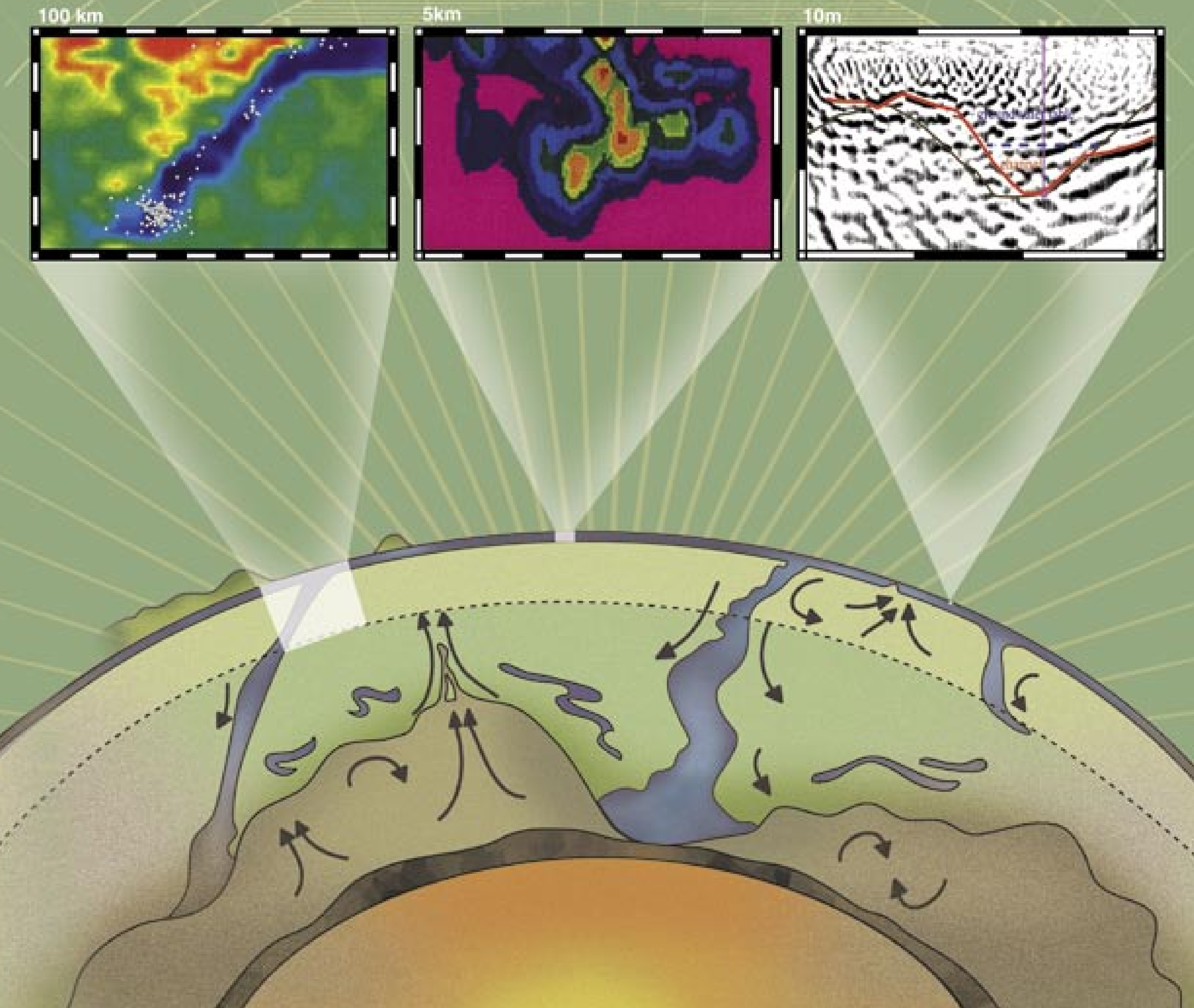
IRIS

Exploring the Earth at High Resolution



About the Cover

From 100-kilometer structures in the mantle to 1-meter features within a paleochannel, the images on our cover span five orders of magnitude and illustrate how IRIS instrumentation and facilities are improving our ability to explore the Earth at high resolution and at all scales.

Bottom figure: This cartoon cross-section through the Earth's interior illustrates possible dynamics of the deep mantle. Depth to the dense layer in the lower mantle ranges from ~1600 km in some areas to ~2700 km near the core/mantle boundary, where it is deflected by downwelling slabs. Plumes rise from local high spots, carrying recycled slab material and some primordial material. High resolution PASSCAL and GSN data are used to study scattered waves and S-and P-wave velocity anomalies in the deep mantle, thus advancing our understanding of this region.

From: Kellogg, L. H., B. H. Hager and R.D. van der Hilst, Compositional Stratification in the Deep Mantle, ***Science****, 283, 1881-1884, 1999.*

Left inset: This image depicts an east-west vertical cross-section of P-wave velocity across the Lau ridge and the Tonga arc. In a two-year deployment, 12 PASSCAL broad-band instruments were used to increase seismic coverage south of the IRIS GSN station AFI on Samoa. Earthquakes within a 40-km width from the cross-section are shown as white circles. P-wave velocity perturbation ranges from -6% (red) to 0% (green) and 6% (blue). This study provides evidence that the geodynamic systems associated with back-arc spreading are related to deep processes such as the convective circulation in the mantle wedge and deep dehydration reactions in the subducting slab.

From: Zhao, D., Y. Xu, D. Wiens, L. Dorman, J. Hildebrand, S. Webb, Depth Extent of the Lau Back-Arc Spreading Center and its Relation to Subduction Processes, ***Science****, 278, 254-257, 1997.*

Middle inset: This figure shows the dynamic slip distribution for the 16 October 1999 Hector Mine earthquake in the Mojave Desert of Southern California. It illustrates how regional and teleseismic broadband data may be used to determine the kinematic parameters of large earthquakes. The model fault plane in this figure extends 60 km SE-NW and 20 km in the dip direction. Through inversion of the broadband data, the spatial extent of the fault rupture can be determined. In this figure, each color gradation is equivalent to slip increments of 1 m. The inversion reveals a peak slip of 8 meters (red), while the distribution of slip shows that the event had a bilateral rupture.

From: Dreger, D. S., and A. Kaverina, Seismic Remote Sensing for the Earthquake Source Process and Near-Source Strong Shaking: A Case Study of the October 16, 1999 Hector Mine Earthquake, ***Geophysical Research Letters****, (in press) 2000.*

Right inset: This high resolution seismic profile was used to map groundwater contamination at Hill Air Force Base, Utah. The pre-stack depth migrated seismic section is 35 meters long and extends to a depth of 17 meters. The seismic data were acquired using a 60 channel IRIS Geometrics and a 60 channel Rice Bison portable seismograph. Geophones were spaced at 30-cm intervals along the profile. Pre-stack depth migration and depth focusing analysis produced clear images of a paleochannel (red line). The site is contaminated by a dense non-aqueous phase liquid (DNAPL) solvent that resides at the base of a shallow (<15m) aquifer consisting of Quaternary gravels, sands, and silty clays. The DNAPL contaminant is concentrated in the paleochannel cut in the clay aquiclude.

From: D. Dana, A. Levander, I.B. Morozov, C.A. Zelt, W.W. Symes, K. Araya, High Resolution Seismic Investigations at a Shallow Groundwater Contamination Site, ***The Millennial 9th International Symposium on Deep Seismic Profiling of the Continents and their Margins****, 18-23 June 2000, Ulvik, Norway.*

This cover design is intended to be the centerpiece for the next in the series of IRIS Education and Outreach posters.

"Exploring the Earth at High Resolution"

the IRIS Proposal

July 1, 2001 - June 30, 2006

**submitted to the
National Science Foundation
Division of Earth Sciences
Instrumentation and Facilities Program**

**by the
96 Member Research Institutions
of the
IRIS Consortium**

**Incorporated Research Institutions for Seismology
1200 New York Avenue, NW, Suite 800
Washington, D.C. 20005**

August, 2000

ABOUT THIS PROPOSAL

This proposal was produced by the IRIS Executive Committee on behalf of the IRIS Board of Directors, who in turn, represent the full membership of the Consortium. Developing a single proposal that represents the collective scientific interests of almost 100 research institutions is a complex task. It requires identifying the common vision, agreeing upon the next generation of data needs, choosing methodologies, and setting priorities across a broad range of scientific sub-disciplines. Although the formal process of this proposal development began in the Spring of 1999, the review, auditing, and self-evaluation that forms the background for this proposal has been an on-going process within IRIS. Text in this proposal has been contributed by members of the 1999 IRIS workshop, the IRIS Science Task Force, the Standing Committees, the Coordinating Committee, the Planning Committee, members of the Executive Committee and IRIS staff.

