144 gigabytes/year) from three data sources. In 1994 the number of data sources had increased to 24 (at a rate of 334 gigabytes per year), yet the number of data technicians increased by only one. Perhaps more significant, the 174 data requests serviced by the DMS in 1991 are projected to grow to more than 30,000 in 1995 and yet only a single data technician has been added. This indicates the cost advantage of coordinated data management. Once facilities and

Data Centers and Networks Contributing Data to the IRIS DMC as of May, 1995

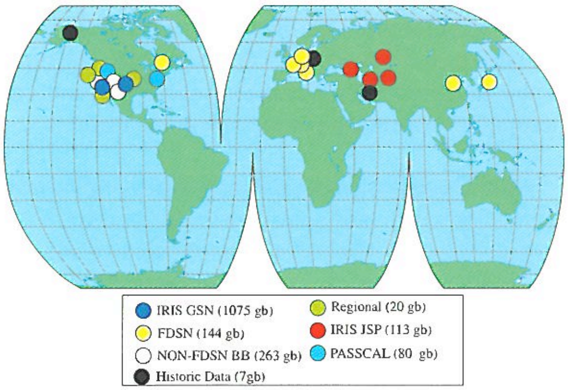


Figure 1. The location of 25 data centers or networks that routinely send waveform data to the IRIS DMC. Figures in parentheses indicate the amount of data that has been sent by each node.

procedures are established, data from a variety of organizations can be made available to the seismological community at a small incremental cost.

The map in Figure 1 shows data centers and networks that contribute to the DMS. The numbers in parentheses indicate data volumes in the mass storage systems at the DMC. There is a total of 1.7 terabytes of compressed data from these networks. Additionally there are several data sets not in the mass storage system but stored on archival tapes. An example is the Apollo Lunar Seismic Data. The IRIS DMC is one of only three locations in the world to possess a complete copy of this dataset. These additional holdings bring the volume of data at the DMC to almost 2.5 terabytes. Figure 2 shows the growth of the data archive.

IRIS and the Federation of Digital Seismographic Networks

IRIS is a founding member of the Federation of Digital Seismographic Networks, an international body whose membership comprises essentially all nations operating broadband seismic networks on regional, national or international scales. The FDSN coordinates activities of its members and encourages cooperation through the development of station siting plans and data exchange standards and techniques. The DMS played an important role in the development and publication of the second and third SEED (Standard for Exchange of Earthquake Data) reference manuals. These manuals are the definitive source of documentation for the SEED data exchange format. In 1990, the IRIS DMC was designated as the FDSN data center for continuous data and all networks operated by FDSN members now contribute continuous waveform data to the FDSN archive at the IRIS DMC.

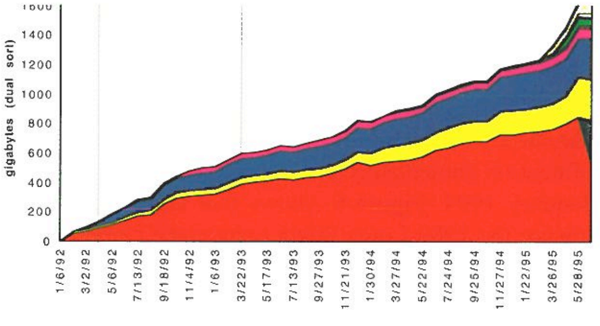


Figure 2. The growth in the archive size at the IRIS DMC. Of particular significance is the increased rate of data ingestion that occurred beginning early in 1995. This resulted primarily from data arriving from new components of the IRIS JSP program as well as data from several FDSN data centers. Data from more than two dozen networks or data centers are now routinely archived at the DMC. The largest contributors in terms of volume are IRIS/USLS (red), IRIS/IDA (blue) and Terrascope (yellow).

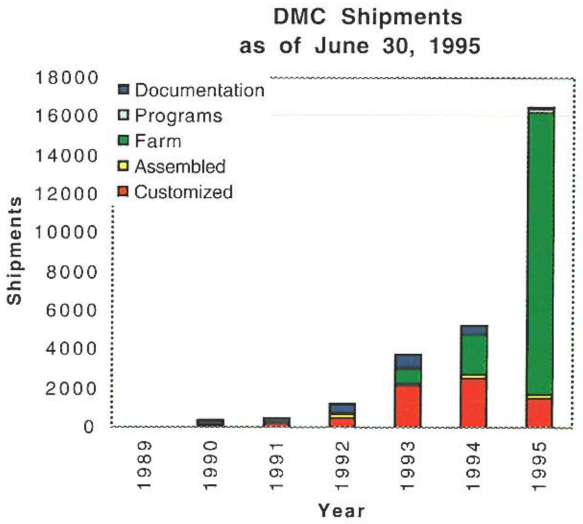


Figure 3. Shipments of data, software and publications. In 1991 the DMC exceeded its originally anticipated annual shipment of data (200). The exponential growth in the output was completely unanticipated but the development of new data distribution techniques has allowed the DMC to actually reduce data delivery time even though the output continues to increase exponentially. More than 35,000 requests are anticipated in 1995, nearly 200 times the original estimate.

One of the primary products of the FDSN is FDSN CDROMs containing data from all FDSN stations for significant earthquakes. After data are received from the FDSN networks, the DMC produces one SEED volume for each event. These SEED volumes are forwarded to the United States Geological Survey where CDROM masters are produced, from which distribution CDROMs are made and distributed to the worldwide community.

The IRIS DMS undertook publication of the first FDSN station book in 1995. This book contains a comprehensive description of all 176 stations in the FDSN network. It has descriptive information, documentation of station instrumentation over time, photographs, summaries of the types of data recorded at a station, noise estimates for all stations, and summary response curves for all channels at each station.

User Tools to Access Data

One measure of the success of the IRIS DMS is the significant number and variety of data requests it services for the seismological community.

The DMS enables seismologists to gain rapid access to seismograms from the terabytes of archived data. Rather than requiring seismologists to expend large resources to assemble the data necessary for a given research problem, the IRIS DMS allows them to expend their energy on science. The growth in the number of data requests attests to the popularity of this concept.

From 1989 until 1993 the demand for data from the DMC increased at an exponential rate. Extrapolations indicated the DMC would not be able to meet the growing demand indefinitely. We noted approximately 85 percent of requests were for data from specific seismic events. This motivated the development of the special event archive called the FARM (see below). In 1993 the number of data requests began to grow dramatically, but far more of these requests are met by the FARM rather than by customized service. Figure 3 shows that through the first half of 1995, more data requests were serviced (16,000) than in the previous six years combined (8,912). Projections for 1995 indicate more than 35,000 data requests will be serviced. The projected volume of data shipped in 1995 is approximately 600 gigabytes, roughly equivalent to the total data generated in 1995 by the IRIS GSN.

There are two basic types of data requests: requests for specific time windows from specified stations and requests for data from earthquakes with specific characteristics, e.g. deep-focus events. The DMC services these requests in one of three ways:

- *Customized requests* allow seismologists to ask for any portion of the seismic data from any part of the two terabytes of data in the archive. Several methods are available for this, ranging from a point-and-click X-window interface over the Internet to database interrogation with the Sprout Structured Query Language (SQL). Customized requests are machine and labor intensive, since prudent data center operation requires individual requests be scanned by a technician and prioritized based on the complexity and size of the request. Seismologists from every organization and from any country are treated with the same priority and yet the DMC has achieved better than 24-hour turnaround for most requests.

- *Assembled data products* are pre-packaged collections of data stored in a variety of formats and usually provided to the user as tape copies with associated documentation. They typically contain data from a single PASSCAL experiment or data from GSN and other permanent stations for a particularly interesting seismic event.

- FARM *(The Fast Archive Recovery Method)* utilizes an on-line assemblage of data sets for all "significant" events, defined as events larger than moment magnitude 5.7 (or 5.5 if deeper than 100 km). These data sets can be obtained via anonymous ftp or via the World Wide Web (WWW). Assembled data sets and FARM products greatly reduce the work required of DMC staff. FARM products typically require no additional work after the initial packaging of the data. Request screening software has been developed to determine if a user's customized request can be serviced more easily by the FARM. If so, a notice is sent to the user and permission sought to redirect the request to the FARM products. This is another example of strategies to improve the efficiency of the IRIS DMS.

There is a wide variety in types of data requests and the way in which users prefer to communicate with the database. The degree of computer connectivity also varies significantly across the user community. For this reason the IRIS DMS developed a variety of methods by which data requests can be made. With all data products in the DMC, complete information about station locations, instrument responses, and documented data problems are contained within the data volumes themselves. The information also can be accessed by a variety of DMS-developed software tools. Figure 4 shows the variety of interfaces developed by the IRIS DMS for seismologists making data requests.

Some of the other resources developed by IRIS to facilitate access to data include the following:

- *SPYDER^{TM}* The DMS SPYDER^{TM} system has evolved into one of the most frequently-accessed systems at the DMC. SPYDER^{TM} was developed and is maintained by personnel at the University of Washington. Responding to triggers from the NEIC, the SPYDER^{TM} system coordinates activities at a large number of international data centers. When an event occurs for which data are desired, e-mail messages are sent to SPYDER^{TM} servers in eight different countries. Stations geographically close to the individual servers are contacted using high speed telephone modems. Data are distributed between server nodes as needed using the Internet. The system employs a great deal of parallelism, cost sharing and international cooperation. Figure 5 shows the connection between SPYDER^{TM} nodes around the world.

The success of the SPYDER^{TM} system was indicated by its utilization immediately after the Northridge earthquake in January 1994. Figure 6. shows that in the two days following the 1989 Loma Prieta earthquake roughly 100 system accesses were made. After Northridge, the SPYDER^{TM} system enjoyed a wider audience. More than 400 system accesses were made in the two days after the event. One professor lectured on the Northridge event to an undergraduate class only two hours after the earthquake occurred, showing data recorded from more than a dozen worldwide stations. Figure 6 also illustrates the international nature of SPYDER^{TM}. The large discontinuity 35 hours after the event resulted primarily from Japanese seismologists accessing the system. The growth of the

SPYDER™ system is driven by improvements in data telemetry. In 1989 only three stations in the entire IRIS GSN were equipped with telemetry. By 1994 data were recovered from nearly 30 stations. By mid 1995, SPYDER™ typically recovered data from nearly 60 stations, many belonging to members of the FDSN other than IRIS.

- *SOD (Standing Order for Data)* Many seismologists have an ongoing interest in well-defined classes of data - for example, events in a certain magnitude range from a particular region, perhaps, to a particular station. SOD allows seismologists to avoid making repeated requests by identifying in advance the characteristics of the data they are interested in. As the data specified in the SOD request arrive at the DMC, they are forwarded to the requester.

- *YODA (Your Own Data Archive)* Often individual researchers have difficulty handling large volumes of data at their home institutions. The first PASSCAL researchers to collect more than one gigabyte of passive-source broadband data discovered weeks or months were necessary to unpack and time-sort their data on workstation magnetic disks. The size of workstation disks has grown since then, but so has the size of the typical PASSCAL experiment. In addition, enterprising GSN-data consumers seek to 'stack' all or a significant portion of the archived data to increase the signal-to-noise of selected wavetrains.The DMS has developed the YODA facility as a method to assist researchers in handling and processing data. Available for a short period of time, YODA has already played a useful role in several experiments. The heart of YODA is a tape-based mass storage system capable of storing 1 terabyte of waveform data in a UNIX file system. Complementing this is a SUN workstation and a variety of tape handling devices such as 4mm DAT drives and 8mm Exabyte drives with robotic tape handling systems. A significant disk buffer of about 30 gigabytes is also available. With YODA the DMS meets the needs of many seismologists with a fairly modest expenditure.

Users of YODA sometimes travel to the Seattle DMC, but some researchers choose to remain at their home institutions and access the facility over the Internet. Both modes work well, depending on the nature of the particular data sets. YODA is an example of the type of facility IRIS can provide to make unnecessary the duplication of large-scale infrastructure at many individual institutions.

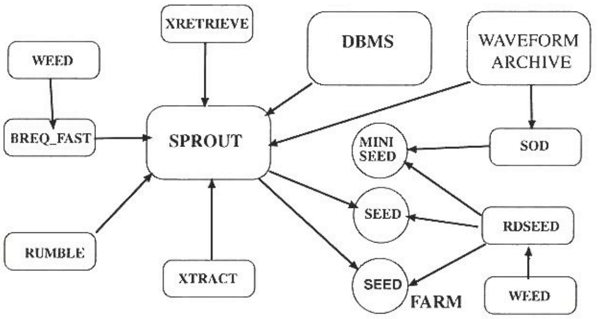


Figure 4. A variety of data request tools have been developed to meet the different needs and resources of our users. BREQ_FAST and RUMBLE are email based tools, XRETRIEVE and XTRACT are GUI tools requiring good Internet connectivity. WEED is a powerful tool run in a client server mode. SOD is a method of requesting data before they are received at the DMC. Most of the growth in DMC output is through the FARM, the DMC on-line collection of data from significant earthquakes.

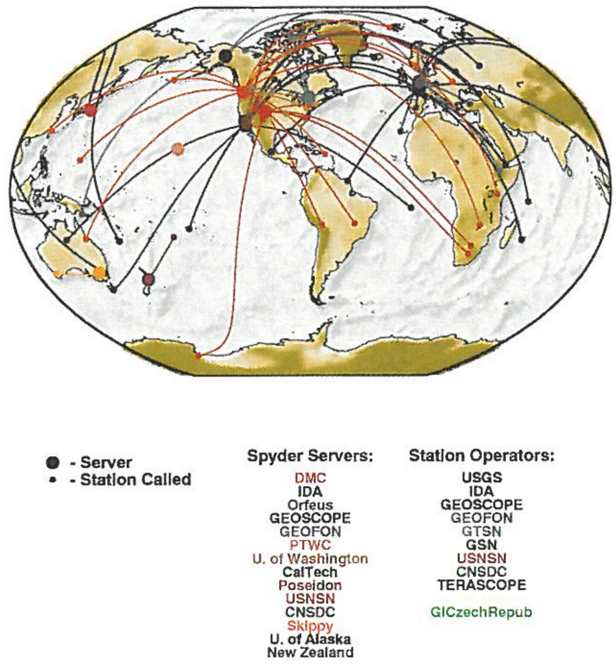


Figure 5. SPYDER™ - A World Wide Web of Connected Data Centers and Seismographic Stations. This figure shows the interconnections between the various Data Centers and seismic stations that participate in the IRIS SPYDER™ system. Up to 60 stations return data, through the web of SPYDER™ servers, to the DMC. Parallel systems in many countries also recover data from regional broadband seismic stations and keep those data at their regional or national data center. SPYDER™ data arriving at the IRIS DMC are retained in Seattle for access by the entire community. Subsets of the total SPYDER™dataset are distributed to a variety of international data centers as requested.

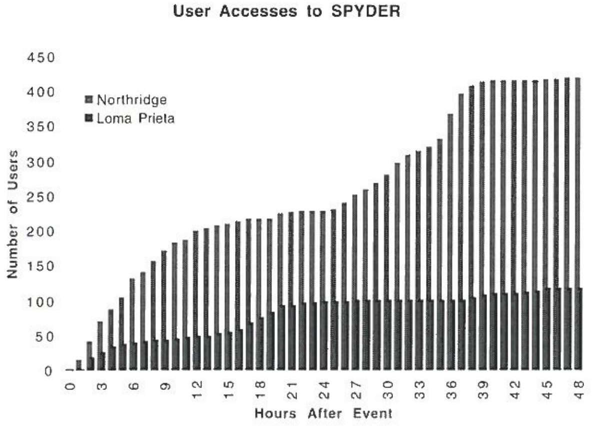


Figure 6. Although SPYDER™ was an important system after the 1989 Loma Prieta earthquake, the use and significance of the SPYDER™ system had increased significantly by 1994 by the time of the Northridge earthquake. The 1989 SPYDER™ system recovered data from only three IRIS GSN stations. The 1994 SPYDER™ system was able to recover data from about 50 stations.

An Overview of The Current Data Management System (DMS)

Significant resources in the past five years were directed toward developing the physical computing environment at the three DMS nodes that lie in the path of the data - the DMC in Seattle and the two Data Collection Centers (DCC) in San Diego and Albuquerque. Five years ago, the 'interim' IRIS data archive was embedded within a large mass-store facility at the University of Texas at Austin, and the DMC had only a small hardware capitalization. Today it is handling data at a greatly increased rate with most of the capitalization now in place. Since major investments have been made in the computer hardware and local area networks needed to manage data, this section will briefly review the computing facility now in place at the three major data handling nodes within the IRIS DMS.

The IRIS DMC Facility

The DMC is the largest node within the IRIS DMS. The DMC acts as the central archive and distribution point for all IRIS data to the seismological community. It also performs additional quality control and is essentially the only IRIS facility where PASSCAL and GSN data cohabitate. It is entirely Sun-workstation and Sun-server based. The DMC is located in Seattle, Washington near the campus of the University of Washington. The major mass storage system of the DMC is located within 20 feet of the major Internet node in the Pacific Northwest and will be connected to the Internet at DS3 speeds (45 megabits/second) in the near future. This is a critical feature as the DMC continues to expand the electronic distribution of data.

The hardware configuration at the DMC is shown in Figure 7. The DMC receives data either on Exabyte or 4mm DAT. The tapes are archived on one of six Sun workstations (tsunami, yoda, seiche, toc, cwave or trek). The archival process includes the insertion of metadata (earthquake parameters, station characteristics) into a DBMS system that is available to users on-line as well as the transfer of waveform data into the mass storage systems. The metadata in the DBMS allows users to interrogate the archive more flexibly e.g., by relating desired data windows to earthquakes. It is essential for the DMC to store data in this tape-based mass storage systems in a sorted order. Data arrive at the DMC in random order and are made available as they arrive with an interim storage scheme. The data sort is accomplished by interim archival in the 0.86 terabyte mass-storage system attached to workstation lear. After six months the assumption is made that most of the data from all stations has arrived. At this time data are migrated from the smaller lear mass storage system to the larger mcbeth (8.6 terabyte) mass-storage system and removed from lear. In this migration the data placed into mcbeth are stored in both a time-sort and station-sort order. This dual sort order provides a degree of redundancy and optimizes processing of typical requests.

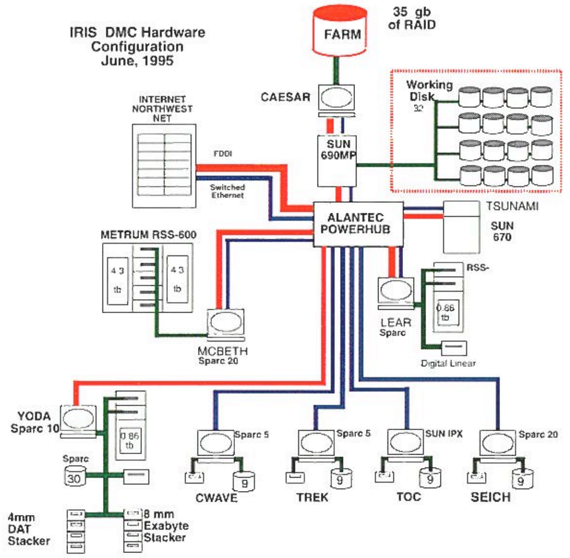


Figure 7. The main computer and storage servers at the IRIS DMC. Two SUN 600MP series servers form the heart of the request processing and archiving systems. Several desktop workstations with significant disk and tape drive capacity are situated on the high speed Local Area Networks and act as parallel archiving systems to handle the large amount of data from more than two dozen data sources sending data to the DMC. MCBETH is a fileserver that controls the main 8.6 terabyte mass storage system. LEAR and YODA act as file servers for two 1 terabyte mass storage systems. YODA is primarily dedicated to support the visiting scientist program and for archiving of broadband PASSCAL data. CAESAR is a file server that supports the RAID disk system that holds the FARM and other on-line data products. All servers and workstations are connected by either high speed FDDI lines or by Switched Ethernet connections.

The diagram shows the major components related to archiving and data request processing that are in place at the DMC. The Sun server dmc is a 690MP and acts as the main user interface computer. This computer stores all of the metadata in on-line magnetic disks and has the 40 gigabyte RAID (Redundant Array of Inexpensive Disks) system attached to it through an FDDI (Fiber Distributed Data Interface) link to a separate file (caesar). The FARM products and other anonymous ftp files are stored in the RAID system. The DMC staff performs all of the request processing either directly on DMC or on a Sun 670MP (tsunami). These machines are normally CPU-bound for most of the day. Performance is augmented by buying additional processors, not entirely new servers. Tsunami has master copies of the metadata databases. When various datasets are appended, a copy of the relevant master DBMS is copied from tsunami and transferred to one of the parallel archival machines. Incoming SEED volumes are processed in parallel and the updated database is checked for integrity and migrated to tsunami. Copies of the metadata databases are migrated to the 690MP (dmc) when not in use by any user. This approach has allowed the IRIS DMC to greatly increase its ability to archive data from multiple sources. The parallelism can be expanded as needed in an incremental fashion giving the DMC a clear path toward future system expansion with incremental costs.

The Local Area Network (LAN) is a key element of the DMC hardware. An Alantec Powerhub has been installed that connects all servers via high speed FDDI links. We normally observe 6 megabyte/s transfers between FDDI-connected servers. Only the main compute servers and main file servers are connected via FDDI. The parallel archive systems are connected to the Alantec Powerhub via switched Ethernet lines. We typically observe 6 megabit/s transfers on these lines. In the event of any LAN failure, all Sun workstations and servers are also interconnected with standard 10 Base T, ethernet type connections. Even with a primary LAN failure, the DMC can continue operating, at a lower capacity.

Data Collection Centers

Data Collection Centers (DCCs) for GSN data are collocated with the two GSN Network Operators. For PASSCAL data the quality control resides with the principal investigators, who use software developed by IRIS for the PASSCAL Field Computer. DCCs are responsible for

1. maintenance of the station database containing the authoritative information about data loggers and the time series they record.
2. quality control related to the timing applied to the time series as well as the quality of the actual waveforms.
3. Reformatting the data to SEED format for GSN and PASSCAL broadband data and to SEGY for PASSCAL active-source reflection and refraction experiments.

The GSN DCCs maintain a copy of all data recorded by their component of the IRIS GSN. The PASSCAL experimenters normally retain one copy of all data collected and forward a copy to the IRIS DMC for archiving and distribution. In 1995, roughly one third of all of the financial resources of the IRIS DMS are being devoted to operation and maintenance of the Data Collection Centers. Although specific methods used at the two GSN DCCs vary, they perform very similar functions. The following sections discuss the two DCCs in greater detail.