This proposal consists of three main sections:

The main proposal includes an overview of the IRIS Consortium and facilities, the role of IRIS in supporting research and education, a description of our resource needs, and a brief outline of our five-year funding request.

Appendix I is a review of our accomplishments over the last 5 years. It includes more than 120 one-page contributed vignettes, which describe projects that have made use of IRIS facilities and resources, and a one-year example of publications based on IRIS data.

Appendix II is an overview of core IRIS facilities. This section contains a review of the development and evolution of these facilities and descriptions of plans and resource requests for each of the IRIS programs.

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EXPLORING THE EARTH AT HIGH RESOLUTION
THE IRIS PROPOSAL

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Project Description

Integrating Facilities and Research

Introduction

From Galileo's telescope and Leeuwenhoek's microscope to the high technologies of the present day, many of the great discoveries in science have come from new tools that sharpen our images of nature. In just the last decade, the Hubble Space Telescope has extended the range of optical astronomy toward the outer reaches of the Universe, revealing its turbulence in the wake of the Big Bang. Atomic-force microscopes are being used to map the topography of individual atoms on material surfaces, enabling rapid progress in nanotechnology. Medicine is advancing through computer-aided tomography and magnetic-resonance imaging of the human body. Multispectral cameras aboard satellites and multibeam sonars on ships are enhancing our views of the terrestrial surface over the land and beneath the sea.

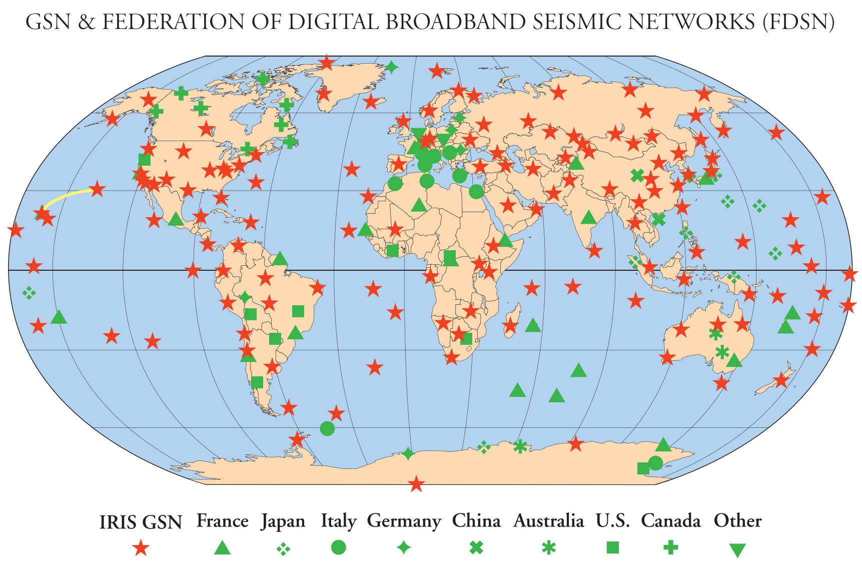
In a similar way, the new tools of seismological imaging are revolutionizing the study of the solid Earth. Earthquakes and controlled sources such as underground explosions generate elastic waves that encode an immense amount of information about the Earth through which they propagate. This information can be captured on arrays of seismic sensors and digitally processed into three-dimensional images of Earth structure and moving pictures of earthquake ruptures. Seismology thus gives geoscientists the eyes to observe fundamental processes within the depths of our planet's interior.

Seismology provides the highest resolution techniques available for exploring the interior of the Earth and connecting surface geological observations to deeper Earth structure. By doing so, we can begin to develop a systems approach that ties the complexity of surface tectonics with phenomena deep in the Earth. Continued progress, however, requires both data with higher resolution and the perspective provided by long-term coverage. Studies of the Earth's dynamic systems requires a commitment to observations that are:

- high-performance – to capture the full fidelity of Earth's signals,
- long-term – to allow observations of change and unique rare events, and
- high-resolution – to allow observation of detailed structure.

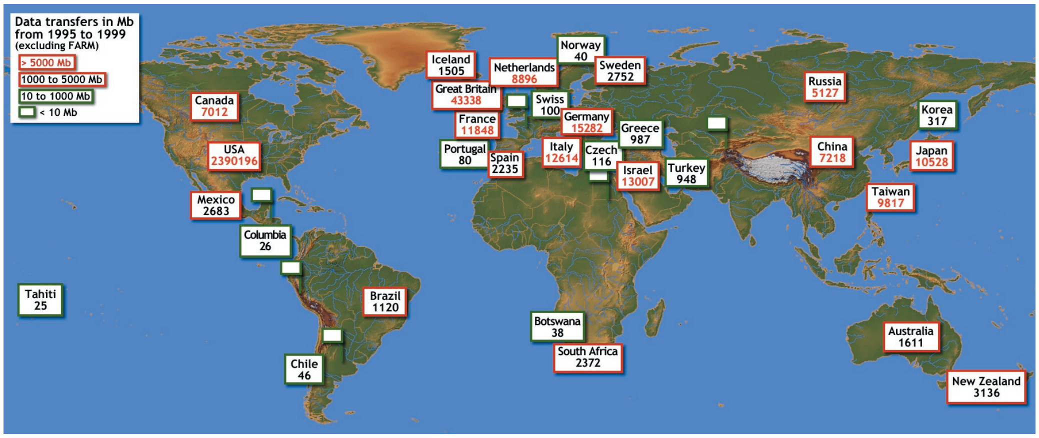
Combined, these observational resources provide scientists with the tools to study the dynamic processes that reveal the way in which the planet is structured and evolves, at a variety of temporal and spatial scales.

As the National Science Foundation (NSF) celebrates its 50th anniversary, it has identified "People, Ideas, Tools" as the cornerstones of its new Strategic Plan. The explicit commitment to facilities as an underpinning of NSF-supported research is echoed in both the Geoscience Directorate's "NSF Geosciences Beyond 2000" and "GEO Facilities Long-Range Plan". These documents reflect a



Global Coverage
The Global Seismographic Network has been a major contributor, in partnership with other national and international networks, in creating a global 2000-km grid of permanent seismological observatories, covering the continents and most of the world's oceans.

Global Data Delivery
Open and free access to data from the Global Seismographic Network, PASSCAL and cooperating networks are provided through the IRIS Data Management System to researchers and educators anywhere in the world.



growing awareness of the Foundation's need to balance its support of basic research with a commitment to the observational and data management tools required to stimulate and support research and exploration. At the same time, by including "People" as a key element in its Strategic Plan, NSF underscores its commitment to the educational process, and emphasizes the importance of communicating our data, results, and experience to the public in ways that are stimulating and accessible.

Under the three previous five-year Cooperative Agreements between the IRIS Consortium and NSF, we have established core facilities – the tools of seismology – that have become an essential part of the fabric of domestic and international research in seismology and the Earth sciences. The IRIS facilities were established with a commitment to high-performance in quality of instrumentation, data resources and user services. Through careful planning and constant re-evaluation, these tools have evolved and grown in response to the changing needs of the research community. In this proposal, we present a plan that continues that tradition of excellence; extends the facilities to higher resolution; establishes a pathway to an enduring, long-term commitment to global observations and preservation of data resources; and encourages public and educational involvement in the excitement of seismological discovery.

IRIS – A Brief Overview

IRIS, a consortium of 96 universities and research organizations, has become a cornerstone of academic research in seismology. IRIS maintains and operates national and global facilities: permanent networks for long-term monitoring, portable instruments for high-resolution imaging, and a data archive that makes seismic data available to a broad spectrum of scientists and educators. These facilities enable cutting-edge research at academic institutions across the US, from traditional major research institutions, to universities with combined research and education missions, to four-year liberal arts and technical colleges.

IRIS operates on the foundation of shared resources and a consortium philosophy that is inherent to the science of seismology. Little can be done with data from a single seismogram. While each individual earthquake and experiment contributes towards unraveling our Earth's structure, collectively they provide the opportunity to build a more complete and coherent understanding of whole Earth structure and dynamic processes. Sharing resources, instruments and data maximizes the return on capital investments, but also promotes intellectual discourse and scientific interactions.