IRIS/IDA DCC

The IRIS/IDA DCC is operated by IGPP located at the University of California at San Diego. In early 1995 the IDA DCC was processing data from 27 stations. The data received at the IDA DCC is uncompressed and generally requires 4 bytes per data sample. The data ingestion rate of the IDA DCC is presently 1.2 gigabytes/day. After processing and compression at the DCC the data rate is approximately 175 megabytes/day, and it is this stream that is forwarded to the IRIS DMC. Figure 8 summarizes dataflow through the IRIS/IDA DCC.

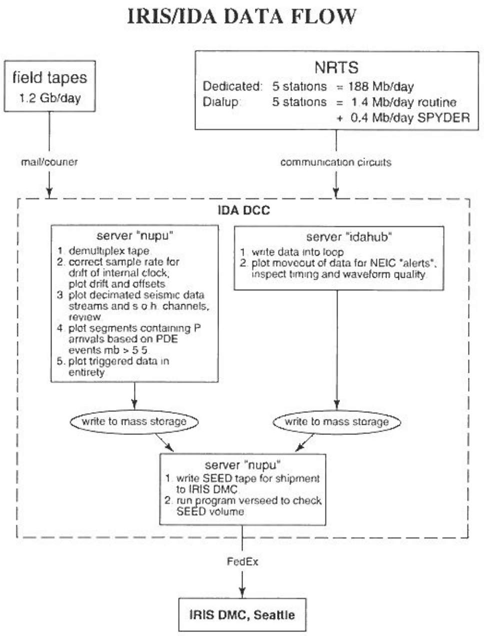


Figure 8. Processes applied to incoming data from the IRIS/IDA component of the GSN and the data volumes that are presently flowing through the IDA DCC.

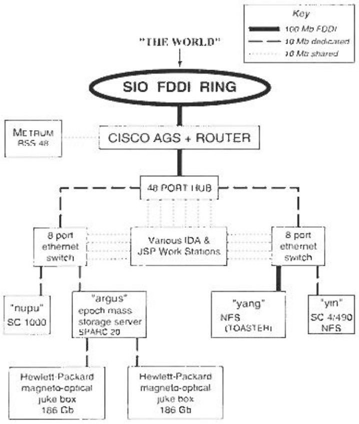


Figure 9. Major computing and networking components at the IRIS/IDA DCC. Note that although the IRIS/IDA DCC has an optical mass storage system as its primary mass storage system, it also has access to a METRUM mass storage system similar to that used by the IRIS DMC and the IRIS/ASL DCC.

The fundamental method of data transfer is magnetic tape, typically 4mm DAT. Nevertheless, the Near Real Time System (NRTS), developed and operated at IDA, recovers windows of data from 10 stations worldwide for events that trigger the IRIS SPYDER^{TM} system. Five other stations contribute data via dedicated links into disk buffers in San Diego. On an average day, the SPYDER^{TM} system operated by IRIS DMS recovers about 400 kilobytes of IRIS/IDA data for use in near real time seismological applications.

As shown in Figure 9, the primary mass storage system in use at the IRIS/IDA DCC is a Hewlett-Packard magneto optical system, controlled by Epoch Systems mass storage software running on a Sparc 20. The capacity of the Epoch-controlled mass storage system is 370 gigabytes. A Metrum 0.86 terabyte RSS-48, identical to those at the IRIS DMC and the IRIS/ASL DCC, is available for interim data storage.

The IDA DCC relies on the Scripps Institute of Oceanography FDDI ring for data transfer to the Metrum mass store as well as other non-DCC workstations. Internally, most computer traffic is routed through switched Ethernet data links. The central computing elements for the IDA DCC consist of a SparcCenter 1000, the Sparc 20 Epoch server, an NFS server and a Sun server 4/490.

The IRIS/IDA DCC has found effective methods by which it can merge data transferred via magnetic tape with data recovered through telemetry. This is useful if data tapes are lost in shipment or arrive unreadable. Since the tele-transmitted data are normally those with the highest seismological value, the most important data are retained even if the standard tape transfer mechanism fails.

All quality controlled data are transmitted to the IRIS DMC approximately once a week. The IRIS DMC presently has 130 gigabytes of data from the IRIS/IDA component of the IRIS GSN in 24,344 station day files.

IRIS/ASL DCC

The IRIS/ASL DCC is collocated with the IRIS/ASL Network Operations Center at the USGS Albuquerque Seismological Laboratory. The IRIS/USGS DCC is maintained and operated by the USGS with financial assistance provided by IRIS. The USGS pays for salaries and provides the physical space for the DCC. The IRIS DMS purchases computer and related equipment and assists with the maintenance of the DCC.

Figure 10 shows the present hardware configuration at the IRIS/ASL DCC. The ASL computing hardware is now totally Sun workstation based. There are two mass storage systems, an older 330 gigabyte Sony Optical Disk-based system and a 0.9 terabyte Metrum RSS-48 VHS tape based system. Presently the ASL DCC is relying on 10 base T LAN technology. ASL still has a large variety of tape input devices to support reading of data from a variety of older station instrumentation that is not part of the IRIS GSN. Even though these data were solely from USGS-operated and financed networks, the USGS has provided data from all networks it operated to the IRIS DMC. These additional data have proven a valuable resource for the seismological community.

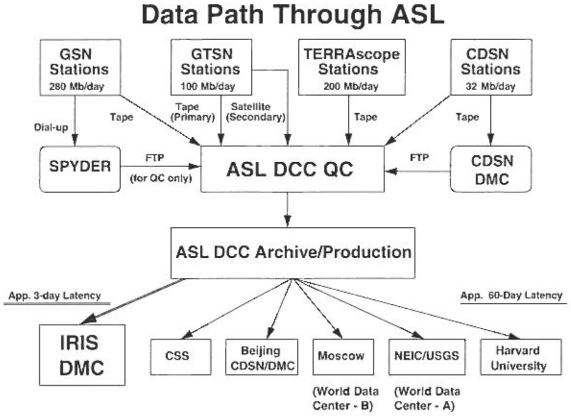


Figure 10. The flow of data from the various networks operated by the USGS whose data routinely flow through the IRIS/USGS DCC in Albuquerque. Other than the DMC, the ASL facility is the only other component of the IRIS DMS that routinely handles data from a wide variety of networks.

Figure 11 shows the present data flow through ASL. In early 1995 the IRIS DMC received data from approximately 60 GSN and similar stations operated by ASL. As of May 7, 1995 the IRIS DMC had received 407 gigabytes of data in 119,330 station day files from the IRIS/USGS, China Digital Network (CDSN) and the Global

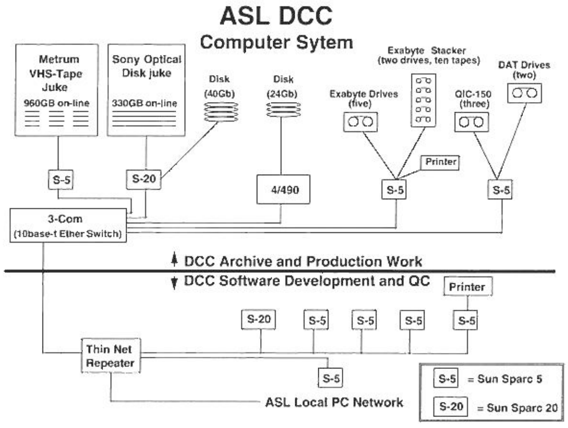


Figure 11. The computing infrastructure at the IRIS/ASL Data Collection Center. Most of the computing at ASL is done on the SUN workstations acquired through IRIS /DMS funds. The primary mass storage system at ASL is a METRUM RSS-48 similar to those used at the IRIS DMC and the IRIS/IDA DCC. Plans to upgrade the ASL Local Area Network are in place and ATM technology should be installed before the end of 1995.

Telemetered Seismic Network (GTSN) operated by the USGS. The TERRAscope network operated by Caltech and the USGS also contributes data, using the IRIS/ASL DCC for quality control and data reformatting. The TERRAscope network has contributed 132 gigabytes of data in 13,137 files. On average the IRIS/USGS DCC at ASL contributes 612 megabytes of data per day.

The IRIS/ASL DCC also acts as a distribution point of global data to some cooperating data centers worldwide. These include World Data Centers in Moscow, Beijing and the NEIC, as well as the Center for Monitoring Research.

The University of Washington

The University of Washington hosts the IRIS DMC, and contributes to its activities in a number of ways, including:

1. *Development and maintenance of SPYDER^{TM}.* The SPYDER^{TM} system was originally conceived and developed by seismologists at the University of Washington who continue to be involved in the development, enhancement and most operations of this system. Future plans call for the incorporation of INMARSAT B satellite terminals into SPYDER^{TM} as well as continued access to even more seismic networks on a global and national level. In the near future, plans call for the development of a WWW interface to SPYDER^{TM} information.

2. *Development of User Interfaces.* DMC staff are primarily computer professionals, not seismologists. Our link to our "customers" is greatly enhanced by the active involvement of the seismologists at the University of Washington in the development of interfaces and support software we develop and maintain. Among these are BREQ_FAST, FARM, WEED, COREL and RDSEED.

3. *Incorporation of Regional Network Data into the IRIS DMC.* Running one of the largest regional seismic networks in the United States, the University of Washington played a crucial role in showing how data from regional networks can be archived in the same manner as GSN data. Scientific investigations of global seismological problems are possible using short-period regional-network data. As regional networks upgrade selected stations to broadband recording, the scientific value of these networks will increase further. It is difficult to gain access to the data from the many network operators. IRIS, as a member of the Council of the National Seismic System, anticipates playing a role in archiving and distributing data from U.S. regional networks.

The Harvard Waveform Quality Center

The research group at Harvard routinely processes very large amounts of GSN data in the calculation of Centroid Moment Tensors, or CMTs. As these data are processed, Harvard researchers find problems with station responses, polarities, timing problems and waveform noise contamination. The Harvard WQC routinely generates Data Problem Reports and submits them to the IRIS DMC. This method of monitoring data problems results in a vastly improved product for the IRIS GSN. It would be difficult to maintain the current high quality of the archive without such comprehensive routine processing.

The Moscow Data Center

Since 1988, IRIS has played a significant role in seismology in the former Soviet Union. Consistent with this tradition, IRIS supports the Moscow Data Center. The MDC supports and enhances the seismic data processing capability for seismologists in the former Soviet Union. It operates and maintains several IRIS-purchased Sun workstations, typically surplus hardware from other operations, and IBM PCs for use by the local seismological community. With IRIS participation, the MDC is presently upgrading its connectivity to the Internet.

In exchange for modest financial support, personnel at the MDC develop software for the IRIS DMS. Activities include enhancements to PITSA, an interactive tool for seismological analysis and development of a program to convert hypocenter information formats into the WMO New Telegraphic Standard.

Proposed Directions for the IRIS DMS

The IRIS DMS has established a very firm foundation for archiving, management, and distribution of data from seismological recording instruments. It is essential for IRIS to maintain this level of activity to realize the scientific potential of the data collected by the Consortium and other seismologists. We propose expanding the role of the IRIS DMS in several activities that should have a significant scientific impact while having minimal impact on both DMS structure and overall budget. We identify eight specific tasks within three broad areas:

Information Services
- Fostering local data management capabilities at universities
- Developing a software platform to deal efficiently with the increased data volumes confronting seismologists
- Developing methods by which additional types of seismic, geophysical and Earth science data recorded by geophysical observatories can be accessed by Earth scientists

Telemetry and Communications
- Exploiting new methods in global communication
- Distributing data via Internet
- Expanding IRIS' role in the international data exchange infrastructure

Enhanced Operations
- The routine execution of certain computational tasks at the DMC
- Enhanced PASSCAL data services

Each of these topics will be discussed in the following sections. Combined with the commitment to maintain and enhance present DMS facilities, this forms the heart of the five-year proposal for the IRIS DMS.

Information Services

Local Data Management Capabilities At Universities

The IRIS DMS can now deliver more data to an individual researcher than the researcher can manage at his or her home institution. In order for seismologists to work productively, it is important that management of the increasing volume of data is done in a systematic way. We propose to develop software resources and hardware configurations which will allow appropriate components of the DMC capabilities, especially for database management, to be migrated to individual institutions. Although the investment in infrastructure is likely to be less at most IRIS-member institutions than at the nodes of the DMS, it is important to develop a systematic approach for management of data at local institutions.

One possibility would be for IRIS to coordinate acquisition of mass storage systems within the geoscience community. By coordinating mass storage system acquisition with the NSF, NSF should be able to leverage its funds against university cost-sharing. By approaching vendors with the possibility of large numbers of system purchases. a bulk discount should be available. By standardizing the method used by universities for management of data, coordination of software development and data distribution discussed in the following sections can be optimized. The IRIS DMS has developed many strategies to handle millions of files in large, tape-based mass storage systems and these techniques can play a central role in equivalent file management strategies at individual universities. Seismology has outgrown the "it's somewhere in these tapes on this shelf" method of file management, and the IRIS DMS can provide positive input in this area, making it more efficient for seismologists to do science.

Software Framework Development

Not only is the number of seismograms in individual projects increasing, the amount of information derived in each study is also increasing dramatically. The IRIS DMS has greatly facilitated the laborious task of gathering data needed for a specific research project. Even so, a great deal of time that could be spent in research is being spent developing software systems to manage data. Feedback from the seismological community suggests that the Consortium address the development of standardized software systems that are powerful, flexible, and adaptable to meet the needs of seismologists. Drawing on software both public-domain and commercial, the DMS is studying how a framework can be developed to make seismological data handling significantly easier, especially for researchers at smaller institutions. It is important to stress that we do not propose developing software from scratch, but rather to adapt, or encourage the modification of, existing software packages in line with an agreed-upon set of specifications.

Since the IRIS community is diverse, the ability to customize interfaces and incorporate user-produced modules must lie at the core of any data-handling system. The software system must be flexible enough to allow experimentation and innovation and provide a free or inexpensive framework that can be enhanced with both public-domain and commercial software.

We propose to coordinate development of a software system that possesses the following elements:

1. An IRIS Database Management System (DBMS) focused on seismological data. The schema should be IRIS-specific but the DBMS itself should use public domain or low-cost DBMS software.

2. A well-documented, well-defined dataflow protocol from one computer process to another, with a complete audit trail to reproduce a processing sequence.
3. A graphical method of interfacing data and programs, such as found in commercial packages like AVS and Data Explorer.
4. Simple links to Geographic Information Systems, both public-domain such as GRASS and commercial such as ArcInfo.
5. Embedded visualization capability.

The NSF-supported Sequoia 2000 project addressed many of these issues and IRIS proposes to adopt aspects of that project which are appropriate for our applications. We intend to coordinate our activities with developers of computer systems and specifically organizations developing software for manipulating and displaying seismic data. Special emphasis will be placed on coordinating and drawing from software development activities within IRIS member institutions. A head start in this area has taken place at the University of Colorado in the IRIS Joint Seismic Program Center. We plan to focus this facility on the software development task. Working with a small but key group of individuals, ideas will be developed, tested and made available for the IRIS software system. In addition, there will be modest growth at the Seattle DMC to ensure the software system is compatible with the data distribution mechanisms at the DMC. While much of the innovation will take place at the JSPC in Colorado, the DMC staff will provide the necessary support for distribution and maintenance of a stable IRIS software system for seismic analysis.

Incorporation of Multidisciplinary Datasets

IRIS proposes to develop methods by which additional types of seismic, geophysical and Earth science information can be accessed by Earth scientists. IRIS has made data from the GSN and PASSCAL programs available to the scientific community, but the complexity of integrative problems in Earth science requires other types of data. If seismic data are easy to retrieve and manipulate, but other data (e.g. magnetic) are not, researchers may opt for a narrow perspective on a large problem.

The IRIS Global Seismographic Network proposes a pilot project in which some of its permanent seismic stations be transformed into "geophysical" observatories. Beyond the hardware concerns of co-locating GPS, magnetic, barometric and other sensors, the DMS would develop strategies and methods for handling data from non-seismic sensors, both at the DCCs and the DMC. Archival and distribution of nonseismic data must be handled on a case by case basis. Some geophysical subfields are well organized and would prefer to manage their data independent of IRIS. The DMS proposes developing "hooks" to these data sources but not to duplicate their data holdings. Other data generators have no systematic mechanism for making their data available. IRIS will approach these sources of data and offer to modify the Data Management System to incorporate those data. Significant software engineering will be required to develop the systems required, but this level of effort is quite modest compared to the development of a stand-alone data-handling system.

For types of seismic data not presently managed by the IRIS DMC, we would like to make access possible through the DMS, whether by housing those data at the DMC or by providing easy pointers to other data centers. For instance, The DMS proposes to develop better access to strong-motion and regional network data, working with the Council of the National Seismic System (CNSS). Data from the Ocean Seismic Network (OSN) will almost definitely be housed at the IRIS DMC. Because only a prototype OSN is envisioned within this five-year plan, the data flow is manageable. Other types of geophysical data that are closely related to seismic data may be better handled by developing links to existing data centers. For instance, seismologists sometimes consider GPS data as very long period seismic data to the extent that it measures ground displacements. "Hooks" into the data systems of groups like UNAVCO could be developed to provide GPS data to the seismological community with the same access tools developed by the IRIS DMC, and to provide geodesists with access to derived seismic data, such as seismic moment-tensor catalogues.

Telemetry and Communications

New Methods in Global Communication

IRIS has exhibited significant innovation in the ability to recover data in near real time from globally distributed data loggers. Working with our colleagues in the FDSN, the SPYDER^{TM} system makes full use of international cooperation, cost sharing, and the Internet to provide data in near-real time for all significant seismic events. The PASSCAL program has implemented the ability to recover state-of-health information using the ARGOS satellite system.

For some stations of particular importance to nuclear monitoring and global earthquake location, IRIS plans to install Inmarsat satellite terminals to enable near-real time recovery of data from remote GSN stations. The IRIS DMS presently has one Inmarsat B terminal that is being interfaced to IRIS/USGS station processors. This terminal can transmit data at 64 kilobits/second and is actually cheaper to operate per byte than existing long-distance telephone connections. However, at $40,000 per terminal, the capital cost is too large to consider as a solution for all

GSN and PASSCAL recording systems. We anticipate the purchase of approximately 10 Inmarsat systems for installation at a key subset of IRIS GSN stations.

Global cellular telephone systems with the capacity to transmit data at very high data rates are now in the planning stages. Some systems that offer considerable promise are the Low Earth Orbiting (LEO) systems planned by Teledesic and the geostationary system planned by Spaceway. Both systems promise multi-T1 communication capability. Costs for terminals are anticipated to be $1,000 per terminal at 64 kilobit/second capacity or up to $8,000 for 2 megabits/second capacity. Access charges are projected to be very attractive. Teledesic anticipates only $0.16/minute for the 64 kilobit/second links. When combined with the fact that IRIS GSN stations generate no more than 9600 bits/second of compressed data, the technology appears to be a very good fit. Teledesic is presently referred to as the system to provide wireless Internet and is a Seattle-based company backed by Craig McCaw (McCaw Cellular) and Bill Gates (Microsoft). IRIS has discussed its needs and the possibility of working together in the area of global cellular computer communications. IRIS DMC's location in Seattle should make it easy to work with Teledesic if this organization proves to be best suited to meet IRIS' needs.

The concept of global Internet connectivity appears viable within the time frame of the next five year plan. With the possibility of real time telemetry in the near future, it will be necessary for the Data Collection Centers and the DMC to adjust to this new mode of data transfer, as well as the increasing data flow. Most of these developments will be in the area of more automated and sophisticated methods of quality control. It may prove realistic to limit the use of physical media (e.g. tapes) in waveform data transfer to the DCCs and to the DMC. For instance, a DCC could exploit the Internet to access waveforms, for quality control, at the DMC rather than at the DCC, and eliminate transit delays.

Internet Data Distribution

The IRIS DMS already uses the Internet for large amounts of data distribution. The heavily-used FARM is entirely Internet based and roughly one-half of other data shipments are shipped electronically by ftp or WWW. The Internet does not yet provide the capacity to distribute the volumes of seismic data of the larger data requests. UNIDATA, an NSF-supported program in the atmospheric sciences, has already developed novel methods of distributing their data over the Internet. Certain needs of the seismological community may not be solved with UNIDATA but IRIS plans to work closely with the UNIDATA program to borrow from their experience.

In an extension of the current SOD (Standing Order for Data) facility, we intend to develop the concept of electronic "agents". Researchers would send an electronic agent to a system at the DMC. The agents would monitor data flowing through the DMC for certain types of seismic events, particular areas of seismic activity or particular characteristics found on waveforms. The agents would activate DMC software when data of interest appear. An Internet data distribution system would automatically move seismograms from the DMC to the agent's home institution. In this manner, seismologists would find the data they desire already at their institutions when they are ready to start or resume a research project. This concept of electronic agents is just now becoming common in cyberspace, and we feel that it is a concept that can be exploited by the seismological community. Many of the resources to accomplish this already exist within the DMS.

Development of International Infrastructure

Many developing countries possess a wealth of talent, excitement and potential to advance significantly the understanding of Earth. They lack, however, a significant infrastructure to support their research. The IRIS DMS and the Data Centers of the FDSN already support seismologists in developing countries. The IRIS DMC distributes seismological data, at no charge, to any organization worldwide. The IRIS DMC typically sends 15%-20% of its data shipments outside the United States and a significant number of these requests go to developing countries.

The FDSN has proven to be an effective framework for IRIS participation in international efforts. Within this framework, IRIS proposes to work with organizations like the FDSN to develop software, systems and documentation targeted toward the advancement of Earth sciences in the international arena. The benefits to IRIS are significant. Since the GSN, JSP, and PASSCAL programs are all active internationally, the presence of an infrastructure in the areas of activity will promote success of IRIS programs. By developing DBMS systems and interfaces for the free exchange of seismological information, the amount of data available to researchers worldwide will increase at relatively low cost to IRIS. We propose to actively develop software and systems that are conducive to the quality control and distribution of seismic data from networks operated and funded by other nations. Where appropriate, we will offer to act as a distribution node for these data. A gradual upgrade of the international infrastructure would benefit US seismology greatly, and should be possible with cooperation and modest resources on the part of IRIS.

Enhanced Operations

Routine Production Tasks as the DMC

The concentration of broadband data at the IRIS DMC is the highest, in the world of seismology. Presently the DMC concentrates on the maintenance of databases containing waveforms and metadata, quality control of data, archiving and long-term safekeeping of the data, and distribution of seismic data to the community. In the archival process, all the data pass through disks at the DMC. It would be relatively simple for the DMC to process the waveform data routinely to add 'derived-information' to the waveforms. Possible tasks include:

Event Detectors- IRIS GSN and PASSCAL data can make a significant contribution toward the production of a comprehensive global bulletin of seismicity. Presently the National Earthquake Information Center (NEIC) only makes use of observed arrivals if the waveforms have been analyzed by someone else or if the data are received at NEIC in near-real time (hours). GSN stations that are not ordinarily reviewed by a seismic analyst or passed in near-real-time through the NEIC automatic picking system do not contribute to the NEIC Bulletin. In the long term, it is our goal to have all GSN stations available, through telemetry, for use in real time by NEIC. In the interim, we propose to develop procedures whereby event detectors will be run automatically against all incoming waveforms. A list of detections and waveform segments containing the detections will be extracted and forwarded to the NEIC. Effective use of this procedure would require close cooperation with the USGS.

New Methods of Seismic Event Detection and Characterization - Historically, earthquake catalogues are produced based on association of observed seismic phase arrivals at individual stations. The IRIS GSN is basically a global array of stations. In general, the signal-to-noise ratio of seismic data can be enhanced by stacking methods that tend to decrease the power of random noise. The IRIS DMS proposes to work with the research community and the NEIC to develop techniques to use the GSN as a global array for the detection and characterization of seismic events.

Routine Waveform Quality Parameterization As data pass through the IRIS DMC disks, a variety of parameters can be estimated that identify specific features of the data. For instance, by passing the data through bandpass filters and estimating power spectra, a characterization of the noise level at a variety of frequencies can be made. We propose to develop a variety of algorithms for waveform quality parameterization and include the results of these estimates in the on-line IRIS DBMS.

The IRIS DMC will work very closely with its member institutions, individual scientists and the USGS to develop these procedures. The value-added information we anticipate is potentially very significant.

Enhanced PASSCAL Services

DMS activities over the past five years have been focused toward developing and maintaining the GSN database and servicing the needs of the global (teleseismic) community. To a large extent this has reflected the disparate traditions of the two branches of seismology which founded IRIS a decade ago. In global seismology, individual researchers drew from a communal data source. In active-source seismology, individual investigators executed their own experiments and had priority access to the data. Under that tradition there was little incentive to develop shared resources for data exchange. A multitude of different formats were used. The primary interest in communal data services was "processing" and simple archival of processed output.

The growth and success of broadband PASSCAL experiments and multi-institutional, multi-PI active-source experiments has resulted in an attitude shift in favor of open data exchange. There is growing interest within the PASSCAL community to expand the services the DMS provides to include similar data management services that it has successfully applied to GSN data. The YODA facility assisting PASSCAL scientists in the handling of data after they have been collected has been well received and will be expanded in the future. The merger of data from broadband PASSCAL and GSN sources has been demonstrated and availability of more PASSCAL data should accelerate in the future and a natural evolution will see the IRIS DMS providing increased services to the PASSCAL community.

The software framework discussed earlier has natural application to PASSCAL data. To a large extent the GSN is global, whereas PASSCAL experiments necessarily cover more limited geographic areas. Nevertheless the manner of processing array data from the two IRIS programs is becoming more and more similar. The DMS strategy for sponsoring data-handling software assumes a substantial narrowing of the differences between GSN and PASSCAL data, both in processing and distribution.

Reflection and refraction data are inherently different from most broadband data. The sophistication of software available to handle these types of PASSCAL data, however, is very mature, as it has been driven by the commercial software industry in support of oil exploration. Unfortunately, sophisticated reflection/refraction software typically exceeds the economic resources of many IRIS member institutions. In an early service of IRIS, several dozen copies of commercial seismic processing software were purchased in bulk. The DMS proposes to work with PASSCAL to revive this service by acquiring one complete commercial seismic processing system for use at the DMC. PASSCAL investigators would access and use this software either by remote login or personal visit to the Seattle DMC. The financial impact on the IRIS budget would be minimal, but the scientific impact this would have for researchers should be quite significant.

The IRIS Joint Seismic Program

Serving the National Interest

While the advancement of science is the primary goal of IRIS, perhaps an equal achievement of the Consortium has been to demonstrate that the scientific community can cooperate on programs that not only improve our understanding of the physical world, but also address the more current needs of our society. Over the past several years, IRIS has contributed to U.S. foreign policy objectives and national security interests through the Joint Seismic Program (JSP).

The JSP represents IRIS's efforts toward the development of an international regime for monitoring a Comprehensive Test Ban Treaty and for deterring the proliferation of nuclear weapons. The JSP is unlike other IRIS programs in that it represents a mission rather than a facility. The JSP draws upon and supports each of the IRIS facility programs to achieve its mission. New resources developed under the JSP are transitioned into the core IRIS programs.

Throughout the last cooperative agreement, the JSP has been focused on expanding the Global Seismographic Network (GSN) into a multi-use resource that can be used not only for fundamental science and earthquake hazard mitigation, but also as a resource for verifying compliance with a future Comprehensive Test Ban Treaty (CTBT). The expansion has taken the form of increasing the density of GSN stations in areas of proliferation concern, and in augmenting the GSN with regional networks and arrays. Associated data facilities developed or supported through the JSP include Data Collection Centers in Obninsk, Russia, the University of California, San Diego, and the U.S. Geological Survey's Albuquerque Seismological Laboratory; and Data Analysis Centers in Moscow and the University of Colorado, Boulder. The JSP analysis center in Boulder, Colorado coordinates the development of advanced software and conducts technical evaluations of the performance of the program's facilities.

Because facilities that contribute to the full range of seismological applications have many advantages, Congress has enhanced NSF support of the IRIS program through directed additions to the research budgets of the Department of Defense, and declared the JSP an item of special Congressional interest. As stated by the Chairman of the House of Representatives' Budget Committee during the FY1995 appropriations:

> *"For the past several years, my colleagues and I have strongly supported funding for seismological research conducted by IRIS. It has been our intention to advance the IRIS programs in order to provide a cost-saving, sustainable, multi-use resource not only for monitoring a future comprehensive test ban treaty, but also for monitoring global seismicity to mitigate earthquake hazards and to advance earth science."*

The JSP operates in response to societal needs; and societal needs are related to the political environment. Accordingly, the JSP has had to adapt to the many changes that have taken place in international politics over the past eight years, especially: glasnost and perestroika in 1988, the break-up of the Soviet Union from 1989 to 1991, the legislation of a U.S. testing moratorium beginning in 1993, the indefinite extension of the Non-Proliferation Treaty in 1995, and the call for the negotiation of an international Comprehensive Test Ban Treaty by the end of 1996. Each of these political events has had an impact on global seismology. In addition, one can also argue that advances in global seismology have contributed to the attainment of several of these policy objectives. For example, previous attempts to negotiate a CTBT were hindered to a large degree by the perceived inability of seismology to adequately monitor treaty compliance. Today, the debate is no longer about whether such a treaty can be monitored, but rather only about the manner in which it should be monitored.

By foreseeing many of these geopolitical developments and creating facilities in anticipation of future requirements, the JSP has created an unprecedented opportunity for both the advancement of earth science and the achievement of U.S. foreign policy objectives. In response to Congressional interest, IRIS developed a plan in 1993 for expanding the Global Seismographic Network into a multiple use facility that could contribute to the monitoring of a Comprehensive Test Ban Treaty. Although the GSN was never envisioned as a network that would supplant the monitoring networks of the US intelligence community, it was seen as an open source of data that could provide the technical equivalent of a global "neighborhood watch" program. The global distribution of GSN stations allows for the broad international participation required for the development a strong verification regime. Congress responded to IRIS's plan by providing funding to complete the full capitalization of the continental portion of the GSN in FY94-95, such that it could be installed in time for a CTBT following the 1995 Non-Proliferation Treaty Review conference.

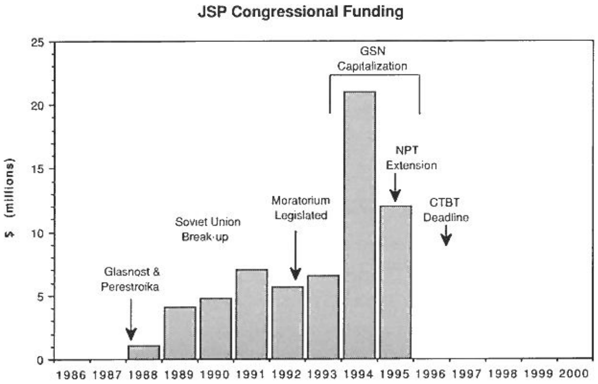


Figure 1. IRIS programs provide a cost-saving, sustainable multi-use resource for the monitoring of a Comprehensive Test Ban Treaty. Accordingly, Congress has enhanced NSF support of IRIS and declared the Joint Seismic Program to be a program of special Congressional interest.

The capitalization of the GSN is allowing a large number of nations to participate in a CTBT and creating a sustainable base of support that extends beyond treaty verification. While many nations have little interest in devoting limited resources to the operation of seismic monitoring systems whose sole purpose is for CTBT verification, many of these same nations have earthquake hazards or scientific organizations that wish to be part of the international geophysical community. Seismic stations that contribute data not only to treaty monitoring but also to a range of scientific and environmental problems will sustain the interest and support of the host country more than specialized seismic stations whose sole purpose is treaty monitoring. Additionally, large numbers of geoscientists indirectly aid the treaty monitoring effort through their active use of geophysical data in related fields of research.

Seismology's contribution to international affairs

Seismology's role in international affairs can be illustrated by an incident that occurred in 1991, when the Government of Pakistan reportedly detected a seismic event in India's Rajasthan Desert (the location of India's 1974 nuclear test). According to a request for information from the U.S. ambassador, Pakistani officials "detected no aftershocks and are therefore suspicious that the event was not an earthquake." The United States, however, was able to confirm that the seismic event was in fact an earthquake and not an Indian nuclear weapon test. According to recent Senate testimony by the Director of the Central Intelligence Agency, the territorial disputes between India and Pakistan "poses perhaps the most probable prospect for the future use of weapons of mass destruction, including nuclear weapons." While it is always difficult to assess what might have happened, in this instance the identification of the seismic event as an earthquake may have played a role in diffusing a volatile situation between two nations.

The U.S. Ambassador's request for seismic data is an illustration of how changes in geopolitics present new challenges for global seismology. The breakup of the Soviet Union and the recognition of advanced nuclear weapons programs in Iraq and North Korea, have shifted U.S. national security concerns from superpower competition to the spread of nuclear weapons and the potential for the outbreak of nuclear war through territorial disputes. To deter the proliferation of nuclear weapons, the United States has pushed for non-nuclear states to forgo nuclear weapons and approve indefinite extension of the Non-Proliferation Treaty. The non-nuclear states, in turn, have increased pressure on the nuclear states to negotiate an international CTBT. While it is generally recognized that the detonation of a nuclear device may not be critical to the development of at least a simple, first-generation nuclear weapon, advocates of a CTBT argue that a ban on nuclear weapons testing will prevent the development of more advanced nuclear weapons, de-emphasize the importance of nuclear weapons for national security, and reduce the discriminatory nature of the Non-Proliferation Treaty regime.

Needless to say, the benefits of such a treaty would be outweighed if meaningful violations could go undetected. While there are many tools for monitoring nuclear testing, the backbone of the monitoring system consists of seismic data collected from around the world. The CTBT seismic monitoring structure being considered within the Conference on Disarmament and endorsed by the United States consists of two tiers. The first tier, called the primary network, is composed of a small number of specialized arrays and stations whose data are transmitted in near-real time through continuous telemetry. The second tier, called the auxiliary network, consists of a larger number of global stations with similar technical characteristics but whose data are accessed on a "dial-up" mode rather than by continuous telemetry.

For the past several decades, the U.S. monitoring effort focused on known testing areas within the U.S.S.R. to ensure compliance with the 150-kiloton limit of the bilateral 1974 Threshold Test Ban Treaty. Under the context of a multi-lateral CTBT, the international community has the broader task of detecting, locating, and identifying low magnitude seismic events in most regions of the globe. Accordingly, we must expand our focus from using a small number of stations and recording low-frequency teleseismic waves (those that travel distances greater than 1500 km), to using a large number of stations and recording high-frequency regional waves (those that generally travel less than 1500 km). The new requirements for an official monitoring system, including the routine analysis of seismic events, will need to be developed within the CTBT negotiations. The scientific community can, however, contribute important data to the task.

Modern seismic stations now record ground motions over a broad range of frequencies and amplitudes, and are no longer restricted by analog recording systems. As a result, seismic stations installed for applications such as scientific research and earthquake studies can also provide important data for use in treaty monitoring. As documented in a recent report by the National Research Council's Committee on Seismology, the technical characteristics of the IRIS Global Seismographic Network exceed the Group of Scientific Experts (GSE) requirements for CTBT monitoring stations, thus opening up opportunities for collaboration and considerable cost-savings. The table below lists the IRIS stations that are either being used as part of the International Monitoring System or have been proposed by scientists of the host country, the United States, or the GSE as contributors to the system. With the inclusion of these countries, the majority of nations contributing to the auxiliary network will be using IRIS stations.

The GSN stations are particularly appropriate for use as auxiliary stations. While such multi-use stations may augment special purpose arrays for the primary detection of events in a few areas, the principal value of the data is for resolving ambiguous events (identification), improving the parameterization of events (location, depth, magnitudes, mechanisms, etc.), providing comprehensive site surveys, and characterizing regional seismic activity and wave propagation. The data also provide a basis for monitoring research. As stated by the Director of the Arms Control and Disarmament Agency: "GSN stations will materially improve our comprehensive test ban treaty verification capabilities."

In coordinating IRIS activities with other programs associated with nuclear monitoring, IRIS participates in a series of inter-agency and international forums. During the last year, for example:

- IRIS presented the GSN siting plan to the U.S. Arms Control and Disarmament Agency and solicited comments on the plan from each federal agency associated with nuclear monitoring.
- IRIS contacted the international Group of Scientific Experts in Geneva and station operators around the

Many IRIS stations have been proposed by scientists of the host country, the United States, or the Group of Scientific Experts as contributions to the International Monitoring System for a Comprehensive Test Ban Treaty.

AAK	Ala-Archa	Kyrghyzstan
ABKT	Alibek	Turkmenistan
ADK	Adak Island	Alaska, U.S.A.
AFI	Afiamalu	Samoa Islands
ANMO	Albuquerque	New Mexico, U.S.A.
ANTO	Ankara	Turkey
ARU	Arti	Russia
ASCN	Ascension	Ascension Island
BOCO	Bogota	Columbia
BORG	Borgarnes	Iceland
BRVK	Borovoye	Kazakhstan
CHTO	Chiang Mai	Thailand
CMLA	Cha de Marcela	Azores
CSY	Casey	Antarctica
CTAO	Charters Towers	Queensland
DAV	Near Davao	Philippines
ESK	Eskdalemuir	Scotland, U.K.
FFC	Flin Flon	Manitoba, Canada
FURI	Furi	Ethiopia
GNI	Garni	Armenia
GRFO	Graefenberg	Germany
HNR	Honiara	Solomon Islands
JTS	Las Juntas	Costa Rica
KBS	Ny-Alesund	Spitsbergen, Norway
KEV	Kevo	Finland
KIEV	Kiev	Ukraine
KIV	Kislovodsk	Russia
KMBO	Kilimambogo	Kenya
KOD	Kodaikanal	India
KURK	Kurchatov	Kazakhstan
LSZ	Lusaka	Zambia
LVC	Limon Verde	Chile
LVZ	Lovozero	Russia
MAJO	Matsushiro	Japan
MSEY	Mahe	Seychelles Islands
MSVF	Monasavu	Viti Levu, Fiji
NDI	New Delhi	India
NIL	Nilore	Pakistan
NNA	Nana	Peru
NRIL	Norilsk	Russia
NWAO	Narrogin	Western Australia
OBN	Obninsk	Russia
PAB	San Pablo	Spain
PET	Petr.-Kamch.	Russia
PFO	Pinon Flat	California, U.S.A.
PMG	Port Moresby	Papua New Guinea
PMSA	Palmer Station	Palmer Peninsula
PTGA	Pitinga	Brazil
RAR	Rarotonga	Cook Islands
RGNB	Rio Gr. de Norte	Brazil
RPN	Rapa Nui	Easter Island, Chile
SDV	Santo Domingo	Venezuela
SEOL	Seol	South Korea
SHIO	Shillong	India
SNZO	South Karori	New Zealand
SPA	South Pole	
SUR	Sutherland	South Africa
TBT	Taburiente	Canary Islands
TEYM	Tepich	Yucatan, Mexico
TIK	Tiksi	Russia
TLY	Talaya	Russia
TSUM	Tsumeb	Namibia
TUC	Tucson	Arizona, U.S.A.
ULN	Ulaanbaatar	Mongolia
WRAB	Tennant Creek	Northern Territory
XAN	Xi'an	China
YAK	Yakutsk	Russia

world encouraging them to use IRIS stations for the International Seismic Monitoring System and the GSE's experiment.

- IRIS participated in the Verification and Monitoring Task Force chaired by Arms Control and Disarmament Agency, and contributed to the annual report to the President's plan for the monitoring of a Comprehensive Test Ban Treaty.
- IRIS presented its plans to the ad hoc working group on Coordination of Federal Support of International Seismic Networks of the White House's National Science and Technology Council.

The importance of an auxiliary network in general and the GSN stations in particular was recently demonstrated when an unusual seismic event was detected near the Ural mountains on January 5, 1995. The seismic event had a magnitude of 4.4, and, based on teleseismic data, appeared to have the characteristics of an explosion. Over a dozen stations were used to characterize the event for the Reviewed Event Bulletin of the International Data Center. The two stations closest to the event were the IRIS stations ARU (Arti, Russia) and OBN (Obninsk, Russia). The IRIS stations were important not only for improving our ability to pinpoint the location, but also for determining that the event was not an explosion. In the Figure 2, the large ellipse, with an area of over 10,000 km2, represents the location based only on the stations being considered for the primary network. The smaller ellipse, with an area less than 800 km2, represents the location based on all the stations listed in the Reviewed Event Bulletin including the IRIS stations ARU and OBN. The difference in the accuracy of the location is important from a monitoring perspective, especially if an on-site inspection were needed. In addition, the station ARU, located at a distance of only a few hundred kilometers from the event, recorded regional data which were analyzed to determine that the event was not produced by an explosion, but rather by a mine collapse.

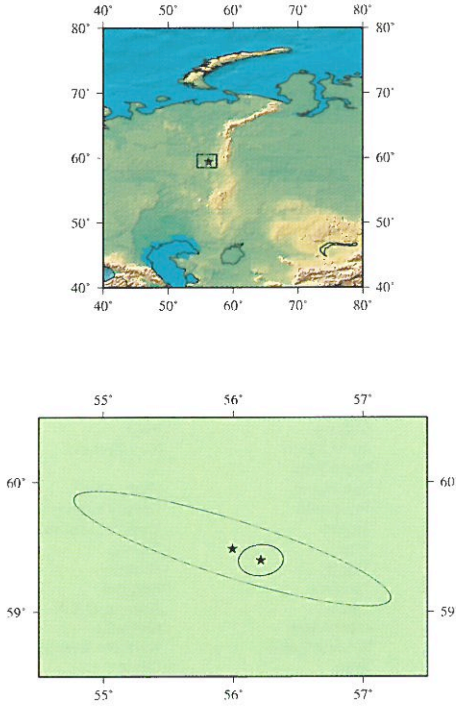


Figure 2. An unusual seismic event was detected near the Ural mountains on January 5, 1995. IRIS stations in Russia helped locate this event and resolve its origin.

The evolution of the JSP

The JSP began in 1988 as a cooperative undertaking among IRIS, the U.S. Geological Survey, and the Soviet Academy of Sciences to install seismic stations within the U.S. and the Soviet Union in support of a possible bilateral arms control agreement that would further restrict the testing of nuclear weapons. Along with the installation of stations, a data collection center was established in Obninsk, Russia, and a Data Analysis Center was developed in Moscow.

Following the 1988 earthquake in Armenia, the Soviet Union requested IRIS to help evaluate areas of high earthquake hazard. Under the JSP, regional networks were temporarily deployed in Armenia and the Caucasus; and a permanent telemetered network was built around the capital city of Bishkek in the Tien Shan mountains of Kyrghyzstan next to the border of Kazakhstan.

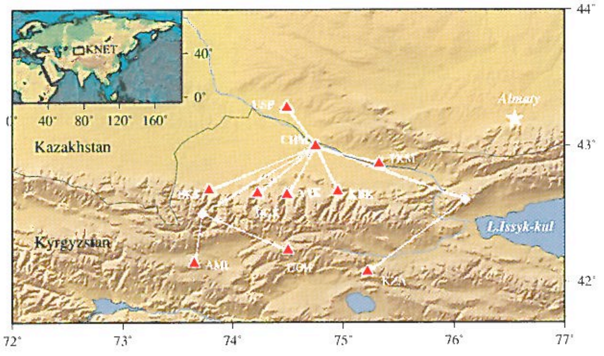


Figure 3. Through the University of California, San Diego, IRIS has installed a 10-station broadband telemetered network around Bishkek, the earthquake prone capital of Kyrghyzstan.

Following the break-up of the Soviet Union, IRIS gained permission to install an eight station broadband network in Kazakhstan. In addition, the JSP revived two, formerly classified Russian military arrays that had been abandoned in Kazakhstan during the break-up of the Soviet Union.

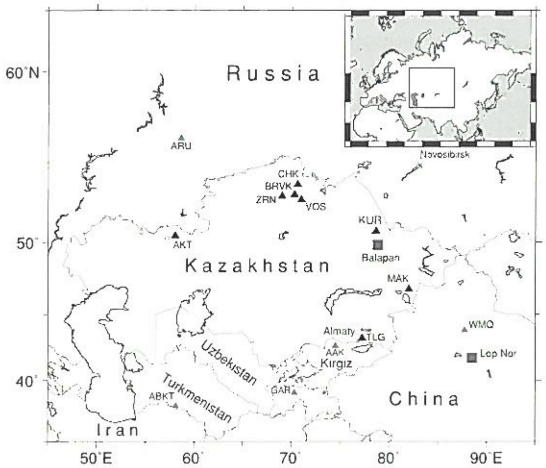


Figure 4. Through the Lamont-Doherty Earth Observatory of Columbia University, IRIS has installed a network of instruments in Kazakhstan and revived two arrays that were formerly used by the Soviet Union to monitor nuclear weapons testing.