Fifteen years ago, only about a half-dozen research institutions in the US could support the facilities required for advanced observational seismology. The technical requirements for maintaining instruments, fielding experiments, and handling large data sets prohibited all but a few from having access to high-quality data sets and state-of-the-art instrumentation. Today, a new generation of scientists has been empowered by IRIS. Every scientist and student with a connection to the Internet now has access to data from global, regional, and local networks around the world. Any individual investigator can now propose an experiment without the burden of establishing an in-house technical capability. The past infrastructure barriers to seismology have been torn down – making our science and data available to new audiences of researchers and educators.

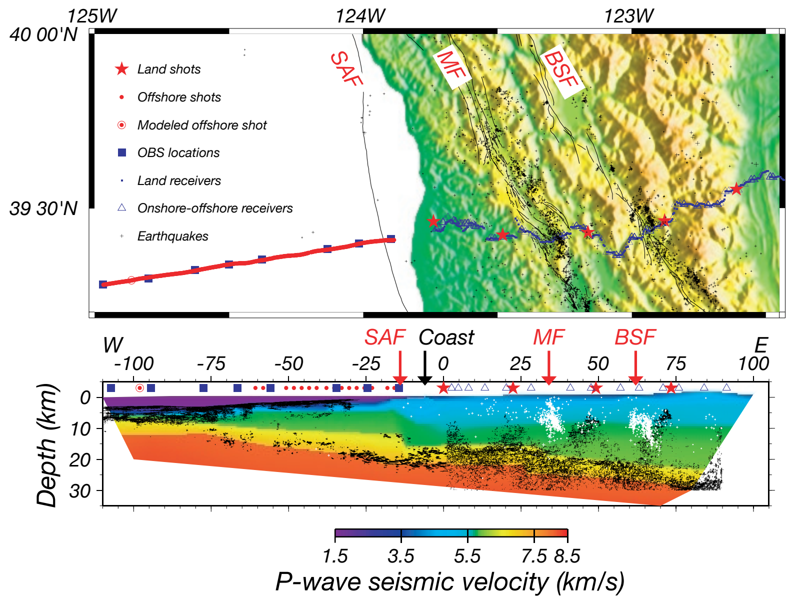
This proposal requests funds from the National Science Foundation to maintain and operate the core IRIS programs as an integrated, state of the art, national facility in support of seismological research. The core IRIS programs include:

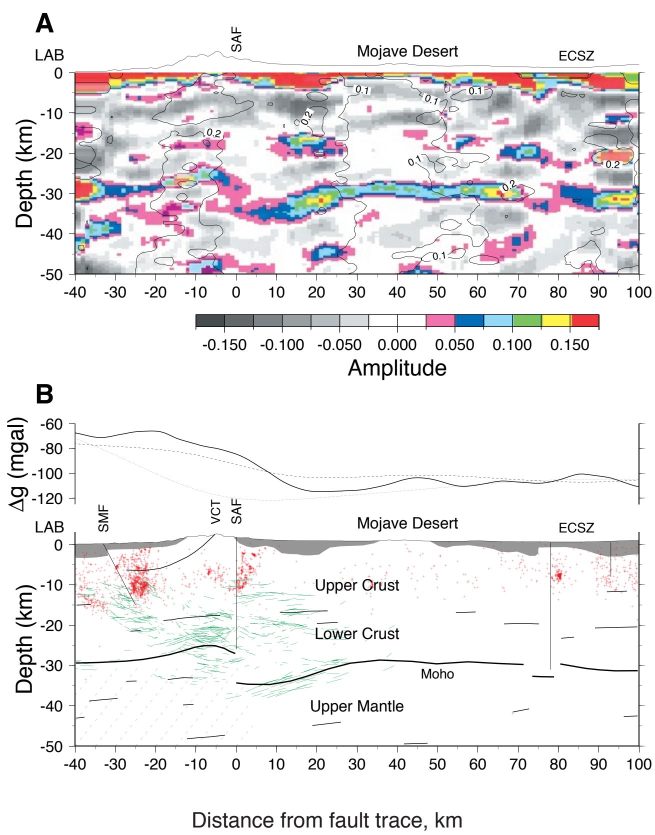
The Global Seismographic Network (GSN) – a permanent worldwide network of over 130 broadband seismological observatories,

The Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) – a program of portable instruments for use by individual scientists for high-resolution experiments in areas of special interest,

The Data Management System (DMS) – a data system

Crustal Scale Faulting
PASSCAL instruments have been used in a number of experiments both on land and in “onshore - offshore” configurations recording both explosions and earthquakes to study the structure of the western margin of the US from California to Alaska. The top map and cross section show velocity, seismic reflectivity (black), and seismicity (white) across the San Andreas Fault system south of the Mendocino Triple Junction in northern California. Offsets can be seen in the lower crustal layer beneath the surface expression of the San Andreas fault system. (Figure provided by Alan Levander, Rice University).
The lower cross sections show similar results obtained along the San Andreas Fault in southern California using teleseismic receiver functions and active source profiling. (Figure provided by Lupei Zhu, Caltech)
These images provide evidence that the faults of the transform system cut through the entire crustal column to the mantle at high angle and are associated with both brittle faulting in the upper crust and ductile deformation at depth. Additional details are provided in Appendix I.





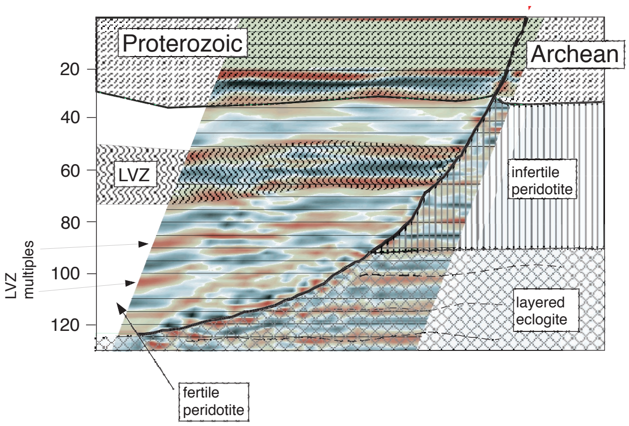
for collecting, archiving, and distributing data from IRIS facilities, as well as a number of other national and international networks and agencies, and

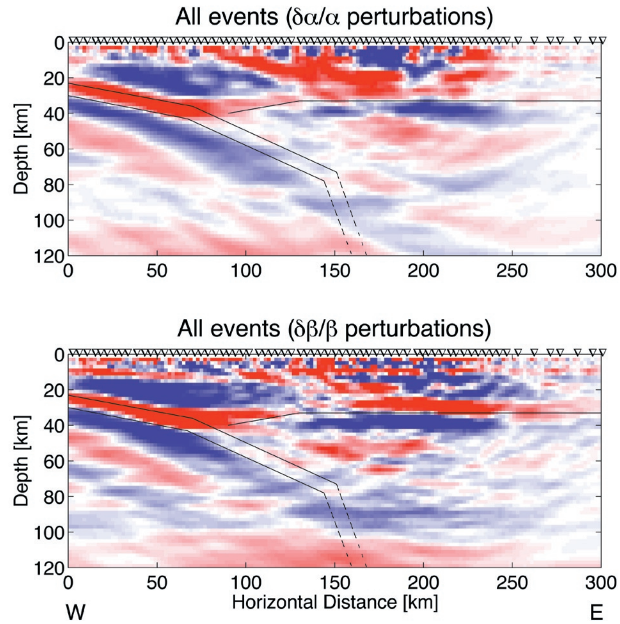
The Education and Outreach Program (E&O) – a program that integrates research and education by making our data and science widely accessible through a variety of innovative programs and partnerships.

The GSN and PASSCAL are complementary programs and the primary tools for the acquisition of new data, designed for global coverage with flexible resolution. The GSN, along with other cooperating networks, provides a baseline coverage of approximately 2000 kilometers on the continents and oceanic islands worldwide. Denser deployments of PASSCAL instruments allow investigations of specific targets with resolution on the order of 100s of kilometers down to the sub-meter scale. The DMS and E&O are also complementary programs and the primary means of distributing data for research and education. By combining and distributing data from different sources, the DMS allows individual investigators to assemble data products tailored to their research objectives. The DMS also serves as a forum to coordinate international cooperation, set data and software standards, and promote data exchange. The E&O program integrates seismological data with educational programs and public outreach, making our data available and useable, not only for research seismologists, but also for educational institutions and the interested public. The E&O program plays an important role in translating scientific results on Earth structure and dynamics into terms meaningful and accessible to the general public.

Facility Themes

Under its Cooperative Agreement with the National Science Foundation, the IRIS Consortium accepts the obligation to establish and maintain the observational resources required to support NSF-funded research in seismology, and to enhance those resources in response to the evolving needs of the research community. As the





New Analytical Techniques
New techniques are being developed to image the lower crust and upper mantle by extracting P-to-S converted and scattered phases from the incident wavefield of teleseismic events, recorded on arrays of broadband PASSCAL instruments. The image on the left is an application of an enhanced migration scheme applied to a magnitude 6.3 South American subduction zone event recorded by the Lodore array of broadband PASSCAL instruments in northwestern Colorado (Figure provided by Gary Pavlis, Indiana University).
The image on the right shows both P- and S-velocity perturbations derived from simultaneous inversion of scattered teleseismic P-waves from 30 earthquakes recorded on the E-W Cascadia profile in central Oregon. (Figure from Michael Bostock, University of British Columbia) More information on both techniques is provided in Appendix I.

members of the IRIS Consortium have been engaged in the development of this proposal, four general themes have emerged to guide our activities over the next five years:

Higher Resolution – Against a backdrop of global tectonic fabric, the PASSCAL program has demonstrated the importance and practicality of high-resolution seismic imaging to illuminate structures and processes at local and regional scales. Combined with other geological and geophysical techniques, and with enhanced interpretative tools, seismology is poised to make significant new contributions to investigating Earth structure. This requires an investment in additional instrumentation to meet the growing demands for higher density observations of different tectonic environments and the deeper Earth.

Long-term Coverage - The Global Seismographic Network has now reached its design goal of uniform coverage over the continents and much of the world's oceans. The IRIS Data Management System has constructed the hardware and software resources that ensure long-term return on PASSCAL and GSN investments in data collection, through effective means for quality control, archiving and distribution. With our partners in the US Geological Survey, we need to ensure the long-term operation and maintenance of these resources. This will require a commitment, on our part as operators, to manage these facilities efficiently, and, on the part of NSF and USGS as funding agencies, to provide the required financial support for operation and maintenance.

High Performance – The instruments that IRIS provides through its core programs must evolve and be upgraded to maintain the highest technical standards and to take advantage of emerging technologies. At the same time, the full facility – including personnel, management, software, training, operational support and membership services – must continue to serve the research community in an effective and efficient manner. This requires the continued investment in tools, technology, and people to maintain the excellence and quality associated with a national facility.

Linking Facilities, Research and Education – The IRIS Consortium, whether through the data resources of its facilities or the intellectual resources of its members, has a responsibility and a unique opportunity to bring the excitement and intellectual challenges of earthquakes and seismology to the public and the classroom. This requires investments in education to communicate our scientific results in meaningful ways to a broad audience and to make the data acquired through IRIS facilities accessible to non-scientists in ways that are useful.

The Need for Higher Resolution

Just as the first microscopes revealed that a seemingly simple drop of clear pond water was in fact a complex ocean teaming with microscopic life, detailed seismographic studies are now beginning to show us a fabric within the Earth's interior that previously lay hidden within the coarser scales of earlier studies. A fundamental goal of the IRIS program is to provide the seismological community with the necessary instrumentation to image the internal structure of the Earth with sufficient resolution to answer important geoscience questions. There is an increasing recognition that 2-D transects, while important, are insufficient to describe the inherent complexity of Earth systems. 3-D observations are required to fully explore the rich diversity of lithospheric and deep Earth structure. With current limits on the numbers and complexity of instruments, investigators must generally choose between 3-D experiments with insufficient resolution, or 2-D experiments with good resolution but whose interpretation requires simplifying assumptions about Earth structure.

Recent studies utilizing high-resolution seismic data illustrate the power of adequate resolution in understanding solid Earth systems and their interactions. PASSCAL experiments in the western US, South America, and Asia have shown that high topography, previously believed to be supported by low density crustal roots, is instead supported by low-velocity mobile mantle material. Crustal scale strike-slip faulting and pervasive, orogen-wide detachment faults penetrate the underlying mantle, implying a degree of mantle control on crustal structure in orogenic belts and along plate boundaries. At the same time, recycling of crustal material and de-watering within subduction zones, and delamination and phase change of mafic lower crust beneath orogenic belts, exert crustal control on upper mantle structures. Measurements of anisotropy in the crust, where caused by fluid filled cracks, can be used to infer current tectonic stress, and where caused by rock fabric, to indicate past crustal strain. Tantalizing images suggest the presence of melts and aqueous fluids in the crust, which may be important factors in controlling lithospheric structure and dynamics.

Where high resolution data are available, imaging of fault zones, characterizations of fault zone processes, and mapping of fault networks provide a better understanding of the complexity of earthquake nucleation, rupture, and propagation, and provide data for input into earthquake simulations. In magmatic systems, tomographic images utilizing dense ray-path coverage have resolved conduits and magma chambers and high-precision earthquake locations have been used to map magma migration. Systematic application of 2-D profiling, vertical seismic profiling, 3-component acquisition, and 3-D data analysis in the near-surface for detailed structural, environmental, and groundwater studies, provide the best opportunity to characterize velocity and density variations and unequivocally link these parameters directly to subsurface geology, groundwater saturation, and flow paths.

In the deeper Earth, high-resolution data sets from both PASSCAL and GSN trace the plumes associated with hotspots deep into the mantle. We can image descending slabs well into the mid-mantle, and in some cases tie them to structures near the core-mantle boundary. Measurement of in-situ anisotropy, reflecting the influence of strain on the alignment of olivine crystals, can be used to map deformation patterns in the mantle lithosphere and flow of the sub-lithospheric mantle. Core-diffracted seismic phases suggest regions of possible partial melt just above the core-mantle boundary.

The complex assemblages of crust and mantle rock that make up the continental lithosphere exhibit a great degree of lateral and vertical heterogeneity. The scarcity of high-resolution data has forced us to average and extrapolate observations over large distances. To fully understand the dynamic processes that shape the Earth and to link observations made at the Earth's surface with underlying structure requires recording an unaliased wavefield in three dimensions. This requires denser sampling of the wavefield in both the temporal and spatial domain as well as advances in imaging science that take advantage of the wealth of information recorded in the full wavefield. Today, regardless of the scale of the investigation, there is a real need for high-resolution data as we expand both ends of the imaging spectrum from investigation of near-surface environments on the scale of meters to images encompassing the whole lithosphere and deeper Earth. Our goal is to achieve the desired resolution routinely in three dimensions. Recent advances in instrumentation that take advantage of new technology to produce cheaper and easier to deploy instruments make reaching this goal feasible.

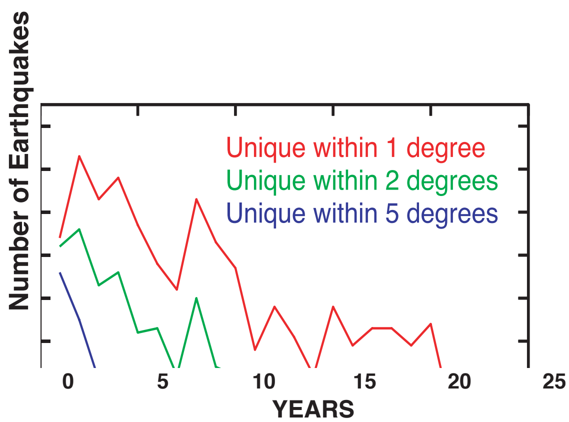
The Need for Long-Term Coverage

Each time a significant earthquake occurs, we have an opportunity to learn about tectonic processes, and sample part of the Earth's interior, as the waves produced by the earthquake travel to seismic stations around the world. Although the public perceives earthquakes as unusual events, on a global scale they occur often enough to allow a facility that monitors the Earth on a time-scale of decades to resolve in four-dimensions processes such as the highly variable rates (decades to days) at which magma accumulates and migrates in the upper mantle and crust, the possible differential rotation of the inner core, and the processes through which strain accumulates over decades in fault systems and is released in seconds through earthquakes.

The scientific value of long-term operation of a global network of seismographic stations is realized in several ways. Seismographic stations are necessary for the detection, location, and characterization (e.g., size, focal mechanism and rupture process) of earthquakes. A time series of earthquake activity, accumulated over years, decades or centuries of observations, is the key datum for studies of seismicity patterns, seismic cycles, and, more generally, regional tectonic loading and deformation. High-quality observations and long time series are both essential for these investigations. In addition, studies of large and otherwise rare or unusual earthquakes are particularly important for providing constraints on the earthquake generation process.