Simultaneous with the development of the regional networks, experiments were held in Pinyon Flat, California to test various patterns of sensor distribution. The Pinyon experiments led to the temporary installation of a broadband seismic array near Ashkhabad, the capital of Turkmenistan. The array was co-located with the IRIS GSN station ABKT at a site that is being proposed by the U.S. government for a monitoring array. The deployment showed, however, that the site is not well suited for monitoring because the regional detection capability is relatively poor in the southern direction, towards Iran. If a monitoring array is installed in this area, it will need to be a full three-component array (unlike most monitoring arrays which are only vertical) to record the S and Lg waves. The Geyokcha array thus demonstrated another way in which the IRIS programs contribute to nuclear monitoring, namely by providing comprehensive site surveys.

In parallel with the program in array and network development, the JSP, in response to the changing geopolitics, expanded its enhancement of the GSN beyond the Soviet Union. In 1992, IRIS sponsored a workshop on "The Proliferation of Nuclear Weapons and the Role of Underground Testing" in cooperation with Lawrence Livermore National Laboratory, the United States Geological Survey, and Princeton University. The purpose of the workshop was to evaluate the role of seismology in deterring the development of nuclear weapons. At the request of the Senate Committee on Governmental Affairs and the House Committee on Foreign Affairs of the United States Congress, IRIS prepared a report from the workshop providing an assessment of how the resources of the international seismological community could be best applied for monitoring underground nuclear explosions in the context of nonproliferation. Following increased Congressional interest in nonproliferation, Congress provided funding to IRIS to complete the installation of the continental portion of the GSN and to enhance GSN coverage in areas of proliferation concern, specifically, Central Asia and the Middle East.

Along with the capitalization of the continental portion of the GSN, the enhancement of GSN coverage in areas of proliferation concern, and the deployment of networks and arrays, the JSP has also supported data collection and archiving activities. Such data activities include: a South American Bulletin produced with the University of Chile, Santiago to evaluate the seismicity levels in South America as part of the Scientific Alliance for South America (SALSA), portable instruments deployed in eastern Russia to evaluate site characteristics for GSN stations, catalogs of seismicity in Central Asia produced by the JSP Center, and historical data archives copied from Soviet seismological observatories for inclusion within the IRIS Data Management System.

In carrying out its program, the JSP has used a Technical Working Group to coordinate its activities and a JSP Center to evaluate its performance. The Technical Working Group, consisting of program investigators and other interested scientists, meets periodically at the JSP Center in Boulder Colorado to review progress and coordinate field schedules. The JSP Center hosts the Technical Working

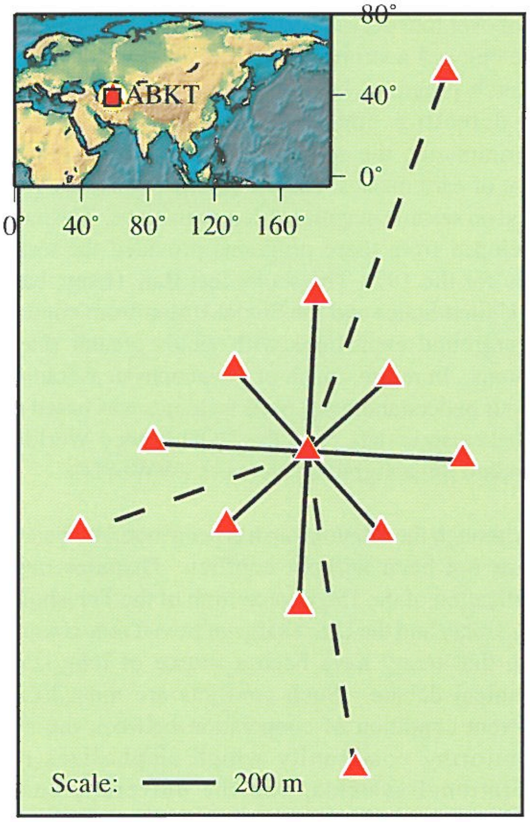


Figure 5. A broadband array was temporarily installed near Ashkabad, the capital of Turkmenistan.

Group meetings and acts as the central analytical resource for the program. The JSP Center continually assesses the overall performance of the program through the production of Central Asian seismicity catalogs and through the analysis of both actual and hypothetical networks. Evaluations made by the JSP Center, in combination with the recommendations of the Technical Working Group, are used to develop program plans that are reviewed by a JSP oversight committee and approved by the IRIS Executive Committee. Technical reviews of the JSP are periodically presented at the IRIS Workshop and published in the IRIS Newsletter (see for example: Summer 1994, vol.XIII, No.2).

One important role of the JSP has been to develop new facilities, and to transition them into the core facilities programs of IRIS. The Moscow Data Center and the JSP Center have become incorporated within IRIS' Data Management System, the Global Seismographic Network stations installed under the JSP are no longer distinguished from other IRIS Global Seismographic Network stations, and the networks and arrays have evolved into an on-going array program that will be carried out under the PASSCAL program.

The Future of the JSP

For over four decades, seismology and national security have enjoyed a strong, symbiotic relationship. Seismic research programs have improved monitoring methods for detecting and locating seismic events, for discriminating the seismic signals of explosions from those of earthquakes, and for estimating explosive yield based on seismic magnitude determinations. The methods developed from these programs provided the technical basis for the 1974 Threshold Test Ban Treaty, banning the United States and the Soviet Union from conducting underground explosions with yields greater than 150 kilotons. In return, much of the geophysical framework for our understanding of plate tectonics was based on the global seismic data from the DOD funded World-Wide Standard Seismographic Network (WWSSN).

Although the relationship has been mutually beneficial, it has not been without conflict. Disputes over the verification of the 150 kiloton limit of the Threshold Test Ban Treaty and the U.S. charge of Soviet non-compliance with that treaty have been a source of long-standing technical debate. Such conflicts are most likely an inherent condition of cooperation between the nuclear monitoring community which emphasizes robust operational systems, and the university research community which emphasizes advanced research and innovation.

Despite the controversies associated with funding transfers, Congressional interest, and conflicting agency priorities, all groups share the common ground of advancing global seismology. To expand this common ground, the Director of the National Science Foundation and the President's Science Advisory formed in 1994 an ad hoc working group to the White House's National Science and Technology Council (NSTC). The working group is charged with developing recommendations for support and coordination of global seismographic networks. In working with the White House Office of Science and Technology Policy and the Arms Control and Disarmament Agency, the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) have put forward a proposed interagency position paper. The proposed interagency position incorporates the findings of the DOD funded National Academy of Sciences reports and presents realistic recommendations for maximizing the overall utility of the combined federal investment in global seismology. The proposed basic tenets of the agreement are:

1) The DOD, NSF, and USGS efforts complement each other in terms of collecting data for the various applications of global seismology. These efforts should be coordinated under the auspices of an interagency organization with interests in all of seismology's applications.

2) Beginning in FY97, each organization (DOD, NSF, and USGS) should independently support their own efforts within these areas, without the requirement of interagency transfers of funding. NSF and the USGS will support the Global Seismographic Network and its role in the auxiliary network for the international regime of a CTBT, along with basic research programs in earthquake hazards and seismology. The DOD will support its monitoring arrays and its basic research program in seismic verification. All groups will provide for the distribution of data through the IRIS DMS as recommended by the National Academy of Sciences.

It is the hope of many that the monitoring community will recognize the advantages of using multi-use stations such as the GSN to meet the technical requirements for the auxiliary network of the International Seismic Monitoring System. If so, global seismology can become a positive example of interagency cooperation by demonstrating how the scientific research community and the Department of Defense can work together to develop programs that meet both our national security needs and our scientific goals.

The investments made by the JSP have advanced all of IRIS's goals through the support of the core programs and through the development of new initiatives that go beyond the boundaries of the facilities programs. The JSP has allowed for the full capitalization of the continental part of the GSN, enhancement of the data collection and archiving systems, the development of networks and arrays, and the development of software for advanced data analysis. The programs in arrays, networks, and radio telemetry have helped bridge the gap between the GSN and PASSCAL and provided cross-fertilization between the science and technology associated with nuclear monitoring and the more general science of seismology. GSN stations are now being used in conjunction with local network stations to provide local and regional observations. Similarly, PASSCAL deployments and local network stations are being used to provide global teleseismic observations. Array processing techniques developed as part of the JSP are now being applied to PASSCAL deployments and local networks. These powerful processing techniques are capable of enhancing and identifying small magnitude teleseismic events, and the small secondary and precursory seismic arrivals from teleseismic events that are associated with important structural features of the deep earth interior. Upon maturity, each of these development programs have been transitioned into the traditional core programs.

As stated in a letter to the President's Science Advisor from the Director of the National Science Foundation, the JSP stands as "a blueprint for the support of multi-use scientific programs that serve the national interest." As IRIS continues, the Consortium plans to develop other mission related programs in such areas as earthquake studies and environmental assessments. In each case, however, we will strive to continue the concepts embodied within the JSP; namely, to enhance the core facilities programs, to develop advanced applications, and to apply the resources of IRIS to the scientific and societal problems of our nation.

Real-time Data Access

Opportunities in Telemetry & Global Communications

Introduction

Communication technology has evolved rapidly since the beginning of IRIS ten years ago. Satellite transmission costs have decreased, land and undersea fiber optic cables are commonplace, telephone service is reaching new remote locations, global computer network connectivity via the Internet is undergoing an exponential expansion and new technologies are being developed for land-based wireless telemetry.

There are profound opportunities which telemetry can provide to a data gathering facility such as IRIS. In the seismological application, we define telemetry as an electronic means to collect data from remote sites. The real-time collection of data from all GSN stations remains a fundamental goal for IRIS. With the growth of long-term PASSCAL broadband experiments, there has been increasing interest in the remote collection of data from these experiments as well. The use of telemetry in arrays of PASSCAL instruments has show the power of array techniques in local and regional studies of seismicity and wave propagation.

In addition to providing new possibilities in experimentation and improving the scientific productivity of current techniques, the utilization of telemetry can significantly enhance operations, improve data quality and reduce operational costs. While the advantages of telemetry have been acknowledged since the inception of IRIS, costs have limited widespread use. Current projections indicate that, within the next 5-10 years, the capital investment for telemetry hardware and the user fees for operation will drop to levels where it will become cost-effective for IRIS to take full advantage of such systems. The transition to telemetry will be a natural one. All IRIS data loggers were developed to be "telemetry-capable" and can incorporate a wide variety of communications technologies. IRIS proposes to work actively with global cellular providers of data services with the intention of acquiring and installing terminals at most if not all IRIS recorders near the end of the next five year plan (2001).

The explosive spread in local and global communications is being driven in the commercial marketplace by forces far removed from seismology. On the horizon are proposals for "global digital cellular telephones" using constellations of low-Earth-orbiting (LEO) satellites, promoted by some of the world's largest technology and telecommunications companies—Motorola's Iridium system, TRW's Odyssey system, and Teledesic, a new venture with support from Bill Gates of Microsoft and Craig McCaw of McCaw Communications.

Global systems for voice communications are developing from pressures in the business community and desires to provide low-cost national phone systems in developing countries. While these voice-oriented systems can also provide data capability through the use of modems, the limited bandwidth (<10 kbaud) and relatively high cost ($'s/minute, or $10's per Mbyte) are likely to continue to limit them as a long-term solution to our requirements for global telemetry. Of more interest in IRIS applications are emerging national and international schemes for high speed digital data broadcast and transmission. The development of these systems are being driven by vast markets in the computer and entertainment industry and they will find application in both private communications and international extensions of the Internet. Proponents of these new systems claim that costs within the next decade will drop to 10's of cents per Mbyte. If these projections hold, the costs of complete real time data recovery from a typical GSN or broadband PASSCAL station ($10-$20/week, for 50-100 Mbytes) could approach the current costs of express mailing magnetic tapes.

Local and regional telemetry of PASSCAL data can also benefit from developments in the telecommunications industry. The rapid growth of the cellular telephone market has led to increasingly sophisticated schemes for maximizing the use of the relatively limited spectrum available for radio telemetry. Radio systems using techniques such as "spread spectrum" (see box) can now be purchased which provide communications channels adequate for transmitting full resolution PASSCAL data over line-of-site paths for distances of tens of km. These systems have the advantage of not requiring a license, a major restriction in the use of previous radio telemetry systems. We see important applications for this form of telemetry in local and regional broadband arrays, based on the pioneering work in Anza, California and Kyrghizia. In many areas, especially in North America and Europe, commercial cellular telephone networks can allow much more freedom in selecting sites for long-term PASSCAL deployments by providing remote access in areas not covered by wire-based telephone service.

Many of our plans depend on the continued growth of the Internet. The concept of global Internet connectivity is extremely viable within the timeframe of this five year

IRIS STATION DATA GENERATION RATES

GSN Stations

- 3 - 20 sample/second channels produce about 10 Mbytes/day
- 3 - 40 sample/second channels produce about 20 Mbytes/day
- sum of all other channels produce about 1 Mbytes/day
- A GSN station recording continous data produces about 31 Mbytes/day

PASSCAL Stations

- 3-20 sample/second channels produces approximately 10 Mbytes/day
- triggered channels and all other channels can produce an additional 10 Mbytes/day
- A PASSCAL data logger produces about 20 Mbytes/day

Data Compression

- Compression algorithms reduce station volume to~10 Mbytes/day

Communication Circuit Capacities

Circuit Type	Circuit Bandwidth (bits/second)	One-Minute Volume (Kbytes)	All Data Compressed (min/day)
Standard Analog Voice Grade V.29 Modem	9,600	60	100-166
High-Quality Analog V.34 Modem	28,000	180	33-55
ISDAN INMARSAT-HSD	64,000	400	15-25

program. To provide access to those areas where Internet is not available, we propose to continue limited experiments with current (high cost) "private-line" systems and begin acquisition of the newer low-cost systems as they become available. We also intend to approach providers of the new global communications systems to explore the possibility of working with them to use applications in seismology as an early demonstration of the utility of their new ventures.

We are convinced that by early in the first decade of the 21st century it will be possible to recover data from all GSN stations and most PASSCAL broadband experiments in near real time. Whether this is feasible during this 5-year plan depends primarily on the rate of developments within the telecommunications industry. Assuming current schedules are met by the industry, our proposed budget allows for the acquisition of new hardware by 2001; if not, the developmental programs we propose will have positioned IRIS to take advantage of the new systems as soon as they become available.

In this section we summarize current and potential applications of telemetry in seismology, explore some of the technical and cost details of trends in telemetry as they relate to IRIS programs and indicate how we propose to phase in enhanced telemetry operations over the next five years.

Advantages of telemetry

Telemetry is the key to the evolution from *stations* to *networks*. Most experiments and applications in seismology are based on simultaneous observations at multiple stations. Recent advances in telemetry open the path to continuing the evolution of GSN and PASSCAL from observations at isolated, independent stations to the IRIS goal of fully coordinated real-time collection of data from true regional and global networks.

(In this discussion we use "*networks*" to describe any coordinated group of *stations* and "*arrays*" to refer to a special class of network where there is a specific geometrical arrangement of sensors, designed to be summed and phased in the enhancement of signal-to-noise and extraction of signal characteristics.)

There are numerous advantages to collecting and recording all data in real time. Only in some applications, such as wireline systems in seismic exploration or tight arrays with radio telemetry, are stations spaced close enough together for this to be easily accomplished. In most seismological experiments, the distances between stations have made real-time recording difficult - until now.

While there have been some significant successes in the use of telemetry by both GSN and PASSCAL, the primary mode of data collection by both programs remains the independent, on-site recording of data at each sensor location. Whether the site is a GSN station, a PASSCAL station in a long-term broadband experiment or a short-term PASSCAL experiment recording a series of explosions, data are usually recorded on a local system (disk and/or tape); collected at relatively infrequent interval (usually weekly or monthly); and returned to a collection center to be checked and collated with the rest of the network.

The scientific, operational and financial advantages of real time access to data from remote stations are numerous.

- The advantages of real time analysis of significant earthquakes, for hazard assessment, response efforts and for fundamental scientific purposes have been highlighted elsewhere in this proposal. The availability of real-time data also enhances the utility of GSN data for applications in nuclear monitoring.
- The availability of a telemetry option with PASSCAL instruments has opened exciting new options in experiment design through the application of phased array and network processing.

- Quality control - Communications with remote data loggers allows the monitoring and control of station operations, in addition to collecting primary data. The ability to continuously monitor station operations greatly enhances data quality and reliability by allowing problems to be detected and corrected quickly.
- In the development path we are proposing, the same PASSCAL recorders will be capable of operation in stand-alone or telemetry mode so that users will be able to design deployments which are best suited to their experiment goals.
- With continuous and reliable data collection via telemetry, the deployment of unattended, fully automatic stations becomes a possibility. These stations would not require weekly servicing to change tapes. They could operate without failure-prone mechanical systems such as tape drives. As experience with national networks in Canada, the US and Australia has show, this mode of operation can be much less costly. This may not be the preferred mode of operation at many of the GSN stations, where local involvement of operators is important, but even at manned sites, remote diagnostics should be able to reduce the frequency of maintenance visits.
- In long term deployments of widely distributed PASSCAL instruments in broadband experiments, telemetry would significantly reduce operational costs. One of the major expenses in these experiments is the travel required for regular service of instruments and collection of data. Remote access and data collection would also assist the PI in experiment planning and quality control. While these cost savings in PASSCAL experiments would not directly impact IRIS budgets, they would reduce the funding required from NSF for experiment support.

Current IRIS Use of Telemetry

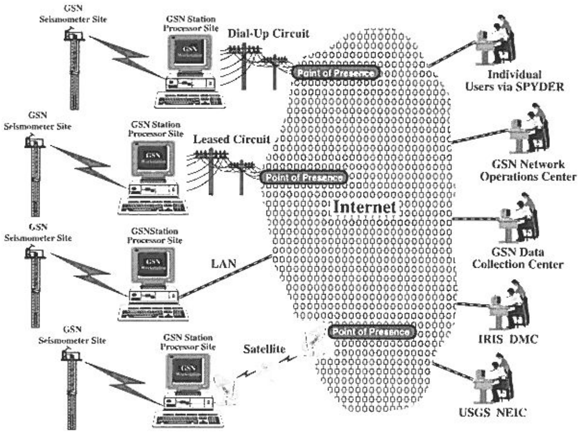
As discussed in more detail in the Program sections of this proposal, IRIS has already stimulated significant innovation in the application of telemetry to data recovery. The greatest successes have been exploitation of the rapidly expanding Internet, coupled with the use of telephone dial-up links to retrieve GSN data and the use of radio telemetry in regional and local arrays.

- Working with our colleagues in the FDSN, the SPYDER™ system at the DMC uses the Internet and telephone dial-up to recover data in near real time for all significant events. In addition, the DMS makes use of the Internet as its primary mode of data distribution.
- The PASSCAL program has implemented the ability to recover "State of Health" information, limited to a few bytes per day, using the ARGOS satellite system.
- The IRIS/IDA network uses leased lines within the former Soviet Union and satellite telemetry as an extension to Internet to obtain real time access to stations in Russia. Other IRIS/IDA stations make use of Internet protocols over dial-up circuits and a NRTS (near real time system) hub at UCSD to retrieve selected station data on a routine basis and event data on request from SPYDER™.
- PASSCAL instruments have been enhanced to allow access to individual data segments on disk, so that modem connection through dial-up circuits can be used to request event data as well as state-of-health.
- The Joint Seismic Program (JSP) has supported several arrays of PASSCAL instruments in network configurations with central recording. Novel telemetry solutions continue to be developed that will ultimately benefit other IRIS programs.
- IRIS has experimented with INMARSAT satellite terminals to enable recovery of data from GSN stations where local telephone access is limited.
- IRIS is involved in discussions with the Joint Oceanographic Institutions (JOI) and UNIDATA, both NSF sponsored projects with goals common to those of IRIS, in the use of remote Internet connectivity for data distribution and communications.

Applications beyond seismology

Seismology could play a leading role in taking advantage of the application to the Earth sciences of new and exciting opportunities in global data collection. In terms of ground based techniques (i.e. excluding scanned satellite imagery), the data demands of seismology exceed those of most other areas of our science. Few sub-disciplines require continuous sampling at remote sites of 10's of samples per second (10 Mbytes/day). Seismology provides the opportunity to develop the infrastructure on which other geophysical and environmental sampling could ride with little impact. In addition, the costs inherent in developing the sites and acquiring the instrumentation for a seismic station are relatively high, so that the addition cost of other sensors is minor in comparison.

Providing data to researchers through the Internet is one of the more successful areas where IRIS has been able to take advantage of modern technology to have a significant impact on seismological research. The distribution of data no longer relies on the user being at a major facility with extensive data storage and computational resources. Enhanced global communications now offers us the opportunity to extend this to the collection side of the data management process as well. We hope to be able to collect data from any part of the Earth's surface, independent of local infrastructure. The impact throughout the Earth sciences can be enormous. As satellite-based

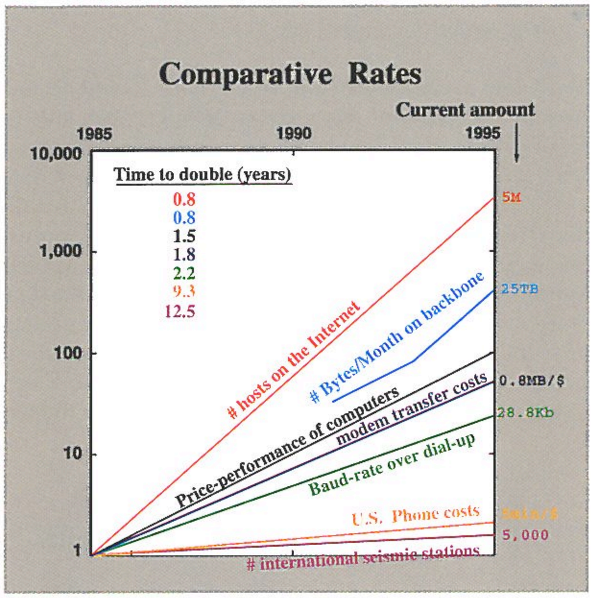


The Internet serves as the access link between the GSN stations and users. GSN stations are connected to the Internet through a variety of communications links. Data access, state-of-the-health and remote system administration are avaiable to network operators and the DMC. Other users have open access to data. (Figure provided by Jon Berger, UCSD) communications networks expand and costs decrease, it will be become logistically and economically feasible to design experiments based on the desired distribution of sampling points, unfettered by the necessity of a pre-existing ground-based infrastruture.