It is worth noting that there have been no truly large ($M \geq 8.5$) earthquakes during the last 25 years (1976-2000), while there were six in the period 1950-1975, among them the M=9.5 Chile and M=9.2 Alaska earthquakes. With the instrumentation available at the time, none of these very large earthquakes were recorded on-scale, and their source processes are correspondingly poorly understood. These infrequent but large events are the major contributors to the energy and strain release during an earthquake cycle. The GSN will, by design, be able to capture the next M=9.0 earthquake on-scale across the entire seismic frequency band, providing a unique data set for studies of the earthquake source process.

Long-term observations are necessary to collect the large data sets of travel times and waveforms that are necessary for global tomographic studies. The non-uniform distribution of seismic sources in both time and space constitutes a major challenge to studies that image the three-dimensional structure of the Earth's interior. At present, the GSN comes close to providing the optimal station coverage that can be achieved, with land-based observatories, for moderate global-scale resolution of Earth structure. Global seismicity patterns now control the frequency at which paths through the Earth are illuminated and, correspondingly, the rate at which information about the three-dimensional structure accumulates. This rate is difficult to quantify, as the information that can be derived from a single earthquake depends not only on its location, but also its size and focal mechanism, as well as characteristics of stations that record the earthquake, such as typical noise levels. For example, IRIS GSN stations on remote island sites in the Pacific Ocean are providing unique new travel time, dispersion, and attenuation measurements for seismic wave paths through the Pacific mantle. Typical surf conditions at these islands, however, make the stations noisy, and only large earthquakes are well-recorded. While each well-recorded earthquake provides important constraints on Earth structure, new observations accumulate slowly and long-term observations are required to realize the benefits of the special station location.



Unique Events
Earthquakes generally occur where earthquakes have occurred in the past. In this figure, a 'unique' event is defined as one that does not have an earlier neighbor within 1, 2, and 5 degrees, based on earthquakes with moment magnitudes greater than 6 in the Harvard CMT catalog. Time is measured from the start of the CMT catalog in 1975. A similar pattern would be expected for other time periods. In terms of sampling 'unique' paths through the Earth and providing new information for tomographic studies, the value of a station or network is greatest during the first 10-15 years of operation. The distribution has a long tail, however, demonstrating the value of long-term operation. More than 50 IRIS GSN stations have operated for less than 5 years. (Figure provided by Goran Ekstrom, Harvard University)

Long-term operation of seismographic observatories is also needed to record the seismic signals from rare earthquakes or other unexpected events. Such rare events may be nuclear tests and other man-made explosions, as well as natural phenomena such as volcanic eruptions, rock-falls, and meteoritic impacts, all of which have been observed and studied using GSN data. Long-term observations have recently been crucial for the discovery of Earth's continuous long-period oscillations, a phenomenon which probably is caused by the elastic coupling of the atmosphere or ocean with the solid Earth. Long-term global observations of seismic as well as other geophysical signals, such as barometric pressure, temperature, wind, currents, etc., are necessary to increase our understanding of how the various Earth systems interact.

Experience has shown that the value of seismic networks and data archives grows with time. Even today, data from the 1960s WWSSN instruments and other analog networks are often "mined" for historical earthquakes with ray paths through structures that have not yet been sampled by more modern stations. The first images of the Farallon plate under North America were obtained from WWSSN data, as was some of the first evidence for discontinuous layering and ultra-low velocity zones above the core-mantle boundary. Researchers have searched records from old seismic stations in Alaska and Sweden for valuable clues regarding inner core rotation. In the long term, the easy access to modern digital archives will make GSN data even more valuable than those from the older stations.

The GSN network is nearing its goal of global coverage. The PASSCAL program is providing high-quality instruments to over 50 experiments each year. The IRIS DMC annually responds to tens of thousands of requests for data. If properly maintained, the scientific value of these programs and their potential to fuel new discoveries will be realized for decades to come. A significant part of the funding requested in this proposal is to ensure the long-term health of the investments made in the data collection and archival components of IRIS. That health will be maintained through carefully planned operation and maintenance of the existing facilities, attention to data quality, and improvements in operating procedures.

High Performance

Modern technology has given us the instrumental capabilities to sense, record, and store the full spectrum and dynamic range of ground motions from earthquakes and explosions. The standards established for IRIS instrumentation and data handling have become a measure of "high performance" at the technical level for both national and international seismology. The Consortium continues to stimulate the application of new hardware and software to improve the quality of IRIS data and the efficiency of their collection and distribution. An important component of this proposal is to continue this tradition of high-performance. We will encourage the development of a new generation of portable instruments that are lighter in weight, lower in power consumption, and more robust. Emerging technologies for global and local telemetry will be used to extend the standards for high performance for data flow "from sensor to desktop".

An example of recent IRIS support of high performance technology is the PASSCAL telemetered broadband array, which demonstrates the advantages of real-time seismology for increasing efficiency, reducing cost, and improving data quality. Once installed in the field and operational, data from the array are transmitted via radio-modem or other communications channels to a central hub where they are linked to the Internet. The data and network performance then can be viewed and monitored in real-time from any location with an Internet connection, and instrument parameters can be modified remotely. Frequent visits for data recovery are not required and field visits need take place only when truly necessary. Data from the entire array are consolidated immediately, obviating the need for the time-consuming process of merging data from separate recorders, and data can flow seamlessly to the IRIS Data Management Center for archiving. The array can be used to locate seismicity in real-time, both within the experiment area and worldwide, and analysis can begin immediately to assure that science goals are being met.

High performance must be maintained throughout IRIS programs – not just through investment in instruments and equipment, but through the full resources that the Consortium provides, including data flow, data access, software support, education and outreach, and membership services.

Linking Facilities, Research and Education

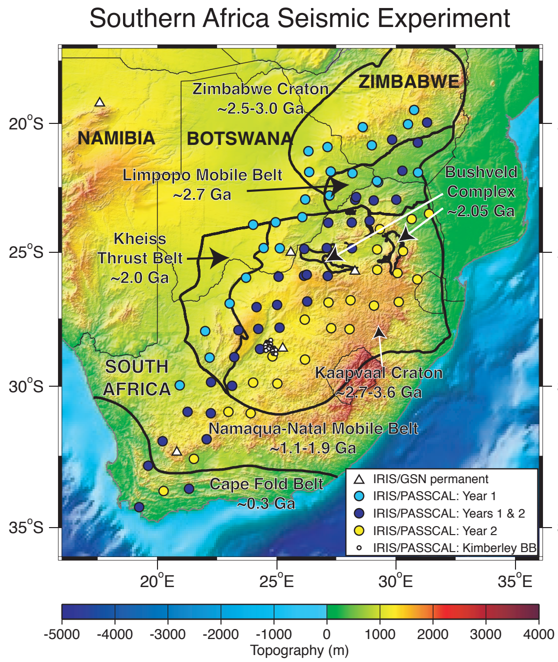
Seismology is a scientific discipline that appeals to individuals of all ages. Through images of Earth's internal structure, seismology provides a look into the inner-workings of our planet. Earthquakes are spectacular events and the public is curious about where and why they occur and what they tell us about our Earth. Media attention to earthquakes can help the public recognize the importance of research in seismology and related Earth science. A strong public awareness of the Earth sciences is important in reducing risks and mitigating losses from earthquakes and from other natural hazards. The exciting and immediate aspect of earthquake seismology provides an educational gateway into broader aspects of the Earth and physical sciences.

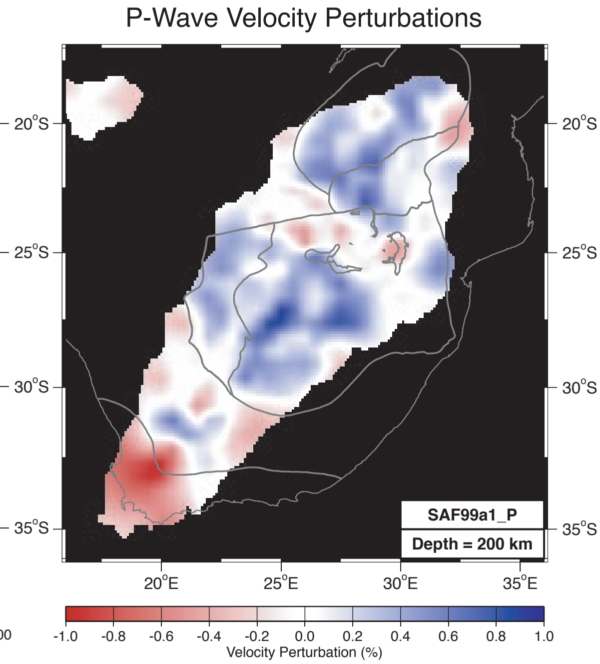
As a consortium of educational institutions with research interests in seismology, IRIS is in a unique position to establish and stimulate links between the Earth science research community and education. IRIS members represent the highest level of national expertise in teaching seismology at the undergraduate and graduate level. Furthermore, many IRIS members are active in local outreach programs to primary and secondary schools and are a resource to radio, television and print media. As a national university consortium, IRIS can partner with NSF and other organizations at the national level, and with its members at the local level, to:

- articulate major research results in seismology and the solid Earth sciences to the broader public,
- provide a clearing house for educational materials related to seismology, and
- help a variety of institutions to improve Earth science education in general, and seismology in particular.

In 1997, IRIS initiated an Education and Outreach (E&O) program that contributes to formal and informal science education at all educational levels. IRIS E&O activities focus on integrating research and education in seismology and include research experiences for students, professional development for K-12 teachers and college faculty, collaborations with several major US museums, and the development of hard copy and electronic educational materials and resources. The IRIS E&O program operates at both the national and local level: local initiatives are facilitated through involvement of the IRIS membership. For example, IRIS E&O sponsors workshops to introduce research seismologists to inquiry-based, hands-on approaches to teaching Earth science at the K-12 level. Participants in these workshops can then assist in professional development of local teachers.

The goals and activities of the IRIS E&O program are consistent with the 1996 National Science Education Standards that emphasize providing quality science education for all students at all levels of the curriculum, and involving students in learning science by doing science. In the next five years, we will continue our efforts to make seismological data easily accessible and more educationally useful, and to reach a significantly larger audience.



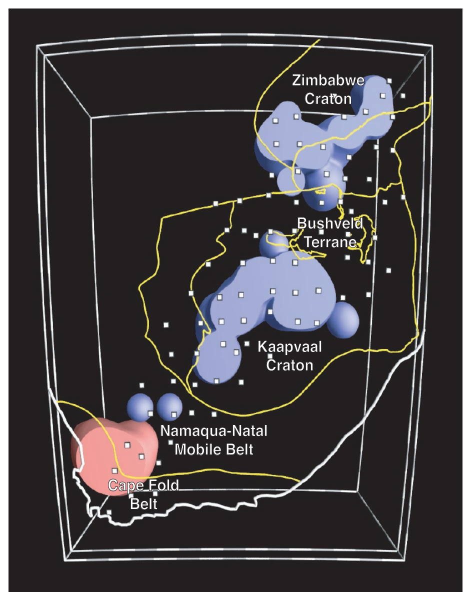


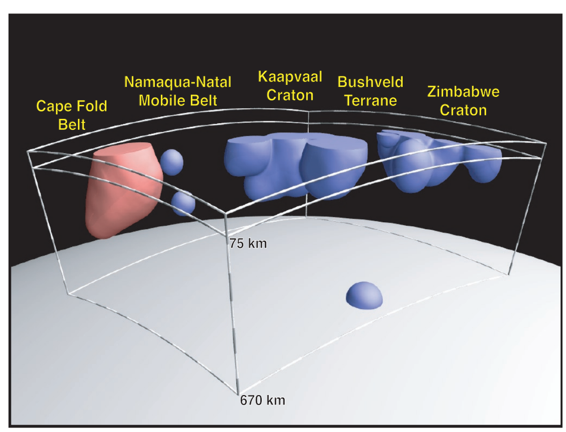
ROOTS OF ANCIENT CRATONS

The southern Africa seismic experiment, summarized in the four figures shown here, was the largest broadband experiment ever undertaken at its time of deployment. The experiment was part of the multidisciplinary Kaapvaal Project, designed to enhance our understanding of continental formation, evolution and dynamics. Analysis of the broadband seismic data has produced dramatic high resolution images of the continental lithosphere and deeper mantle beneath the ancient core of southern Africa. The seismic studies were closely coordinated with geochemical and petrologic investigations of mantle samples rafted to the surface in kimberlite pipes. These integrated studies are revealing for the first time the detailed anatomy of ancient continental roots, showing not only that they extend to depths as great as 250-300 km, but also that they are highly depleted chemically relative to the rest of the mantle and that they are as old as the overlying crust.

The map figure in the upper left shows locations of broadband stations deployed during 1997-1999 superimposed on principal geologic provinces and topography. The upper right figure is a horizontal section of velocity perturbations at 200 km depth. Blue indicates postive velocity anomalies and red indicates negative anomalies. Velocity structure was obtained from the tomographic analysis of teleseismic travel time delays for about 8000 P-wave rays recorded on the 82 stations of the broadband array. The two figures on the right are perspective views of volumes enclosing high and low P-wave velocity anomalies, plotted from 75 to 670 km depth. The high-velocity regions are enclosed by blue surfaces, and the low-velocity regions by red surfaces. View of top image is from directly above the target region and shows boundaries of geologic provinces (yellow lines) as well as broadband station locations (white boxes). The view of the bottom image is from the southeast and above ground level. The tectospheric roots of the ancient (~3 Ga) Kaapvaal and Zimbabwe cratons are shown clearly as high velocity volumes extending 200 to 300 km beneath the surface expression of the Archean cratons. Low velocities in the upper mantle are seen beneath the Phanerozoic Cape Fold Belt of southernmost South Africa. The disruptive effect of the massive Bushveld layered intrusion (2.05 Ga) is evident as an intermediate velocity (neither blue nor red) E-W swath cutting through the northern region of the Kaapvaal craton.

(Figure provided by Matt Fouch, John VanDecar, and David James, Department of Terrestrial Magnetism, Carnegie Institution of Washington)





Science Supported by IRIS Facilities

While this proposal directly requests funding for the facilities of the IRIS programs, these facilities are of value to NSF and the scientific community primarily through the scientific research they support. In this section, we present examples of several questions and research directions that will be central to the Earth sciences during the next decade, and to which seismological research and the IRIS facilities contribute significantly. The one-page vignettes that accompany this document, all contributed by users of IRIS facilities, provide a more comprehensive view of the wide range of scientific investigations which have developed as a result of NSF's investment in IRIS.

Lithospheric Structure and Dynamics

Plate tectonics works well to explain the structure and dynamics of oceanic plates, but it does not provide an encompassing theory for evolution of the continents. The architecture of the lithosphere, acquired over the lifetime of the planet, records 95% of Earth history. The long-lived inherited structures and compositional variations modulate modern tectonic processes, and likely play a role in determining the patterns of the global convection system.

A wide range of seismic methods from high-resolution seismic reflection profiling of the near surface to lithospheric-scale imaging with both active and passive source array experiments are now standard tools for extending geologic observations made at the surface to depth. In the past decade, the PASSCAL program has allowed for a remarkable increase in the deployment of experimental programs to understand the tectonic evolution of continents; how they have been assembled, disassembled, and altered with time; how the lithosphere is connected to the deeper mantle in global convection models; and how coupled surface and deep tectonic processes modify the lithosphere. These results, integrated with potential field, geochemical, and geologic data, point to previously unknown processes involved in continental dynamics.

Surface wave studies using both GSN and PASSCAL data suggest that the base of the lithosphere extends to 200-250 km beneath most stable continental interiors, reaching depths as great as 300-400 km beneath some cratons. Such estimates are consistent with heat flow data and petrologic studies of mantle xenoliths. In places, this cool, chemically buoyant upper mantle material is mechanically coupled to overlying cratonic crust. In other places, the upper mantle merely acts as the edifice upon which a series of detached crustal sheets ride. Generally, it appears that the tectospheric mantle is mechanically decoupled from the underlying mantle and the mantle transition zone. The variability in lateral extent and thickness of lithospheric roots, both globally and within tectonic domains, suggests that continental lithosphere is formed by a complex set of processes that include modification by volcanism and tectonism through time, such as lithospheric stacking during collisional events, basal erosion during rifting, and small scale convection associated with plate motion.