Internet and Global Data Collection

The Internet provides both a model and a vehicle for IRIS in our pursuit of more effective and efficient means for collecting and distributing data. Internet will continue to provide the backbone for our data distribution and, as it grows, will become increasingly important in data collection.

As costs of international telecommunications continue to decrease and their availability becomes more global, private communications channels, using Internet protocols, will be able to extend worldwide and provide us with connectivity to remote stations anywhere in the world.



A comparison of the exponential rates of growth of the Internet and changes costs and capabilities of some commincation links. "Current amount" on the right sets the absolute scale for each parameter, relative to the logarithmic scale on the left. Note that the use of the Internet more than doubles each year. The increase in communication speed ("baud rate over dial up") combined with the realtively low rate of increase in telephone costs has resulted in rapidly decreasing costs for data telemetry (increasing MB/$). (Figure provided by Steve Malone, University of Washington)

In anticipation of the continuing spread of telecommunications availability to a near-global scale, a system is being developed and implemented at some of the GSN stations which treats the stations themselves as nodes on the Internet. This system is designed to provide both continuous and occasional data telemetry from the stations to remote (from the station) users with the following goals in mind:

- To support real-time seismology
- To expedite data collection
- To aid station operation and maintenance
- To provide a "standard" computing environment for applications development
- To provide a networking environment with the following minimum application level services:
  Electronic Mail
  File Transfer
  Remote Login
- To facilitate access to Internet and its associated telecommunications infrastructure for the local host organizations.

As illustrated in the accompanying figure, this system relies on various privately supported communication modes to reach an Internet "point of presence" (IPoP) and create a wide area network (WAN) - an enterprise Internet. In essence, this structure is different only in scale from the local area network in the office or laboratory - "private" communications channels provide connection between nodes and to the Internet, with the entire system relying on Internet, or similar, protocols. The figure illustrates the variety of possible interconnects between a GSN site and the Internet; similar modes of telemetry could support remote PASSCAL deployments:

- Connection through a local area network (LAN) already on the Internet.
- Connection through a dedicated (leased) telecommunications circuit to an Internet "point-of-presence"
- Connection through a dial-up telecommunications circuit to an Internet "point-of-presence"
- Connection through a satellite circuit for those stations unreachable by existing telecommunications circuits

The station node, interfaced to the GSN data acquisition system, provides access to all data normally recorded on-site. The standard communications protocols of the Internet, the TCP/IP utilities, can support both continuous data telemetry and occasional data request and delivery. Additionally, they can provide major support for operation and maintenance functions such as message traffic with the station operators, and, through TCP/IP's remote login utility, monitoring station state-of-health and remote systems administration.

Perhaps the most important element of this system, is that by its design and implementation it provides the local host organization and/or station operator with Internet access. Not only does this provide the familiar suite of information access for the local personnel but it helps immensely in drawing them into the international seismological community through email and exchange of data and processing tools.

A Practical Application - Real-Time Telemetry of GSN Data to NEIC

As an example of the practical use of real-time telemetry, we describe ways in which data from GSN stations can be used to improve the USGS NEIC Automatic Alert, Early Alert and QED bulletins.

The Automatic Alert is, as the name implies, a bulletin-producing system that operates without analyst intervention. It uses telemetered real-time data mostly from the US National Network to produce preliminary locations of event within minutes of their origin time. The reception of the Alert Bulletin message at the DMC triggers data collection by the SPYDER™ system. Once analysts are notified by the output from the Automatic Alert system, the Early Alert and QED systems go into operation. The IRIS DMS automatically supplies waveform data to these systems through SPYDER™ and there have been significant improvements in the quality of event location from the Early Alert and QED systems since GSN data have become available.

The Automatic Alert provides excellent coverage for the continental US and good coverage for North America. The sensitivity of global coverage would be greatly improved if there were immediate access to stations outside North America. It is through the provision of real-time data from selected GSN stations overseas, that IRIS can make a significant contribution in the improvement of this NEIC capability.

The USGS has developed software called a "Virtual Data Logger" which, when installed on a suitable station processor, acts as the interface between the station and the Automatic Alert System. For GSN stations which have dedicated telemetry links or direct Internet connections, this provides a mechanism for convenient real-time access by NEIC. This software is now running experimentally on some IRIS/IDA stations and will be extended to all GSN stations with real time capability.

We will continue to work with NEIC, and with the international nuclear monitoring community, to identify important stations for improving global coverage. As the costs for telemetry decrease and our "enterprise Internet" expands, increasing numbers of GSN stations will be able to provide continuous data to NEIC in real time. In the meantime, priority will be placed on insuring that critical stations are equipped with appropriate modes of dial-up access for use in refining epicenters with data collected by the DMC through SPYDER™.

Communications Tariffs - 1995

Circuit Type	Speed	Tariff	Cost/ station-day
International Leased Actual for 5 sites in former USSR	9.6 Kbps	~$100/day	~$100
International Dial-up Voice Circuit	9.6 Kbps	~$1.25/min ~$20/MByte	~$200
INMARSAT-B High-Speed Dial-up Circuit	64 Kbps	~$10/minute -$25/MByte	- ~$250
Dial-up ISDN (very limited availability)	64 Kbps	~$2/minute ~$4/MByte	~$40
Communications Tariffs - The Future?†			
Global Cellular	64 Kbps	~10¢/minute ~25¢/Mbyte	~$2.50
Global Cellular	2.0Mbps	<$2.50/minute <20¢/Mbyte	~$2.00

† These estimates are based on projections for systems which will not be available until at least 2000. Whether the systems arrive on-schedule and on-price is a matter of some debate. However, these estimates are indicative of directions within the telecommunications industry and systems with these capabilities are very likely to emerge within a decade, if not within the next five years.

IRIS and Arrays

Extending the PASSCAL Facilities

As seismology advanced into the computer age, the science went through a series of evolutionary changes that involved both the theoretical and observational disciplines. For seismologists, the digital computer and associated mass store and instrumentation are powerful tools that continue to open many new possibilities for exploring the Earth. Traditional forms of analysis, involving hand-measured onset times and amplitudes from analog records, have yielded to full waveform processing using high quality all-digital data streams.

At the forefront of the digital revolution in seismology are researchers who have employed large scale, multi-channel data processing techniques to image directly the 3-dimensional seismic wavefield or to image directly or indirectly three-dimensional Earth structure. Such efforts require combining data from a set of spatially distributed sensors, commonly referred to as seismic arrays.

All seismic arrays offer substantial "vision" improvements over traditional single-site observatories. The coherent spatial sampling of an array increases the dimensionality of observational space and sharpens the image of the elastic wavefield relative to what we see with a single-site sensor or recordings from a network of sensors treated as separate waveforms. Using arrays, we can decompose the seismic wavefield into a wide spectrum of primary and secondary observations that we can apply directly to the problems of source, structure and propagation.

Large scale, multi-channel waveform processing using seismic data from arrays of all spatial scales is an increasingly important observational technique for all seismologists. We can cite many examples of the observational effectiveness of seismic arrays. Outside of the exploration and active source domain, most older examples involve nuclear monitoring arrays at teleseismic and regional distance. These arrays employ the simplest type of plane-wave slant-stack processing and make use of the signal focusing and phase identification properties of the arrays for source detection, location and discrimination. Nuclear monitoring arrays typically have small aperture (2-10 km) and operate in a frequency range where static time and amplitude corrections, although computed and normally used, are unimportant in the basic functioning of the array.

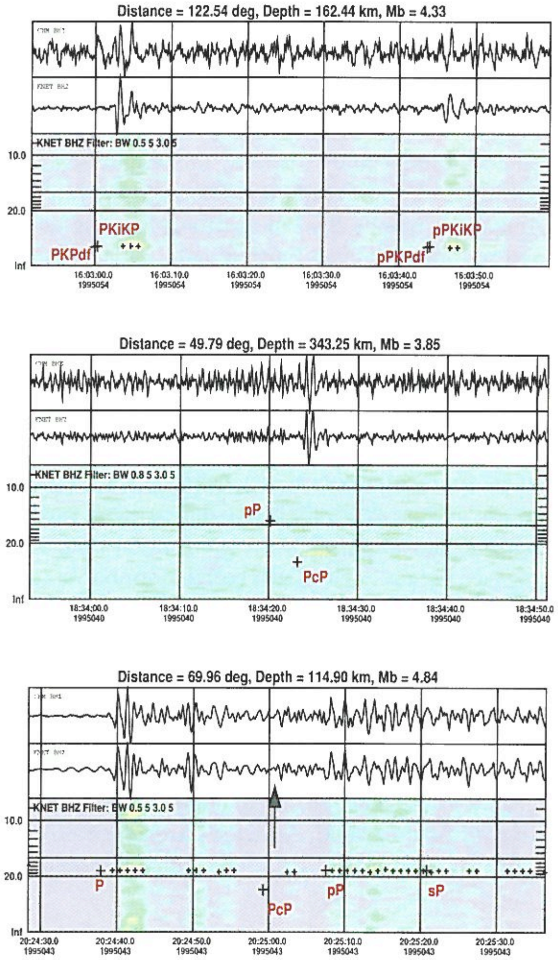


Figure 1. Use of the Kyrghyz Network as a seismic array for teleseismic events. Each panel shows: (top)a bandpass filtered version of the reference station (center) a similarly filtered "best" slant-stack beam, (bottom)a time-slowness grid of beam power. Predicted phase times and slownesses, using travel time tables, are shown as the dark red labels and '+' characters. Slowness-time grid values with high coherence across the array are shown as black '+' characters.
The topmost panel shows enhancement of small magnitude events. The middle panel shows enhancement and indentification of a PcP phase instead of pP.
The bottom panel shows how an array can be used to enhance and identify small precursory or coda phases and discriminate near receiver scattering from scattering that takes place far from the receivers. Although there is an arrival (shown by the green arrow) close to the predicted PcP time, this arrival has the same slowness as the depth phase and therefore cannot be PcP. This is possibly a depth phase precursor and could be an underside reflection from a shallow Moho. Most of the coda energy following the first P arrival is similar to the initial P arrival indicating that the coda was most likely generated near the source region.

There are more recent examples of array deployments that illustrate the wide range of observations these facilities provide. Small aperture 3-component array data are being used to observe the detailed characteristics of scattering properties along regional distance propagation paths using eigen-system analysis methods (Wagner, G., Owens, T., Regional wavefield decomposition and characterization using three-component seismic array data, Submitted to Journal of Geophysical Research, March 1995) and beam-stack imaging (Hedlin, M., Minster, J., Orcutt, J., Resolution of prominent crustal scatterers near the NORESS small-aperture array, GJI 119, 101-115). These processing methods allow us to identify and locate scattering bodies spatially and to separate the parts of the seismic coda produced by forward, anisotropic scattering and backward, isotropic scattering. The large aperture array in Kyrghyzstan (about 200 km aperture) is being used to enhance and identify deep Earth phases, such as PcP; to enhance and identify near source secondary phases, such as depth phases and depth phase precursors; to enhance and identify surface reflection phases and precursors, such as PP; and to analyze the scattering properties of surface waves. We have found that the wavefield is sufficiently coherent to allow us to stack the data up to a frequency of several Hz for most events at distances greater than about 25 degrees, as long as we apply two dimensional slowness varying time and amplitude corrections to the data before stacking (see Figure 1 and "Cross correlation analysis using teleseismic events recorded by the JSP Kyrghyz Network for crust and upper mantle time residuals" in Part II of this proposal).

The power of seismic arrays in making observations relevant to earthquake and tectonic processes was clearly demonstrated in a recent project to monitor seismicity near an active oil field in South America (Archambeau, C. B., "A study of fine scale structure and microtectonic phenomena using cluster arrays", Seventh annual IRIS workshop, Summer, 1995). A technique was used (Gurevich, V., Kiselevich, V., Shoubik, B., "ASET - Array based seismic emission tomography", IRIS Newsletter, v. 14, no. 1, pp. 10-11, 1995) in which noise was stacked to sub-surface spatial coordinates to produce an image of low-level seismic "emissions" associated with very small seismic disturbances and what would normally be considered aseismic fault slip. These emissions correlated with known fault geometry determined from well logs, geologic maps and 3-D seismic reflection surveys and they were used to define the spatial-temporal variations in slip along the fault.

Some of the most productive research in the last several decades has involved using the global seismic network as a seismic array. The work done by Shearer (Shearer, P., "Imaging global body-wave phases by stacking long-period seismograms", J. Geophys. Res., 96, 20353-20364, 1990) is a clear example of using GSN data to form global-wide "gathers" for subsequent array processing to clarify wavefield images showing teleseismic arrivals. Studies by Revenaugh and Jordan (Revenaugh, J., Jordan, T., "Mantle layering from SCS reverberations 3. The upper mantle", JGR, v. 96, pp. 19781-19810, 1991), used stacking and migration techniques, applied to global network data to determine mantle layering. We can consider the very productive work done by a variety of researchers who have used global network normal mode and surface wave waveform data to invert for Earth structure as an exotic and effective form of array processing. A number of studies using regional networks as large aperture seismic arrays have been conducted within the past five years. A good example of this is the work of Vidale and Benz who combined some 800 stations from regional networks in the western United States into a giant array to look for

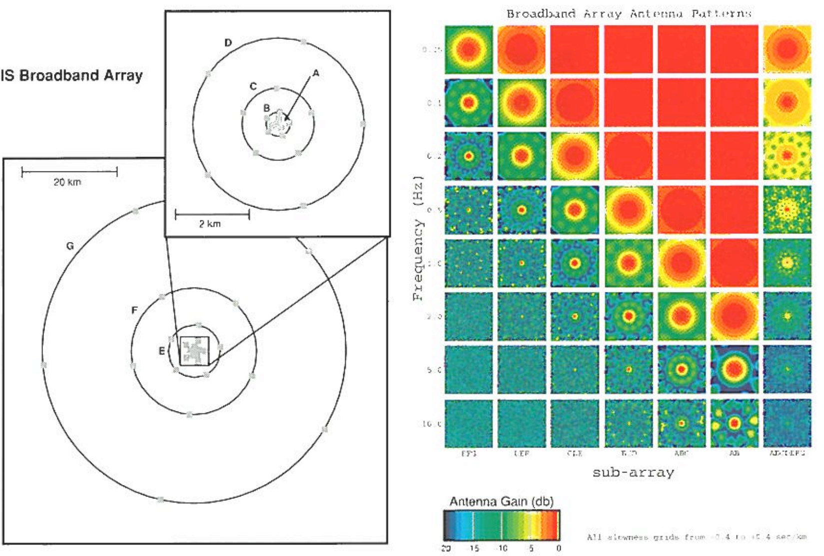


Figure 2. The panels on the left show the layout of a proposed IRIS Broadband Seismic Array, designed to provide enhanced array performance from 0.05 to 10.0 Hz. The total number of array sites is 34. A geometric rule was used to determine the radius to each of seven concentric rings that make up the array. This non-uniform spacing provides a nearly uniform mix of spatial scales while requiring a relatively small number of stations. Array antenna gain patterns in the east-west north-south slowness domain at fixed frequencies are shown in the panels on the right. We have computed the gain patterns for a number of frequencies, shown along the left of the grid, and using various sub-array configurations, shown along the bottom of the grid. The sub-array identifications show the rings that were used to produce the gain patterns (the center element was included in all of the sub-arrays). In a real array processing system we would process in the frequency domain and apply continuous frequency variable weighting functions to each array element before stacking to produce optimum antenna focusing properties.

upper mantle discontinuities (Vidale, J., Benz, H., "Upper-mantle seismic discontinuities and the thermal structure of subduction zones", Nature, v. 356, pp. 678-683, 1992).

A seismic array provides a wealth of new information that cannot be obtained from a single-site sensor deployment. This new information relates to the spatial characteristics of the seismic wavefield that are essential to determining the 3-dimensional properties of the Earth's structure, clearly an important goal in many ongoing scientific endeavors. Arrays can also be used as far reaching seismic telescopes for clarifying the images associated with near-source and deep Earth propagation paths. Except for telemetry, the instrumentation for seismic arrays is functionally equivalent to existing networks. The network becomes an array when the individual channels are treated as coordinates in a network-wide "gather" vector and these gathers are processed to return detailed wavefield and/or structure parameters.

Only recently has array seismology moved beyond the areas of low frequency global seismology, nuclear monitoring and shallow structure. In the past, using seismic array data was hindered by the inavailability of data and a variety of technological concerns, including inadequate seismic instrumentation, insufficient computer processing and memory, and the lack of software to manage and process such large volumes of information. In the past, the application of array techniques to the global seismic network required extensive effort in acquiring, organizing and managing the data. The problems could only be solved with large expenditures of money, thus the richest members of the seismological community – chiefly those involved in exploration and nuclear monitoring – were the only ones who could afford the technology. Later, as the technology improved and the cost dropped, researchers at a few well-funded institutions were allowed into this select group of scientists with sufficient financing to use array seismology.

Over the past five years IRIS has made significant quantities of data available to the entire community in a standardized form, and the technology has made giant strides as well so nearly all researchers can afford the computer and processing resources required. Today's computers are more than adequate to handle the work required by array seismology, and expansion of the information super-highway has introduced many free software resources to aid in data management.

Paralleling the revolutionary developments in computer hardware and processing software since 1980, the array field data acquisition systems have also been transformed. Seismic array data acquisition systems consist of four primary elements. The first element is the sensor which in modern systems is a broadband seismometer or a force-balanced accelerometer. These active sensors, which have been developed during the past 10 years, have the unique and desirable properties of having extremely wide dynamic range (~140 dB) along with a broadband frequency response (3 to 4 decades in frequency). Simultaneously, digital data-loggers were designed using low power 24-bit A/D converters and digital signal processors to provide multiple data streams, sampled at different rates, with similar dynamic range to the sensors. The most critical element in operating an effective seismic array is to devise a timing system that will synchronize all digitizers to sample each channel simultaneously. This requires a common time base that can be accomplished by sending a common signal to all stations from a central site or system. In practice the most effective methods are to broadcast a radio or wireline signal (for array apertures less than several kilometers) or to use the recently available GPS satellite time signals. The final element of implementing a seismic array is the collation and storage of the data. In the standard GSN network configuration, or PASSCAL experiment, the data are stored on site and then delivered by tape to a data center where the combined network or array dataset is assembled.

Sponsored by the IRIS Joint Seismic Program a new array data acquisition system was developed called the JSP Broadband array. This system uses broadband sensors, PASSCAL dataloggers and time keeping systems, forming the first three of the previously defined elements (see Figures 2 and 3). However, there is a significant change in the collation and storage of the data for the JSP Broadband array. This new system uses digital telemetry to transmit data to a central site where the data from every station are combined into an array data stream. This array data stream is processed in real-time which allows sophisticated signal detection algorithms to be implemented. The telemetry requirements for the JSP Broadband array will support use of many types of digital telemetry, including wireline, narrow-band FM and spread spectrum radio, and telephone communications systems. The flexibility of the JSP Broadband array design was demonstrated in temporary deployments of small aperture arrays at Pinyon Flats, California; Geyokcha, Turkmenistan; and in a 200 kilometer aperture seismic network in Kyrghyzstan. This system can also be deployed as part of RAMP responses for major earthquakes to provide real-time aftershock locations and magnitudes in places where there is no existing infrastructure or if the existing seismic monitoring systems are damaged.

We can now provide a significant boost to the scientific productivity of our community with a relatively small investment in money, people and time. Not only can we glean more information from the considerable amount of data in our archives, but we can also provide powerful tools that can be used with virtually every new PASSCAL broadband experiment. We can leverage the investments in seismic instrumentation and data management, made through the various IRIS programs, into a new generation of seismic observational facilities with greatly expanded capabilities. We propose to build upon the accomplishments of the IRIS programs by providing the research community with enhanced array facilities, along with the data management and processing tools necessary to make the most effective use of array data. We also propose to continue the technological developments that resulted in the current capabilities, namely radio telemetry and software development.

Enhancements to the PASSCAL and DMS programs, described in the PASSCAL and DMS implementation plans, would provide the research community with new array capabilities. These include:

- Procurement of a set of telemetry-based data acquisition systems and development of an array support center. These systems will be used in the same manner as stand alone PASSCAL systems, i.e. to support research efforts funded through NSF or DOD. These systems will provide versatile array facilities for deployment over a variety of scales from small aperture to apertures of up to several hundred km. The array center would be responsible for support in deployment of the arrays and development of new array technology
- Support of software development, through a software development center as part of the DMS, to provide the research community with tools for managing and processing data associated with array deployments. This center would work closely with both the DMC and the new Array Instrument Center to provide the software tools needed by PIs using the new array equipment. Software would be standardized and distributed through the DMS.

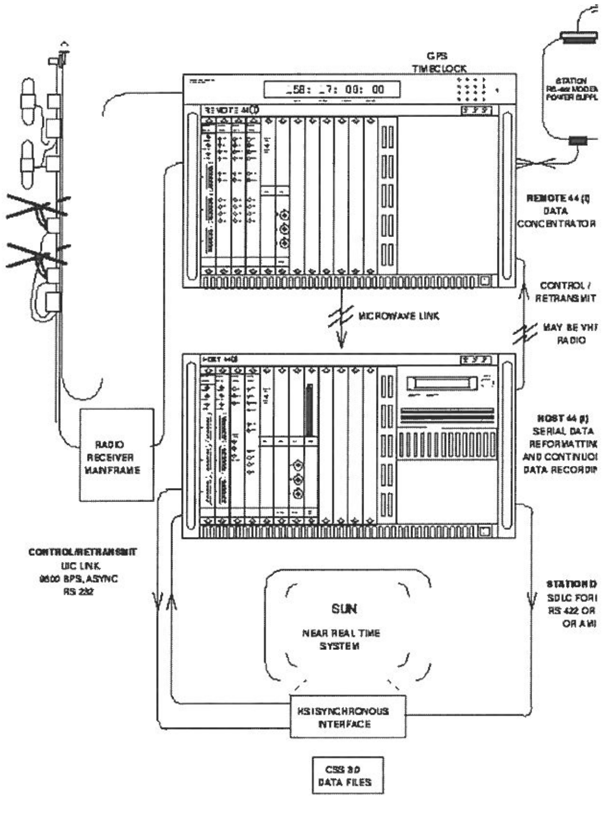


Figure 3. Diagram of central array processing site. The REMOTE 44(I) functions include the following:
1) transmits commands and time to each of the remote stations.
2) sets array time using the co-located GPS clock.
3) receives compressed data packets from each station.
4) requests packets to be retransmitted if one has been corrupted.
5) transmits all data packets through an SDLC high-speed serial link to the HOST 44(I).
The serial link can be either use wireline, microwave, or satellite communications.
The HOST 44(I) functions include the following:
1) receives data packets through an SDLC high-speed serial link from the REMOTE 44(I).
2) requests data to be retransmitted if a packet has been corrupted.
3) decompresses data packets.
4) time aligns the data.
5) records continuous data stream on DAT tape.
6) transmits all data packets through an SDLC high-speed serial link to the SUN near real-time system.
The SUN near real-time system will determine event triggers, record data, and allow for INTERNET connection to access any data of interest.