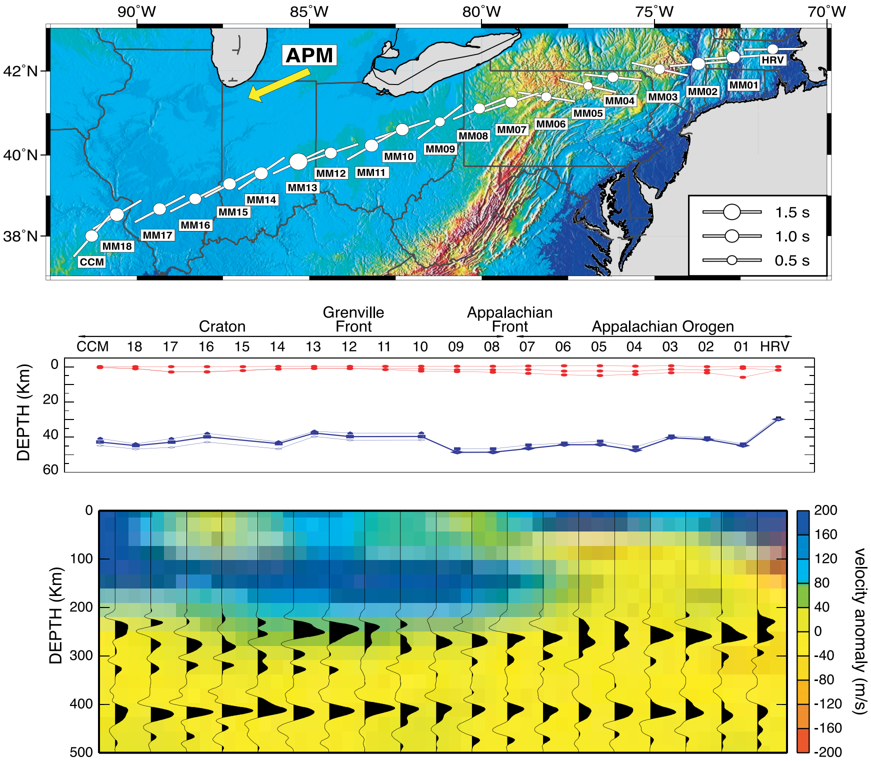
The Himalayan region, the site of ongoing continental collision, provides a unique opportunity to determine the active processes associated with collisional orogenesis. Seismological studies, using a variety of GSN and PASSCAL resources, have been used in concert with other geological and geophysical techniques in multi-disciplinary investigations to unravel the structure and evolution of continental collision. Understanding modern collisional belts provides insights to help us interpret the record left behind in older orogens. Both passive and active seismic source PASSCAL experiments in Tibet point to lateral heterogeneity and complexities on all scales. Low P-wave velocity mantle, inefficient Sn wave propagation, and high Poisson's ratio in the crust suggest that the Asian lower crust beneath northern Tibet is partially molten. Strong P-to-S conversions in wide-angle active source data, bright spots in vertical incidence reflection data, receiver function analysis of teleseismic data, and magnetotelluric observations all suggest that fluids (partial melt, true magma, or aqueous) also lie under part of southern Tibet. Collectively these results indicate that the lower crust may be very weak and capable of significant flow and hydrostatic effects.

PASSCAL experiments in east Africa show evidence of large-scale crustal underplating during the early stages of rifting with the mantle lithosphere thinning considerably more than the crust. At the same time, the adjacent Tanzanian craton seems to have retained its identity, suggesting the presence of a continental keel that has survived intact for over 2.5 Ga including the recent 30 million years of rifting and plume activity. Global tomography indicates an underlying low-velocity region that may extend to the core-mantle boundary. GSN data suggest that the low-velocity areas under Africa are caused by upwelling of the lower mantle, which, in turn, results in large surface uplifts.

In the western US, seismology has contributed to a number of multidisciplinary projects stimulating major re-thinking of the architecture and dynamics of continental

The MOMA Experiment

The 1995-1996 Missouri to Massachusetts Broadband Seismometer Experiment (MOMA) was designed to use sources in the southwest Pacific to investigate structure at the base of the mantle, and in the lithosphere beneath the eastern US. The lower figure shows receiver functions on a background of velocity anomalies from the NA98 model combining data used by Van der Lee and Nolet [1997] with waveforms recorded by the MOMA array. The receiver functions show a discontinuity at roughly 280 km in the mantle outside the sub-cratonic lithospheric keel and a discontinuity at 320 km beneath the keel, both of which may represent the base of a low velocity zone. No significant long wavelength topography exists on the 410 km velocity discontinuity across the keel's eastern margin. At stations located above the keel, shear-wave splitting fast directions (top figure) are roughly parallel to each other and to the direction of absolute North American Plate motion, but fast directions are much more variable outside the keel. The crust thins(middle figure) by roughly 5 km just to the west of the Appalachian Mountains. (Figure provided by Karen Fischer and Matt Fouch, Brown University). Additional details and studies are described in Appendix I.



lithosphere across complex tectonic provinces. PASSCAL data from the Sierra-Nevada show that the mountain range has no significant crustal root but rather is supported by the underlying mantle. PASSCAL experiments in the Basin and Range show that the crust is still relatively thick (30 km), despite having undergone at least 100% extension. In the Wyoming craton, PASSCAL experiments found that the Archean crust, over 50 km thick in places, has an unusually thick, high velocity lower crust, suggesting that an underplating process has altered the lower crust in this region. Different crustal terranes have different upper mantle structures and, despite similar Archean ages, almost as much variation is found within the cratonic crust as between it and adjacent younger crust. Moreover the transition from cratonic tectospheric mantle to tectonically mobile upper mantle occurs over a relatively short lateral distance (~150km) and is associated with a Proterozoic age suture.

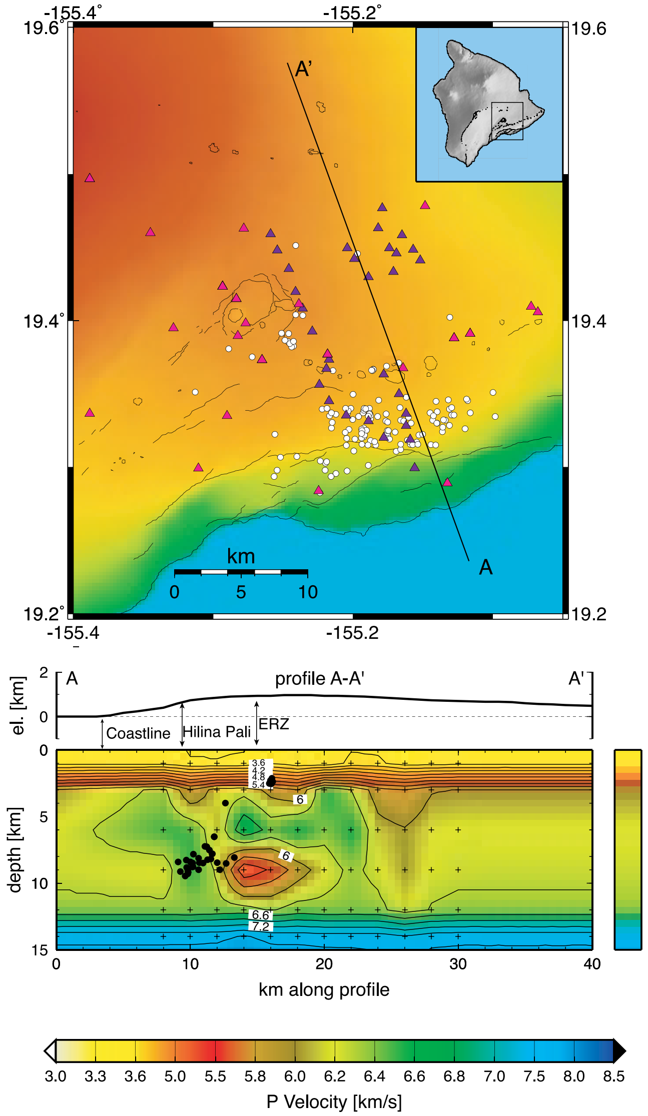
Collectively these results suggest a degree of interplay between the crust and tectonic mantle lithosphere not previously recognized, and challenge the Earth science community to develop new ideas and more comprehensive models of how the Earth's lithosphere and upper mantle work at ever-finer scales. Where high-resolution observations are available, we see that mantle structure is extremely heterogeneous. Trends in surface features often correlate with mantle structure, indicating that surface exposures and topographic detail are frequently, although not always, the manifestation of deeper-seated geologic processes.

Seismic studies frequently use a variety of information – travel-times, amplitudes, spectra, multiple phases, and multiple components – to determine details of structure, composition, and physical properties of the subsurface. Recent advances in observational capabilities and analytical techniques have improved our ability to discern and image structural details, and characterize heterogeneity on a variety of scales. These advances are fueled by data from the flexible pool of PASSCAL instruments, which can be deployed in a focused manner to address key issues of lithospheric structure, evolution, and dynamics. New insights from these dense deployments and high-resolution studies lead to a healthy positive feedback between experiment design, data analysis, and instrument development.