Shallow Imaging

Structure and Wave Propagation in the Upper Kilometer

Introduction

Human observations of and interaction with the Earth occurs most directly in the uppermost region of the Earth's crust, yet this is an area traditionally overlooked by seismologists. One of IRIS-PASSCAL's goals since its inception has been to use seismology to understand geologic processes, properties of earth materials, and seismic wave propagation. We now seek to work on a new scale, in the upper 1 kilometer of the Earth's crust, where we can address these questions in detail with the opportunity to verify our results with ground-truth testing. High-resolution geophysical methods, in particular high-resolution seismic reflection profiling provides a unique opportunity to image the near surface directly addressing a host of geologic questions with both scientific and societal relevance. The primary goal of this initiative is to facilitate the acquisition of unaliased 3-D data sets to assist geophysical imaging of the near surface.

The shallow subsurface is an incredibly heterogeneous region and provides an exciting natural laboratory to look at theoretical problems in wave propagation in highly heterogeneous medium. In shallow profiling it is quite common to record frequencies in the 100-500 Hz range yielding resolution of less than a meter allowing us to image subsurface structure and stratigraphy in incredible detail. Collection of shallow subsurface profiles is straightforward making the routine acquisition of 3-D data volumes possible. We can begin to address geologic problems from a 3-D perspective, that up until now we have only looked at on spatially limited 2-D cross sections, and as a result, greatly increase our understanding of a variety of tectonic processes. Since these seismic investigations are focused on the near surface, results of profiling can be verified by shallow drilling or in some cases by rock outcrop. Collection of high resolution geophysical data sets is quite feasible and is cost effective using current technologies. Shallow imaging by its very nature affords us the opportunity to produce high-resolution images with ground truth control. As seismologists we can make concrete contributions to Earth science and society, directly impacting the way we interact with our environment. This initiative, to use seismology to investigate the upper 1 km of the Earth's crust has direct applications to geological investigations, theoretical seismology, and societal issues and will equip Earth scientists with important, relevant skills as we head into the 21st century.

Application to Geologic Investigations

High-resolution images of the upper 1 km of the subsurface can lead to a broader understanding of the processes shaping the Earth's crust. High-resolution images are probably our best means for directly imaging subsurface faults and understanding the genesis of fault plane reflections. Specific reflection events or patterns of reflectivity can be unequivocally tied to fault zone characteristics, zones of cataclasis, mylonitization, mineralization, or pore fluids. High-resolution profiling can also be an aid in neotectonic studies by identifying and mapping both discrete and broad zones of deformation in the subsurface. In active tectonic areas, high-resolution imaging techniques can be used to map fault networks in the shallow subsurface in both two and three dimensions relating surface observations from geodetic measurements to the tectonic processes causing uplift or subsidence. In addition these techniques can be used to directly image seismically active faults zones helping us learn about fault plane rupture and propagation as well as the geometry of buried faults.

High-resolution shallow profiling can also be used to map subsurface stratigraphy with applications to studies of Quaternary stratigraphy and climate change. Subsurface profiling can be used to define the geomorphology and history of sea-level change, glacial advances and retreats, the record of erosion, and sediment budgets. High-resolution profiling can increase our understanding of sedimentalogical processes and depositional systems in terrestrial, lacustrine, esturine, and shallow shelf environments, particularly when tied to selectively placed shallow sediment cores.

This text was prepared by Anne Meltzer at Lehigh University and reflects conversations held with many other seismologist over the last year at AGU meetings, the ILIAD conference, and IRIS annual meetings. In particular these ideas were significantly improved and clarified by input from Sue McGeary (U. of Delaware), Alan Levander (Rice University), Dave Okaya (USC), Tom Pratt (USGS), and Bill Stephenson (USGS).

Finally, high-resolution shallow reflection profiling allows Earth scientists to extrapolate surface observations of geology into the sub surface. These profiles can be used to map crustal structure on the scale of meters to hundreds of meters in both two and three dimensions, and can be used to tie surface geology to standard crustal scale reflection profiles.

Application to Theoretical Seismology

Shallow seismic studies have great potential to increase our understanding of seismic wave propagation and the seismic technique. In shallow seismic studies we can sample the near-source wavefield and image rocks that can be directly sampled and whose material properties can be measured in the laboratory. This provides seismologists with the opportunity to study reflectivity patterns from both a deterministic and stochastic perspective. In a controlled environment we can observe and measure the linear portion of the wavefield and directly examine in situ the attenuation, absorption, and anisotropy of Earth materials with a minimum of assumptions. Near surface profiling provides an unprecedented means for the direct comparison of physical properties with the seismic wavefield, linking rock and seismic properties. These types of theoretical investigations are equally applicable to both compressional and shear wave studies.

Applications with Societal Relevance

An understanding of the upper 1 km of the Earth has direct impact on societal issues including evaluation of groundwater and mineral resources, mitigation of environmental hazards, earthquake hazard assessment, and education. Currently the most common technique used to characterize near surface materials in both groundwater and environmental hazards studies is shallow well boring. This can be expensive and in the end only provides point by point information about the subsurface. One knows little about the lateral extent of key horizons, structures, and material properties (porosity and permeability) in the highly heterogeneous near surface. Shallow reflection and refraction methods are non-invasive techniques that can be used to define the continuity of stratigraphic layers, pinch-outs, fault geometry and distribution, and depth of overburden (depth to bedrock), all of which are important parameters in geotechnical investigations. Shallow seismic profiling can be an inexpensive and efficient means of developing an effective strategy for sampling using well bores. High-resolution seismic profiling is extremely useful for delineating potential earthquake hazards in seismically active areas, particularly when active faults do not break the surface. Seismicity patterns established from local and regional seismic networks can be further investigated using reflection profiling techniques and information on material properties can be used in source function analysis.

Instrumentation

The primary goal of this initiative is to use seismology to understand geologic processes, material properties, and seismic wave propagation. To accomplish our goal we require unaliased 3-D data sets. Shallow seismic imaging of upper 1 km of the crust, as opposed to the whole crust or combined crustal/upper mantle experiments, requires the use of sensors ranging from 6 Hz to 100 Hz deployed at spacing of 0.25 to 50 meters. Sensors are typically cabled together. These recording capabilities, which are not

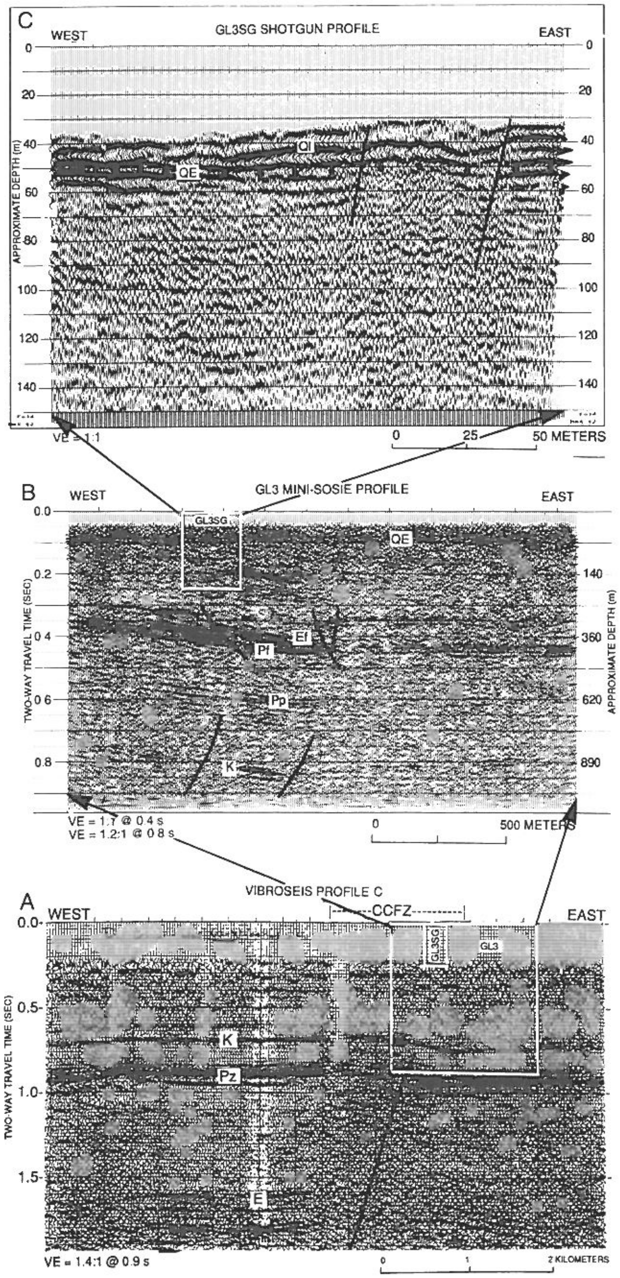


Figure 1. Examples of high resolution seismic imaging at different scales. Reflection profiles over the Crittenden County Fault in the New Madrid seismic zone. (from R.A. Williams et. al., The Leading Edge, January 1995, p. 30-34)

inherently expensive, are not currently met by the PASSCAL instruments or other equipment available through IRIS. The current generation of PASSCAL REFTEK instruments are not suitable for common-midpoint seismic reflection profiling because:

- Either continuous recording or a very large number of programmed windows are required to record hundreds of sources.
- Reflection experiments typically use "roll-along" acquisition. REFTEK instruments would need to be moved regularly from the back to the front of the recording array - this is both time and labor intensive.
- The cabled REFTEK system requires moving large numbers of bulky instruments in addition to heavy unwieldy cables (take-outs at 50 m) and geophones.
- Scheduling REFTEK instruments for high-resolution near-surface profiling will conflict with larger crustal and array experiments. Scheduling the existing PASSCAL instruments is already difficult - demand exceeds supply. As demand continues to grow and as new applications for profiling develop, this problem will continue to worsen. In the end we will be limiting our science solely because of inadequate instrumentation.

It is time for IRIS PASSCAL to include the capability to collect high-resolution, unaliased, 3-D reflection data sets in the upper kilometer of the Earth as part of its facilities. At a minimum we would like to have available 2500 channels of recording capability for university researchers. 2500 channels will provide us with enough channels to record a high-resolution 3-D seismic survey. A near surface high-resolution imaging capability can be provided either by multichannel cable systems or perhaps the proposed "Walkman seismograph". Multichannel cabled systems represent "off the shelf" technology. These instruments are available now on the open market; no development costs would be incurred by IRIS. These instruments could be used as single clusters for relatively small experiments to obtain high-resolution images of near-surface strata, as a linked set of instruments for larger experiments requiring more channels, or to augment the REFTEK pool of instruments during crustal-scale experiments. Whether the need for a high-resolution imaging capability is meet through the acquisition of multichannel cable systems, or through the "Walkman seismographs" it is important to point out that both technologies put more channels on the

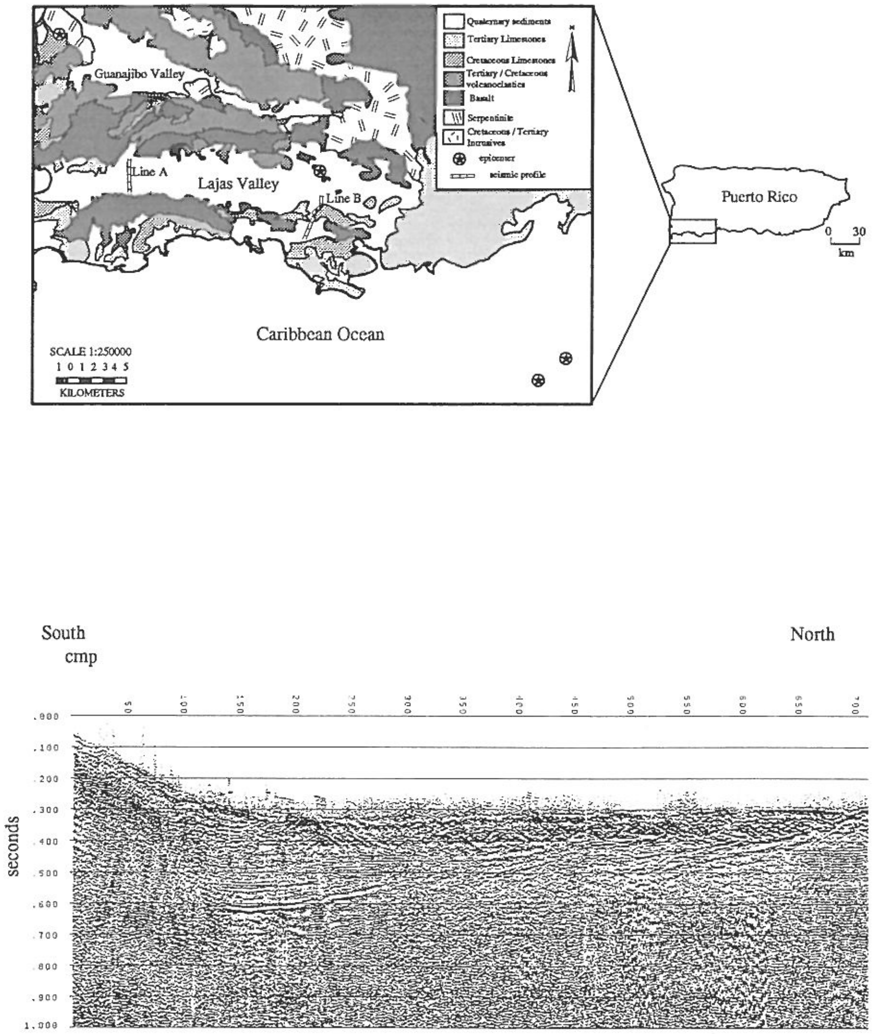


Figure 2. Location map (top) of high resolution seismic reflection profiles collected to define the geologic and geophysical characteristics of the Lajas Valley, Puerto Rico. These structures are assoicated with the current seismicity occuring in southwest Puerto Rico. Brute stack (bottom) of line A. High resolution reflection surveys may image the internal structure of the valley fill sediments and basement contact in areas of active seismicity were there is no surface expression of faulting. Temination of reflectors at 0.6 s two way traveltime near shotpoint 125 indicate the Lajas Valley is a fault bounded structure. (Figure provided by Anne Meltzer, Lehigh University)

ground at considerably less cost than the current REFTEK instrument, going a long way towards meeting the original IRIS goals.

Providing the equipment necessary for high-resolution near surface crustal imaging will fill a void in the current IRIS PASSCAL instrument pool, anticipating the growing demands for this capability and its importance in future seismo-logical investigations. Over one third of the IRIS member institutions recently responded to an informal survey expressing an interest in near-surface geo-physical investigations. There is a great deal of enthusiasm in the community from investigators using high-resolution geophysics to study a range of problems in the near surface including: hi-resolution reflection profiling (2-D, 3-D), 3-D imaging, environ-mental studies, hydrology, neotectonics, fault imaging, theoretical seismology, Quaternary stratigraphy, depositional processes, climate change, geomorphology, rock properties, earthquake hazards, environmental remediation, engineering applications, and archeological applications. There is a wide diversity of equipment in the community - different vintages, makes, and models of multichannel seismographs and types of geophones and cable configurations. This situation is somewhat analogous to instrumentation within the earthquake community prior to the founding of IRIS. It is clear that the next 5-10 years holds the real potential for exciting and innovative research in imaging the upper 1 km of the Earth's crust , true 3-D imaging of complex structures, and insights into understanding wave propagation in real media and site response. If IRIS can provide a facility to allow investigators to conduct these types of experiments, we will see a real advance in our science as well as significant contributions to society.

The Ocean Seismographic Network

Broadband Seismology in the Oceans

Scientific Rationale

There are two types of scientific objectives that require an Ocean Seismic Network (OSN): global problems requiring as broad a distribution of permanent seismic stations as possible, including coverage in the oceans; and regional questions that address the seismicity, structure and tectonics of specific features within the ocean basins. These two types of studies require different types of instrumentation, although there is overlap in the questions that can be addressed with each.

It is clear large gaps in station coverage of the Global Seismographic Network (GSN) exist in the Eastern Pacific and Southern Oceans and cannot be satisfied with island station. These gaps:

- prevent mapping of much of the core-mantle boundary and lowermost mantle—the region that is probably the origin for hot spots and may be the resting place for old, subducted slabs;
- limit resolution of inner core anisotropy;
- restrict the scale of features that can be resolved in parts of the lower mantle, especially in the southern hemisphere;
- introduce bias into spectral studies of mantle convection;
- cause aliasing between lateral heterogeneities and azimuthal anisotropy in the upper mantle;
- limit azimuthal coverage for studies of seismic sources;
- increase the detection threshold for earthquakes and explosions in some areas.

There are many major scientific questions of regional scale involving lateral heterogeneity, anisotropy, and seismic activity that can best be studied by PASSCAL-like array deployments of broadband ocean bottom seismometers (BBOBS), including:

- Do the velocity anomalies beneath spreading centers indicate passive or active upwelling?
- Are there mantle roots to oceanic plateaus?
- What is the depth extent of asthenospheric anomalies associated with hot spot swells?
- Can hot spot plumes be detected in mid-mantle? What is their form and diameter?
- Are there channels linking off-axis hot spots and mid-ocean ridges?
- What is the difference in mantle structure between tectonic corridors that subside rapidly away from mid-ocean ridges compared to those that subside slowly?
- Is there wide-spread azimuthal anisotropy in the oceanic mantle? Is it frozen into the lithosphere or generated by flow in the asthenosphere?
- Is the decrease in apparent azimuthal anisotropy with increasing age of the seafloor in the Pacific due to the randomizing effects of the onset of small-scale convection?
- Do gravity lineations in the central Pacific overlie small-scale convective rolls?
- Does the apparent direction of anisotropy in the North Atlantic represent large-scale, return-flow in the upper mantle?
- Are the hot spots in the North and South Atlantic that were involved in splitting the continents linked at the asthenospheric level?
- Is there a uniformly distributed level of background, intraplate seismicity in the oceans?
- What causes long-lived earthquake swarms in the ocean basins?
- What is the form of convective flow between the upper and lower mantle in the vicinity of subducting slabs?

History and Plan

In April 1988 a workshop was held in Woods Hole, Massachusetts to discuss the construction and operation of a permanent network of broadband seismic observatories located in the deep ocean (Purdy and Dziewonski, 1988). The clear positive scientific justification and expression of wide community support that resulted from this workshop prompted the formation of a small steering committee, jointly sponsored by Joint Oceanographic Institutions, Inc. (JOI) and IRIS, to lead a continuing effort to achieve this ambitious objective. This group has stimulated numerous planning activities during the past several years, including the important success of having a hole drilled by the international Ocean Drilling Program (ODP) that is dedicated to the testing and evaluation of measurement strategies for oceanic downhole seismic observatories. During March 1991, ODP drilled hole OSN-1, located approximately 225 km south-southwest of Oahu over a "normal" section of thinly sedimented deep ocean crust on the Hawaiian Arch (Dziewonski, Wilkens, Firth, et al., 1992).

Report prepared by Ellen Kappel, JOI, on behalf of the Ocean Seismic Network Steering Committee (G.M. Purdy, chair, J. Orcutt, D. Forsyth, B. Romanowicz and A. Trehu). An expanded version of this report is available from JOI.

Shortly thereafter a meeting in June 1991, co-sponsored by JOI and IRIS, recommended the elements of a pilot experiment(s) that should be carried out at OSN-1 to investigate technological and seismological issues that need to be resolved before it is practical to begin installation of a globally distributed ocean seismic network (Forsyth et al., 1991). One important recommendation called for simultaneous measurements on an island and on nearby seafloor to compare signal characteristics from teleseismic events with broadband noise spectra.

Since that time, with NSF funding, Scripps and Woods Hole scientists have packaged a broadband borehole seismograph (Teledyne-Geotech 54000) and recording system for downhole use in the deep ocean and have tested it in a wethole in Piñon Flat. With NSF and IRIS funding, investigators from the University of Miami, Scripps and Woods Hole are designing and building two prototype BBOBS with sensor packages that can be buried remotely in the surficial sediments. Thus, development of all the hardware for the pilot experiments has been funded. A proposal is currently under consideration at NSF for this critical pilot experiment to take place in 1996 at the Hawaii locations.

While the issues surrounding borehole seismometers versus seafloor or buried OBS are being examined, a proposal is also pending at NSF for scientists at the University of Hawaii, IRIS, Woods Hole and Scripps to re-use the Hawaii-2 undersea cable for long-term geoscientific monitoring of the seafloor. The cable would provide power to the observatory, but also would provide a mechanism for two-way, real-time communications. A broadband Guralp seismometer and hydrophone package already developed for the Navy's ULF/VLF program would be deployed. The location of this proposed observatory is midway between Hawaii and California, optimizing coverage for the GSN. This site would be one of the first OSN seafloor observatory sites.

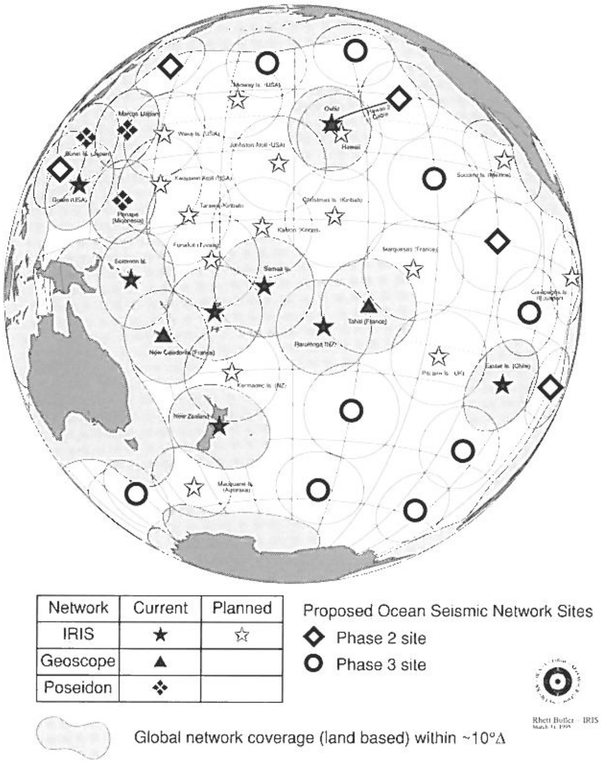
The success of an initiative such as the Ocean Seismic Network is dependent upon collaborations with other nations interested in ocean seismic networks as well as several complementary U.S. national and international earth science initiatives. To that end, OSN convened an international technical workshop in June 1993 to forge closer ties between engineering groups at institutions and universities around the world that are involved in developing ocean floor seismometers and to make some real progress in identifying successful strategies to solve the technical problems. Several scientists representing initiatives such as OSN, RIDGE and InterRIDGE (mid-ocean ridge-related research), BOREHOLE (a U.S. initiative to re-use ODP boreholes as long-term observatories), and ODP, participated in an international workshop, "Multidisciplinary Observatories on the Deep Seafloor," convened by the International Ocean Network, in January 1995. The goal of this international workshop, was to define the scientific impact of long-term geophysical observatories in the deep ocean, review the current state-of-the-art and develop strategies to establish a long-term, multi-disciplinary program for monitoring of the various components of the dynamics of our planet on a global scale.

In February 1995, the Ocean Seismic Network Steering Committee convened a meeting of 22 U.S. scientists to devise a five-year plan that will provide the U.S. seismological community with the capability to collect broadband seismological data in the global oceans (Broadband Seismology in the Oceans, JOI, Inc., 1995). Meeting participants recommended the following important elements be included in the OSN Program Plan:

- Learn how to make the measurements, e.g., the Pilot Experiment Plans;
- Continue to develop effective technologies to support and enhance the capabilities of long-term ocean floor observatories, and in particular take advantage of unused submarine telecommunication cables for power and data recovery;
- Establish the science return from long-term ocean floor seismic measurements by installing approximately three prototype observatories;
- Develop a practical and portable broad-band ocean bottom seismometer;
- Carry out a demonstration experiment with a modest network of BBOBS to prove their research utility;
- Establish a PASSCAL-like facility to make BBOBS technology readily available to the community;
- Establish links to other geoscience communities to develop multidisciplinary observatories.

Budget

The table outlines the cost estimates for a program supporting broadband seismology in the deep oceans as outlined above. The estimates for the OSN Pilot Experiment are reasonably accurate because a detailed proposal is pending with NSF to carry out this work. Engineering development is estimated to require approximately $0.75M per year throughout the duration of the program. This is seen as support at the $200K to $300K level for two to three separate programs. Because a detailed proposal exists for the Hawaii-2 cable effort these cost estimates are also reliable—$1M per year in 1996 and 1997, then $0.25M per year for continued support and maintenance. Estimates for the other two prototype observatories are necessarily more uncertain. Higher cost estimates associated with the years following installation are due to the fact that in these locations data retrieval, most probably, will require visits by research vessels on a yearly basis. It is proposed to install the Equatorial Pacific site in 1998-1999, and the Nazca Plate site in 2000-2001. The development of broadband ocean bottom seismometers (BBOBS) is supported at the $0.5M level through 1995-1996, increasing to $1.5M in 1997 and 1998 when the instruments required for the demonstration experiment would be constructed. The demonstration experiment would take place in 1999-2000, and the establishment of the community-wide BBOBS facility would begin in 2001. Support for the development of multidisciplinary observatories would continue throughout the program at a modest ~$0.5M per year level. Again, this would most probably take the form of two to three separate research programs supported at the level of ~$0.15 to $0.20K per year.



Reports available at Joint Oceanographic Institutions, Inc.

Forsyth, D., S. Sacks, A. Tréhu, JOI/IRIS Ocean Seismic Network U.S. Pilot Experiment Task Force Meeting, JOI Inc., 1991, 21 pages plus figures.

Purdy, G.M. and A. M. Dziewonski (convenors), Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean, 1988, 331 pages.

Ocean Seismic Network Newsletters, March 1990, April 1992, Winter 1992/1993, Summer 1994.

Broadband Seismology in the Oceans: Toward a Five-Year Plan, Joint Oceanographic Institutions, Inc., 1995

Other references:

Dziewonski, A., Wilkens, R., Firth, J., et al., 1992, Proc. ODP, Init. Reports, 136: College Station, TX (Ocean Drilling Program).

Proposed Ocean Seismic Network sites in the Pacific. Existing and planned island sites of the FDSN are also shown. Circles show the nominal 10° radii for 128 station, uniform global coverage. OSN Phase 1 involves a pilot experiment off Hawaii. Phase 2 and 3 OSN sites have been selected in areas where no islands exist.

Broadband Seismology in the Oceans: Towards a Five Year Plan
Projected Costs (in $M)

Project	1995	1996	1997	1998	1999	2000	2001
Pilot Exp at OSN-1	0.5 M	1.0 M	0.5M				
Observatory engineering development	0.75M	0.75M	0.75M	0.75M	0.75 M	0.75M	0.75M
Hawaii-2 Cable Observ.		1.0 M	1.0 M	0.25M	0.25M	0.25M	0.25M
Equat. Pacific Observ.				1.0 M	1.0 M	0.5 M	0.5 M
Nazca Observ.						1.0 M	1.0 M
BBOBS development and construction	0.5 M	0.5 M	1.5 M	1.5M			
BBOBS Demo Expt.					1.5 M	1.5 M	
Establish BBOBS facility							2.0 M
Multi-purpose observatory development	0.5 M	0.5 M	0.5 M	0.5 M	0.5 M	0.5M	0.5 M
Totals	2.25M	3.75M	4.25M	4.00M	4.00M	4.50M	5.00M

Budget Plan

Budget Plan

This section presents a review of prior funding to IRIS and the proposed budget plan for the activities presented in this proposal. An overview of the proposed budget is provided, along with additional detail for each of the IRIS core programs and the central office.

Review of prior funding

To provide a basis for comparison for the budget presented in this proposal and as a measure of the past performance of IRIS, we present in this section a brief overview of the IRIS funding provided under two NSF cooperative agreements over the past 10 years.

1985-1990 – *EAR-84-19149* – The initial 5-year proposal from IRIS to NSF was for $107M to establish a program of 128 GSN stations, 1000 PASSCAL instruments and a Data Management Center. The first five years of NSF funding was reviewed in detail in the previous (1990) IRIS proposal. Total funding under the first Cooperative Agreement between NSF and IRIS amounted to $20M. Annual funding rose from $2.0M in 1986 to $4.9M in 1990. In the initial years, primary support was for development of design goals for GSN and PASSCAL instrumentation and the data management facility and establishment of the IRIS headquarters. The designs of the IRIS-1 GSN data logger and REFTEK PASSCAL instruments were completed under this agreement. Initial field programs using PASSCAL instruments were supported by IRIS. The Joint Seismic Program for installation of GSN stations in the Soviet Union was started in 1988. At the end of the first cooperative agreement 25 GSN stations had been established, PASSCAL had acquired 90 portable instruments and an interim Data Management Center had been established at the University of Texas, Austin. In the final year of this cooperative agreement, the first PASSCAL instrument center was established at Lamont Doherty Earth Observatory and the permanent DMC was established at the University of Washington. Further details of the early history of each of the core programs can be found in Section III of this proposal.

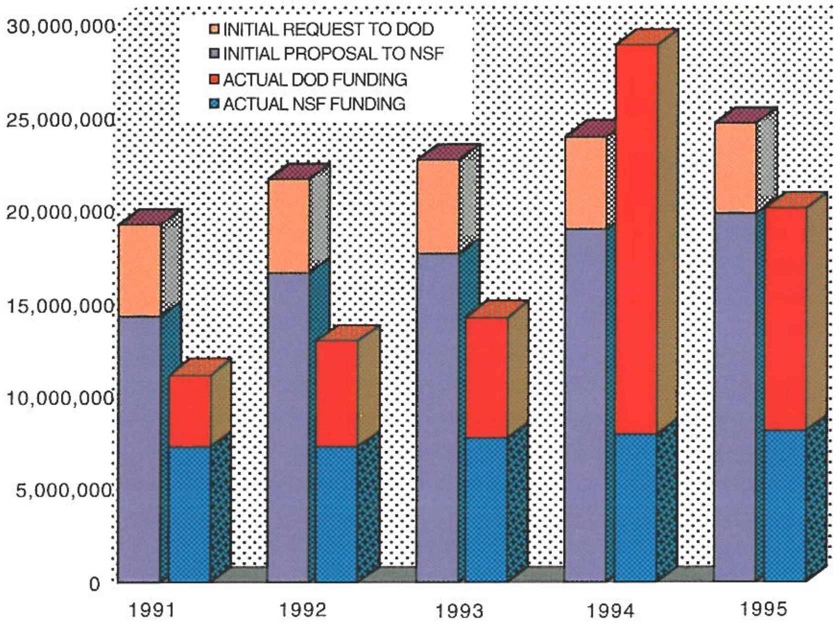
1991-1996 – *EAR-90-23505* – IRIS emerged from the first 5- year program with a solid foundation for all of its core programs - production instruments were available for PASSCAL and the GSN and a permanent Data Management Center had been established. In addition, the JSP provided the opportunity for IRIS, through all three programs, to contribute to the application of seismology in the area of nuclear monitoring. The proposal submitted to NSF in June, 1990 again called for the completion in five years of the original IRIS goals of 128 GSN stations, 1550 (6000 channels) of portable instruments and a full service data management system. The total proposed budget was $87.4M from NSF and $25M for the Joint Seismic Program from DOD for a total of $112.5M over five years. The review of that proposal strongly endorsed IRIS in concept and supported the validity of the program goals, but funding realities resulted in funding levels significantly below those proposed. However, the funding structure approved by NSF and the National Science Board gave considerable flexibility for IRIS to work with NSF through the provision of the Cooperative Agreement to develop additional funding. The Cooperative agreement committed NSF to a baseline funding level of $35M, and an augmented level of $50M, but provided authorization up to $75M. In effect, the 1991 proposal process and review led to an endorsement of the overall IRIS program with a strong commitment for base level support from NSF and an endorsement to seek additional funding, consistent with the original program goals, from other sources. It is this flexibility that has allowed IRIS to come much closer over the past five years to achieving its initial goals, than would have been possible with NSF funding alone.

The accompanying table and figure summarize the proposed and actual funding for IRIS over the past five years. The proposed funding includes both the NSF and DOD (JSP) requests in the 1990 submission. The amounts indicated as "Planned NSF Funding" are the annual amounts indicated as the base level of funding in the NSF/IRIS Cooperative Agreement. The amounts indicated as "Actual Funding" include both the amounts received directly by IRIS from NSF and DOD and the amounts transferred via inter-agency agreement from NSF and DOD to the USGS for support of the GSN.

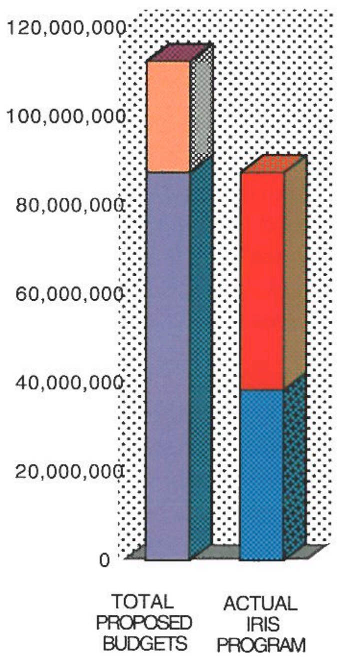
Under the base level funding to be provided by NSF ($35.6M), the 1991- 1996 IRIS/NSF Cooperative Agreement called for a total of 65 GSN stations, 450 of

COMPARISON OF PROPOSED AND ACTUAL FUNDING LEVELS BY YEAR, 1991-1995

	1991	1992	1993	1994	1995	TOTALS
INITIAL PROPOSAL TO NSF	14,299,000	16,635,000	17,678,000	18,974,000	19,796,000	**87,382,000**
INITIAL REQUEST TO DOD	4,986,000	5,090,400	5,032,500	5,007,500	4,921,500	**25,037,900**
TOTAL PROPOSED BUDGETS	**19,285,000**	**21,725,400**	**22,710,500**	**23,981,500**	**24,717,500**	**112,419,900**
PLANNED NSF FUNDING	**6,200,000**	**6,800,000**	**7,200,000**	**7,500,000**	**7,900,000**	**35,600,000**
ACTUAL NSF FUNDING	7,300,000	7,260,987	7,754,619	7,896,563	8,099,858	**38,312,027**
ACTUAL DOD FUNDING	3,871,200	5,700,000	6,500,000	21,000,000	12,000,000	**49,071,200**
ACTUAL IRIS PROGRAM	**11,171,200**	**12,960,987**	**14,254,619**	**28,896,563**	**20,099,858**	**87,383,227**



1991-1995



PASSCAL instruments, and a Data Management System with the ability to archive and distribute the data produced by these programs. By the end of the Cooperative Agreement in June, 1996, current projections are that there will be 90 GSN stations in operation and approximately 430 PASSCAL instruments available through the PASSCAL Instrument Centers. In addition, 40 PASSCAL data loggers are in use in JSP arrays, and GSN capitalization funds, received in 1994 have been used to develop a partial inventory of station hardware for new stations to be installed during the next 5-year program. During the current 5-year Cooperative Agreement, the Data Management System has not only developed into a multi-service resource capable of handling all data produced by IRIS programs, but it has taken on the additional responsibilities for assisting in the archiving and distributing data from other national and international networks.

The funding provided through DOD has resulted from a special Congressional interest in a Comprehensive Test Ban Treaty. As these presentations clearly show, this Congressional interest created a unique opportunity for IRIS to advance much further towards it initial goals, especially in terms of GSN stations and the DMS facility, than would have been possible with NSF funding alone. The funding was initially provided for a special project to install GSN stations in Soviet Union and led to the establishment of the IRIS JSP program. As the focus in nuclear weapons concerns shifted from an emphasis on the Soviet Union to global non-proliferation, the emphasis of IRIS projects in support of nuclear monitoring has evolved to one which supports the global deployment of seismic station through the GSN and the associated data management and distribution facilities. Most of the DOD supplemental funding has been applied to expansion of the GSN and related data management services.

IRIS-2000 Budget Plan

Budget Summary

The plan and budget presented in this proposal cover the five year period, July 1, 1996 to June 30, 2001. The budget which we propose consists of three parts: baseline support from NSF; a contribution from the U.S. Geological Survey for support of the Global Seismographic Network; and a request for program endorsement and authorization by the National Science Board, to seek additional funds from NSF and other agencies to support new initiatives.

Baseline Program support from NSF

Support for the completion, operation and enhancement of the existing core facilities is contained in the baseline budget to NSF. The total request is for $93,087,000, an average of $18,617,000 per year. The program descriptions in Seciton III and the budgets presented in this section provide details on the costs and activities included in the baseline programs.

Operation and Maintenance of the USGS Component of the GSN

The operation of the Global Seismographic Network and associated activities of the Data Management System are closely integrated with the Global Seismology program at the U.S. Geological Survey. The USGS operates approximately 60% of the stations of the GSN. Based on a Memorandum of Understanding between the USGS, NSF and IRIS, IRIS provides new equipment at existing stations, and provides for both equipment and installation at new stations. The USGS pays for the operation and maintenance of stations once they are established as part of the IRIS/USGS network. In the budgets presented here for the GSN and DMS, the complete costs for station operation and data collection for the entire GSN are included. The total request to NSF has then been reduced by $3M/year, assuming that this level of support will be available from the USGS. Discussion are currently taking place between NSF and USGS to develop a new Memorandum of Understanding and funding structure for the long-term support of the GSN.

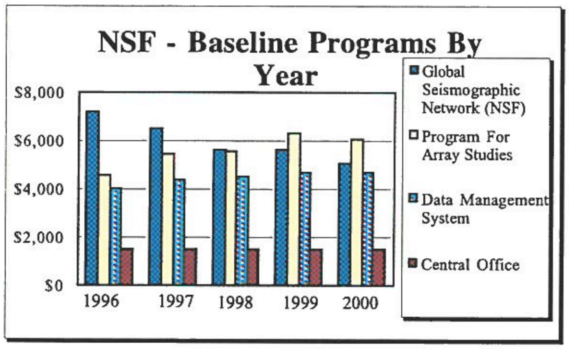
National Science Board Authorization for New Initiatives

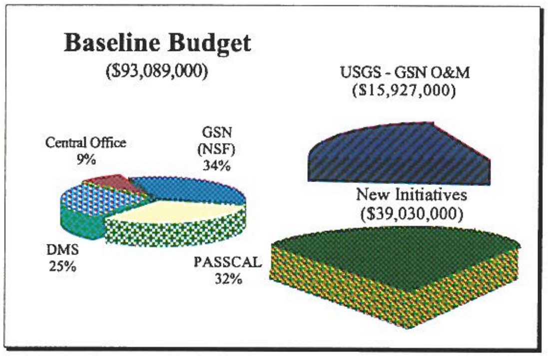
In addition to the baseline support for core programs, new initiatives are proposed in the development of multi-purpose, global geophysical observatories; broadband seismology in the oceans; and extensions to PASSCAL in aftershock monitoring, arrays and shallow imaging. The total request for these new initiatives in $39,030,000. We request National Science Board approval and the authorization to work with national and international partners to seek additional funding for these projects from NSF and/or other federal agencies.

The IRIS Budgetary Process

Based on the review of this proposal, it is anticipated that the National Science Foundation will enter into a third Cooperative Agreement with IRIS to support the activities recommended during the review process. This 5-year Cooperative Agreement will specify a overall authorization level for the entire IRIS operations, indicate the level of support that NSF is prepared to provide, and establish the scope of work to be performed under the agreement. The actual budgets and detailed plans for implementation are set during an annual cycle of program review and budgeting. The annual budget proposals result from an intensive and interactive process guided by IRIS management but ultimately determined by the scientific community. Each major IRIS program (GSN, DMS, PASSCAL) has an advisory Standing Committee that helps to shape the scientific direction of the programs. Ultimate responsibility for the approval of proposed budgets rests with the Executive Committee of the IRIS Board of Directors.

IRIS Program Summary





Requested Amounts

In thousands of dollars

	1996	1997	1998	1999	2000	Totals	Avge / Yr
1. PROPOSED TO NSF - BASELINE PROGRAMS							
Global Seismographic Network (NSF)	$7,203	$6,501	$5,644	$5,631	$5,041	**$30,020**	**$6,004**
Program For Array Studies	4,542	5,427	5,534	6,298	6,089	**27,889**	**5,578**
Data Management System	3,973	4,379	4,475	4,671	4,701	**22,197**	**4,439**
Central Office	1,510	1,510	1,510	1,510	1,510	**7,548**	**1,510**
Total NSF Baseline	**$17,228**	**$17,816**	**$17,161**	**$18,109**	**$17,340**	**$87,654**	**$17,531**
Inflated @3%/Year	**$17,228**	**$18,351**	**$18,207**	**$19,788**	**$19,516**	**$93,089**	**$18,618**
2. EXPECTED FROM USGS - GSN O&M SUPPORT							
Global Seismographic Network (USGS)	$3,000	$3,000	$3,000	$3,000	$3,000	**$15,000**	**$3,000**
Total USGS	**$3,000**	**$3,000**	**$3,000**	**$3,000**	**$3,000**	**$15,000**	**$3,000**
Inflated @3%/Year	**$3,000**	**$3,090**	**$3,183**	**$3,278**	**$3,377**	**$15,927**	**$3,185**
3. REQUESTED NSB APPROVAL - NEW INITIATIVES							
Geophysical Obs.	$1,290	$1,290	$1,290	$1,290	$1,290	**$6,450**	**$1,290**
Ocean Siesmology	3,750	4,250	4,000	4,000	4,500	**20,500**	**4,100**
RAMP	685	25	25	25	25	**785**	**157**
Arrays	582	1,289	882	882	882	**4,517**	**903**
Active Source	611	1,197	1,005	843	843	**4,499**	**900**
Total New Initiatives	**$6,918**	**$8,051**	**$7,202**	**$7,040**	**$7,540**	**$36,751**	**$7,350**
Inflated @3%/Year	**$6,918**	**$8,293**	**$7,641**	**$7,693**	**$8,486**	**$39,030**	**$7,806**

Total Amount Requested for NSB Approval	***$148,047***
Total Amount Requested from NSF - EAR/IF	***$93,089***

GLOBAL SEISMOGRAPHIC NETWORK

Budget Highlights

1 Management costs include personnel, travel, and other supplies and services. Personnel costs are for one full time person (salary + benefits) — the GSN Program Manager. Travel costs include domestic and foreign travel for the Program Manager and GSN Standing Committee meetings. Other supplies and services include publications, shipping, communications, computers, consulting, etc. Management costs reflect projections from current levels.

2. The costs for completing the Global Seismographic Network, and for its continuing operations and maintenance (O&M), are the primary components of the GSN budget. These costs are based upon current experience in station installation, operations and maintenance. Network costs include management, equipment, site surveys and site preparations, station installations, spares, and O&M of existing stations. O&M tasks include station operation, network maintenance, documentation, station re-supply, equipment repair and replacement, engineering/programming support, training, field maintenance, and direct station support (for a detailed discussion of Network O&M and its costs, see Global Seismographic Network Operations and Maintenance, Peterson, 1995, available from IRIS or NSF). Costs are not corrected for inflation.

Network costs for the UCSD IDA and USGS elements of the GSN are shown, together with total numbers of installed stations. There are 12 FTE's at IDA and 24 FTE's at USGS. Currently 1.5 FTE's are contributed by UCSD and 3.3 FTE's by USGS. UCSD also provides cost sharing from the Cecil and Ida Green Foundation and university funds. The UCSD IDA Network is funded by subaward. The USGS element of the GSN includes equipment and site preparations funds which are distributed directly by IRIS Headquarters in coordination with the USGS, and inter-agency transfer of funds via NSF to USGS for installation, operation, and maintenance. Total USGS costs are shown, which are offset in part by the proposed USGS contribution of $3M/yr to GSN O&M. Costs for the year 2000 primarily reflect O&M for the completed network.

Equipment includes data acquisition systems, near-real-time telemetry interfaces (dial-up & Internet), seismometers (broadband, high-frequency, and low-gain) for borehole or vault installations, and microbarographs. Site preparation costs include either building a new seismic vault or drilling a borehole. There is equipment currently in the GSN inventory to partially outfit 14 of the proposed sites. Current Network operating funds will be able to partially complete site preparations at 5 proposed site.

3. Other subawards include support for the IRIS University Network element of the GSN through matching funds to universities for new stations and maintenance of existing stations. Support for continued coordination of software development between the GSN and the universities is included.

4. Telemetry includes costs for purchase and installation of INMARSAT B terminals during the first three years. In years four and five, it is expected that the telecommunications focus will be global cellular systems. Operations costs for telemetry are in the DMS budget.

5. Four GSN sites will be equipped with GPS and geomagnetic instrumentation. Costs reflect current standards of the GPS and geomagnetic communities ($30K and $100K each, respectively). System integration costs of $100K are included in the first year.

6. Research and development activities ($100K/yr.) will be focused toward the improvement of long-period horizontal noise performance in shallow and near- surface seismic vaults through the measurement of broadband tilts.

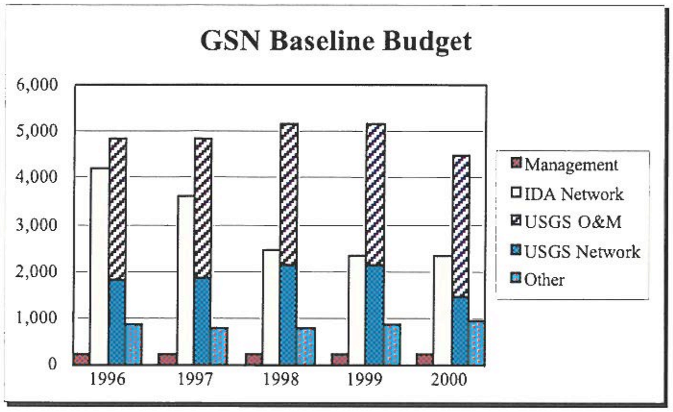
7. IRIS GSN proposes to directly fund Ocean Seismic Network development activities, including broadband ocean bottom seismometers, at $150K/yr.

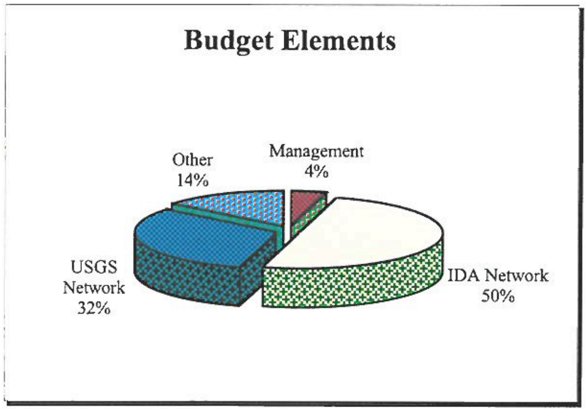
8. Equipment and installation costs for one portable GSN station per year are proposed.

9. New Initiatives include both Geophysical Observatories and the Ocean Seismic Network, which extend the scope of the modest funding which the GSN proposes as part of its five year program. IRIS GSN seeks NSF authorization to develop funding for these programs external to its standard NSF Earth Sciences funding.

Thirty GSN stations would be broadened into geophysical observatories. Instrumentation would include GPS and geomagnetism (costs noted in item 5), weather/climate ($5K each), and radionuclide monitoring ($80K each). Costs for the OSN initiative reflect the programmatic plans developed by the OSN community. A workshop report with detailed costs — Broadband Seismology in the Oceans — is summarized in Section III of this proposal. The full report is available from IRIS, JOI or NSF.

Global Seismographic Network





			1996	1997	1998	1999	2000	**Totals**
BASELINE								
MANAGEMENT	Personnel		$150	$150	$150	$150	$150	**$750**
	Travel		55	55	55	55	55	**275**
	Other Supplies & Services		50	50	50	50	50	**250**
	Subtotals		**$255**	**$255**	**$255**	**$255**	**$255**	**$1,275**
OPERATIONS	Network Operators							
	IDA Network		$4,225	$3,606	$2,448	$2,363	$2,363	**$15,005**
	USGS Network		4,839	4,856	5,157	5,154	4,489	**24,495**
	Total Stations							
	IDA Network	*32	36	40	43	43	43	
	USGS Network	62	68	74	80	85	87	
	*Stations prior to 1996.							
	Other Subawards		200	200	200	200	200	**1,000**
	Telemetry		100	100	100	175	250	**725**
	GPS & Geomagnetism		204	104	104	104	104	**620**
	R & D		100	100	100	100	100	**500**
	OSN/BBOBS		150	150	150	150	150	**750**
	Portable GSN Stations		130	130	130	130	130	**650**
	USGS O&M		(3,000)	(3,000)	(3,000)	(3,000)	(3,000)	**(15,000)**
	Subtotals		**$6,948**	**$6,246**	**$5,389**	**$5,376**	**$4,786**	**$28,745**
BASELINE TOTALS			**$7,203**	**$6,501**	**$5,644**	**$5,631**	**$5,041**	**$30,020**
NEW INITIATIVES								
	Geophysical Obs		$1,290	$1,290	$1,290	$1,290	$1,290	**$6,450**
	Ocean Seismology		3,750	4,250	4,000	4,000	4,500	**20,500**
NEW INITIATIVES TOTALS			**$5,040**	**$5,540**	**$5,290**	**$5,290**	**$5,790**	**$26,950**
GRAND TOTALS			**$12,243**	**$12,041**	**$10,934**	**$10,921**	**$10,831**	**$56,970**

PASSCAL

Budget Highlights

1. Management expenses include salary, benefits, and travel of the Program Manager, who also serves as Chief Engineer; travel costs of the PASSCAL Standing Committee and Instrument Center personnel; consultant services; and other incidental costs

2. The primary subawards are the PASSCAL Instrument Centers at the Lamont-Doherty Earth Observatory of Columbia University and at Stanford University. The Lamont Center will run at essentially the current level for the next five years. The Stanford Center will need more personnel — two hires in 1997 and one more in 1999 — as IRIS acquires new instruments.

3 The Array Center will be a new center funded via subaward. This Center will be opened when we start acquiring array hardware. The Center will start with three personnel, with two additional hires in 1997 and one more in 1999.

4. Miscellaneous costs include insurance and $50k/year to cover the initial expenses associated with startup of RAMP deployments following significant earthquakes.

5. Instrument development includes funds in the first two years to complete array development and for integration of a commercially developed simple instrument ("Walkman"). Funds are included in the final two years for developing the next generation PASSCAL system.

6. Maintenance costs are costs allocated to keeping the current instruments running. This includes repair services from the manufacturer, spare parts, and costs associated with implementing engineering changes, but not major upgrades.

7. Annual capital investment cost for equipment is proportional to the number of instruments to be acquired (as specified in the budget table), and the annual maintenance cost is proportional to the installed base. The equipment budget is based upon established purchase price for existing instruments and estimates for new instruments. In addition to field recorders and sensors, other equipment includes field computers, shipping cases, auxiliary recorders, GPS clocks and other upgrades to existing equipment.

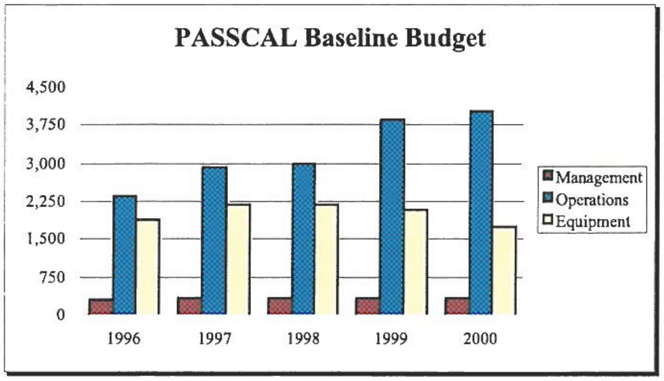
8. RAMP, ARRAY, and Active Expansion are listed as new initiatives. The details on these initiatives are found in the PASSCAL Program Plan.

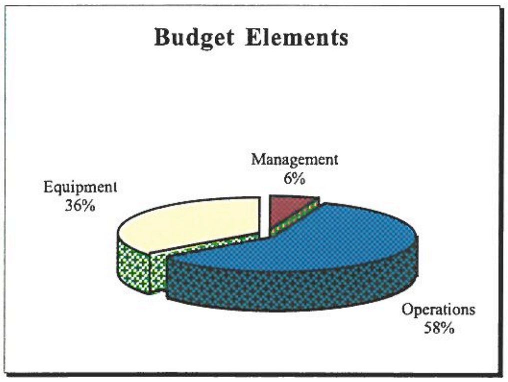
RAMP - a full 20 element array is included in the first year, plus $25k/year for additional field support for RAMP deployments.

Arrays - The baseline budget array element contains funding for telemetry and central recording equipment only - field units and sensors would come from existing stocks. This initiative would provide full data acquisition systems and sensors for six 20-element arrays and additional staffing and support for the array center.

Active source expansion - This initiative would provide for an additional 1500 channels of instrumentation for active source lithospheric studies and shallow imaging. The balance between multi-channel shallow imaging systems or single-channel "Walkman" recorders would be determined based on experience with recently acquired systems.

PASSCAL





		1996	1997	1998	1999	2000	Totals
BASELINE							
MANAGEMENT	Personnel	$150	$150	$150	$150	$150	**$750**
	Travel	75	80	90	90	90	**425**
	Consultant Services	40	50	50	50	50	**240**
	Other Supplies & Services	50	50	50	50	50	**250**
	Subtotals	**$315**	**$330**	**$340**	**$340**	**$340**	**$1,665**
OPERATIONS	Subawards						
	Lamont Center(2)	$800	$800	$800	$800	$800	**$4,000**
	Stanford Center(3)	450	650	650	750	750	**3,250**
	Array Center(4)	350	550	550	650	650	**2,750**
	Misc	170	214	217	217	216	**1,034**
	Instrument Development	100	100	0	500	500	**1,200**
	Maintenance(5)	475	616	779	944	1,101	**3,915**
	Equipment						
	Instruments						
	6-Channel	160	160	160	160	160	**800**
	3-Channel	500	100	200	100	100	**1,000**
	Walkman	75	375	375	375	375	**1,575**
	Sensors						
	4.5 Hz	40	104	108	104	104	**460**
	Intermediate	160	320	320	320	80	**1,200**
	Broadband	150	150	150	150	150	**750**
	Telemetry	200	200	300	300	225	**1,225**
	Other Equipment	597	758	585	588	538	**3,066**
	Subtotals	**$4,227**	**$5,097**	**$5,194**	**$5,958**	**$5,749**	**$26,225**
BASELINE TOTALS		**$4,542**	**$5,427**	**$5,534**	**$6,298**	**$6,089**	**$27,890**

Total Equipment Available		1996	1997	1998	1999	2000
6-Channel Instr	*120	130	140	150	160	170
3-Channel Instr	290	340	350	370	380	390
"Simple" Instr	0	50	300	550	800	1,050

*Intruments available prior to 1996.

		1996	1997	1998	1999	2000	Totals
NEW INITIATIVES							
	RAMP	$685	$25	$25	$25	$25	**$785**
	Arrays	582	1,289	882	882	882	**4,517**
	Active Source	611	1,197	1,005	843	843	**4,499**
NEW INITIATIVES TOTALS		**$1,878**	**$2,511**	**$1,912**	**$1,750**	**$1,750**	**$9,801**
GRAND TOTALS		**$6,420**	**$7,938**	**$7,446**	**$8,048**	**$7,839**	**$37,691**

Data Management System

Budget Highlights

1. The present staff of ten full time people will increase to 13. A Director of Software Development (DSD) will be added to develop and maintain the IRIS software framework, and two software engineers will be hired to report to the DSD. An interface specialist has recently been added to the DMS staff to develop and maintain WWW tools as well as X Window tools to provide improved user access.

2. Other management expenses such as travel and supplies are projections from current levels, but adjusted to reflect additional personnel. The DMS will continue to make use of consultants to perform some software projects, as this is more cost effective than hiring permanent staff. Rent for the Data Management Center facility in Seattle is also projected from the current levels.

3 Funds for mass storage systems and other equipment are budgeted for the IDA and ASL Data Collection Centers. Major mass store replacement for the DMC, and the IDA and ASL DCC's have been distributed in different years to balance the annual budgets. The IDA DCC includes employee costs and the ASL DCC will have contract personnel costs.

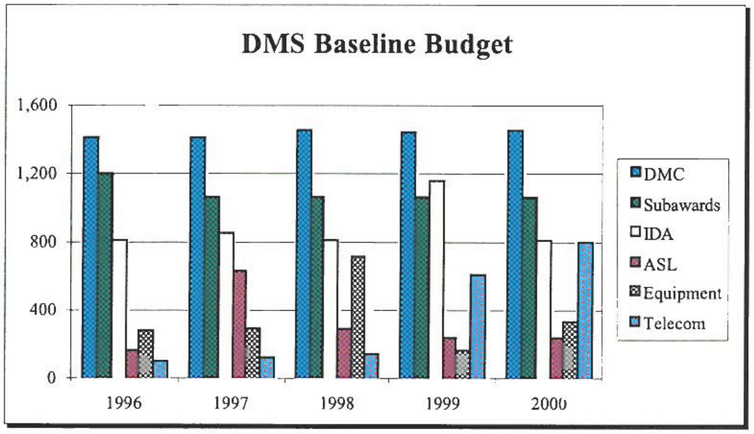
4. The University of Colorado is a continuation of the JSP Center, which is now being managed as part of the DMS. Colorado's activities will be focused on the development of the software framework. The center will have 5.5 FTEs.

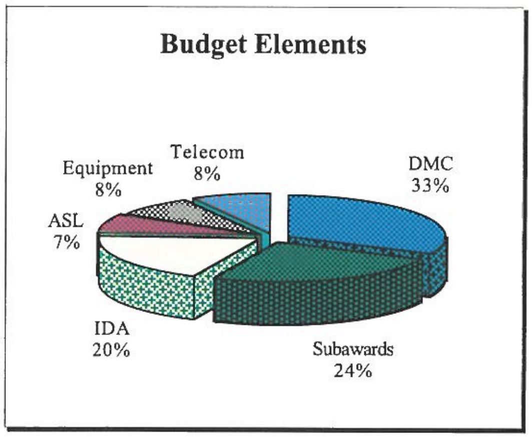
5. Continuation at the current levels is proposed for the Waveform Quality Center at Harvard University, for DMC support at the University of Washington, and for the Moscow Data Center.

6 In the equipment budget, the values for the workstations assume replacement of three workstations at the DMC with newer models each year. In the first year, one additional workstation will be purchased, and the workstation base will be renewed every five years. The main computer servers will be upgraded in 1997 and 2000, and the budgets for those years is indicative of the present cost of acquiring a Sparc 2000 class server. The DMS requires a large number of peripherals such as disk drives, tape drives, tape handling robots, and communications equipment. Commercial software will be purchased where appropriate for applications such as GIS, visualization, RDBMS, and network monitoring. In addition, an industry reflection processing package will be purchased in the first year. Current projections indicate that the DMC archive will require a high performance mass storage system with a capacity of roughly 50 terabytes in the third year, but the technology is changing too rapidly to recommend a specific mass storage system at this time.

7. Telecommunications is a major item in DMS operations. The collection of data from significant earthquakes by SPYDER™ will involve an increasing number of stations as the GSN expands. Internet will be used wherever possible, but dial-up communication will still be required. INMARSAT terminals will be purchased under the GSN program, with an anticipated migration to global cellular systems by both GSN and PASSCAL in the fourth and fifth years. The DMS will be responsible for communications costs related to the retrieval of data from GSN stations and long-term PASSCAL deployments.

Data Management System





		1996	1997	1998	1999	2000	**Totals**
DMC ADMINISTRATION & DATA MANAGEMENT	Personnel	$954	$954	$954	$954	$954	**$4,770**
	Travel	75	80	80	80	80	**395**
	Publications & Printing	25	10	25	10	25	**95**
	Consultant Services	75	75	75	75	75	**375**
	Other Supplies & Services	280	295	320	320	320	**1,535**
	Subtotals	**$1,409**	**$1,414**	**$1,454**	**$1,439**	**$1,454**	**$7,170**
OPERATIONS	Subawards						
	IDA	$806	$856	$806	$1,156	$806	**$4,430**
	ASL	170	630	290	240	240	**1,570**
	Univ. of Colorado	791	656	656	656	656	**3,415**
	Harvard Univ.	63	63	63	63	63	**315**
	Univ. of Washington	247	247	247	247	247	**1,235**
	Moscow Data Center	60	60	60	60	60	**300**
	Other Subawards	35	35	35	35	35	**175**
	Equipment						
	Workstations	65	45	45	45	45	**245**
	Servers	10	120	10	10	120	**270**
	Peripherals	85	100	85	85	100	**455**
	Major Software	125	25	75	25	75	**325**
	Mass Storage Systems	0	0	500	0	0	**500**
	Telecommunications						
	Phone Lines	60	60	60	40	10	**230**
	INMARSAT-SPYDER	32	48	64	80	40	**264**
	INMARSAT-PASSCAL	15	20	25	15	0	**75**
	GSN-Global Cellular	0	0	0	215	430	**645**
	PASSCAL-Global Cellular	0	0	0	260	320	**580**
	Subtotals	**$2,564**	**$2,965**	**$3,021**	**$3,232**	**$3,247**	**$15,029**
GRAND TOTALS		**$3,973**	**$4,379**	**$4,475**	**$4,671**	**$4,701**	**$22,199**

Central Office

Budget Highlights

1. This budget shows all direct costs, not readily attributable to the costs of the major programs, of operating the corporate office in Arlington, VA. The corporate office budget has historically been about 10% of the overall budget.

2. We anticipate a similar level of staffing — about 10 FTEs — in future years as in recent years. The key members of the central office staff include the President, the Director of Planning, the Business Manager, and the Manager of Administration. Both the business and administration groups have additional professional and support personnel. In the interest of maintaining permanent staffing at lean levels, IRIS's practice is to hire temporary personnel for sometimes extended periods rather than overstaffing our offices.

3. Travel is budgeted for domestic and foreign travel of the staff and for domestic travel of the IRIS Executive Committee, which meets at least two times a year.

4 The equipment budget is based on projections from past expenditures. Equipment purchased for the corporate office is typically desktop computers, furniture, copiers, and other general purpose equipment.

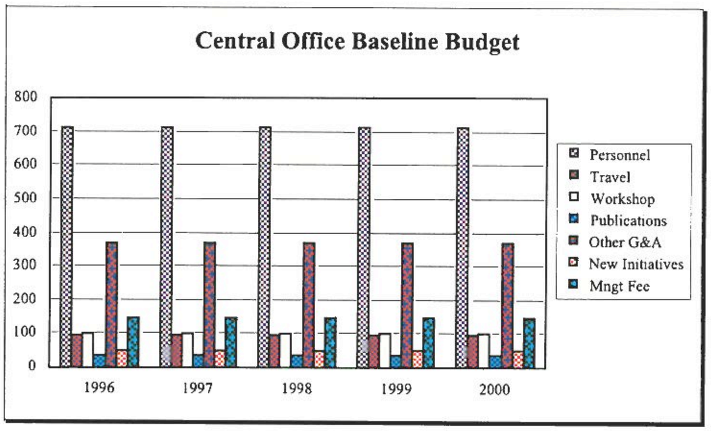
5. IRIS conducts an annual workshop for IRIS member universities and affiliates. These workshops have been acclaimed as a highly successful method for information dissemination and community interaction. In recent years, IRIS has provided partial support (accommodations, but not travel) for one representative per member institution and full support for IRIS Committee members, speakers and twenty students/post-docs. Although the workshops receive positive reviews, IRIS has reduced this budget item by $20,000 per year from the previous five-year proposal. IRIS is currently reviewing methods for reducing costs.

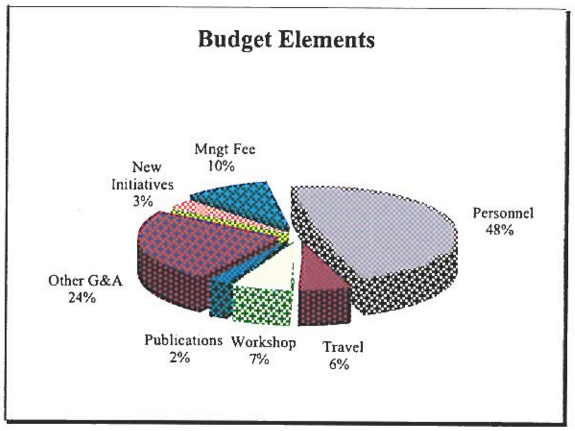
6. The publications budget is slightly higher than current experience, as IRIS expects to enhance the quality and quantity of newsletters and other general publications. The newsletter is published quarterly, and is distributed free of charge to 1500 individuals and institutions. Use of electronic "publication" on the World Wide Web will increase.

7. The corporate office's other largest expenditures are for professional services and office rent. Arthur Andersen & Co., the major audit firm, audits IRIS annually. IRIS has found that legal advice is becoming more important to IRIS's administrative operations. The budget for rent is based on our current rent in Arlington, plus normal annual increases spread out over five years.

8. IRIS does not charge a general and administrative (G&A) indirect cost on total program costs. Office rent, administrative salaries, and other items of cost commonly associated with G&A expenses are direct charges as a part of this central office budget. A 1% management fee is included to cover unanticipated or unallowable expenses. Experience has shown that the current pool of unrestricted funds (at this stage derived only from initial membership fees) is inadequate to offset the exposures inherent in managing a multi-million dollar program. A fund balance is required to pay for common unallowable expenses incident to operating a corporate entity and for unforeseen costs that arise in normal operations.

The IRIS Central Office


Central Office Baseline Budget


Budget Elements

	1996	1997	1998	1999	2000	**Totals**
Personnel	$711	$711	$711	$711	$711	**$3,555**
Travel	95	95	95	95	95	**475**
Equipment	25	25	25	25	25	**125**
Workshop	100	100	100	100	100	**500**
Publications	35	35	35	35	35	**175**
Materials & Supplies	28	28	28	28	28	**140**
Other Direct Costs						
Professional Services	35	35	35	35	35	**175**
Rent	120	120	120	120	120	**600**
Communications	31	31	31	31	31	**155**
Meetings	30	30	30	30	30	**150**
Postage & Shipping	10	10	10	10	10	**50**
Other	90	90	90	90	90	**450**
New Initiatives	50	50	50	50	50	**250**
Management Fee	150	150	150	150	150	**750**
GRAND TOTALS	**$1,510**	**$1,510**	**$1,510**	**$1,510**	**$1,510**	**$7,550**