In the next five years, IRIS facilities will make possible higher-resolution observations from a diverse range of local, regional, and global scale studies. These observations, integrated with other geophysical and geologic data, will link crustal tectonic provinces with dynamic topography and underlying mantle structure; determine how lithospheric mantle is coupled to sub-lithospheric mantle, determine rheological properties and lateral heterogeneity within and between orogenic belts, plateaus, rifts, and cratons; and constrain mass flow and lithospheric deformation during mountain building and continental rifting.

Volcanic Processes and Magmatism

Volcanoes are obvious surface expressions of deep-seated



Imaging Volcanoes
An array of 29 PASSCAL instruments has been used to augment the Hawaiian Volcano Observatory network in an investigation of the rift-flank system of Kilauea volcano, Hawaii. A tomographic model of Kilauea's East Rift Zone (ERZ) shows a low velocity region centered at about 9 km depth that appears to be the seismic expression of a deep magma body that has been steadily inflating over at least the past 25 years, causing rapid seaward movement of Kilauea's South Flank at a rate greater than 10 cm/yr. This inflation is mechanically coupled with earthquakes and aseismic slip on a decollement fault beneath the South Flank, and volcanic intrusions and eruptions along the ERZ. (Figure provided by Cliff Thurber, University of Wisconsin - Madison.)

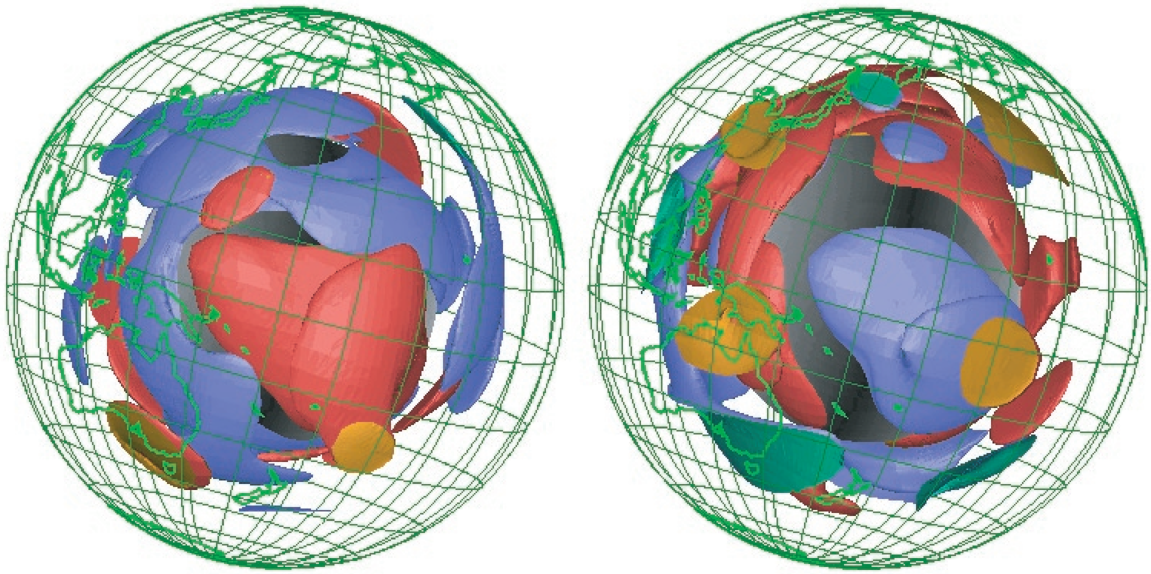
Earth processes. Throughout geologic time, volcanism and other magmatic processes have played a central role in the formation and modification of both oceanic and continental crust and lithosphere. Although melting is clearly necessary for magmatic activity, the prerequisites for melting and melt behavior remain enigmatic.

While active volcanoes are a natural hazard, they also are a source of geothermal energy and ultimately of mineral resources. From a natural hazard reduction perspective, seismology has played a major role in the successful prediction of volcanic eruptions.

Results from passive and active source experiments in the Valles Caldera, and recent observations of large mid-crustal magma bodies under the Rio Grande Rift and the Altiplano-Puna Volcanic Complex in Bolivia show that magmatic underplating is a common way to build continental crust. Active source seismic data have been used for direct wavefield imaging of wet basaltic intrusion in the lower crust in northernmost California and for imaging silicic melt, or silicic/aqueous fluids in upper-middle crust of the Tibetan Plateau. The former case shows surprisingly complicated reflections, akin to deep crustal reflectivity patterns in extensional terranes, whereas the latter are surprisingly simple and perhaps widespread. However, the frequent lack of association of regions of magmatic underplating with shallower volcanic activity remains puzzling. Buoyancy is thought to control magma levels in oceanic lithosphere, but the factors important in continental settings are not yet well understood.

In the Andes, a classical convergent margin setting, PASSCAL and other studies have produced images of the subduction zone which suggest a relationship between thickness of the mantle wedge and the ability to produce melt, but the role of slab devolatilization requires further investigation. PASSCAL studies of the Tonga-Fiji back-arc region have found very low seismic velocities and strong attenuation which, based on comparisons with laboratory data, is consistent with the presence of partial melt to depths of 100 km. Further work on the relationship between seismic velocities and temperature will help to identify regions of partial melt in the back-arc setting, and elsewhere.

Active volcanoes are natural targets for PASSCAL experiments since they involve geophysical processes that take place on spatial and temporal scales amenable to real-time field experiments. Physical changes within a volcanic system occur over time scales much shorter than changes in a tectonic system, yet much longer than a single earthquake, allowing for the observation of a complete cycle – from quiescence, through reawakening, eruption and a return to quiescence. The small spatial scale of an individual volcano or volcanic complex makes possible the high-resolution imaging of entire volcanic systems. At Mammoth Mountain a PASSCAL deployment recorded temporal changes in the Vp/Vs structure under the volcano, and at Karymsky Volcano degassing explosions and periodic tremor have been observed and characterized over time. While many geophysical and geological observations of this process are important, seismic observations often are the most extensive, covering the largest temporal and spatial extent with continuous sampling.

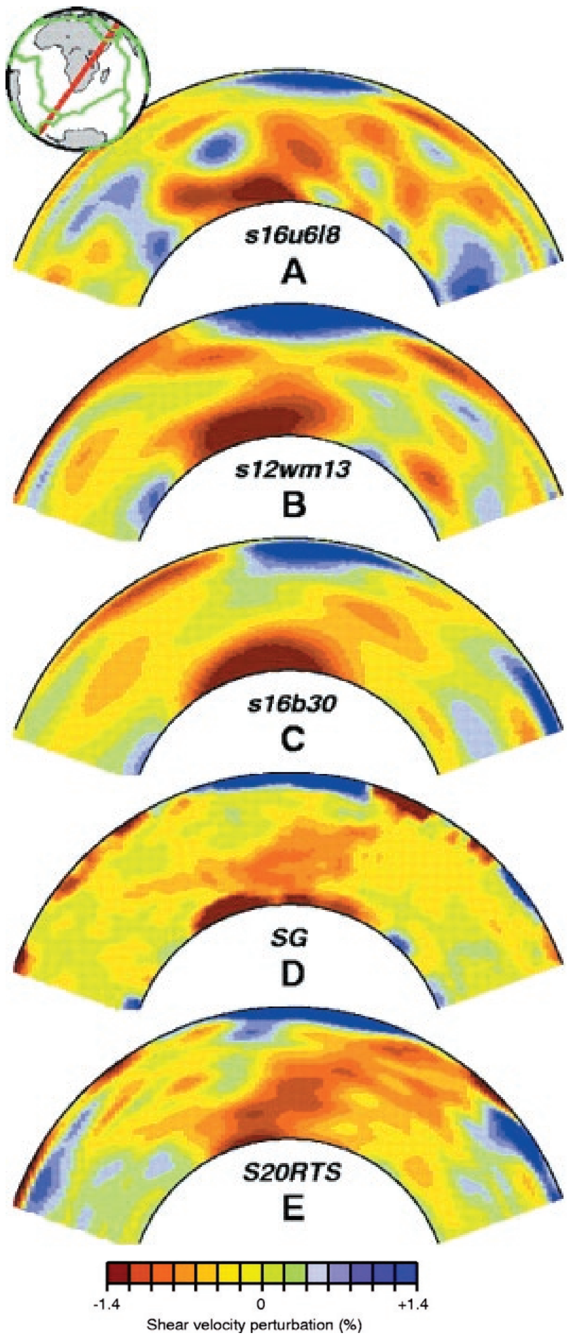


Composition of the Lower Mantle
Recent studies give the surprising result that, in the lower mantle, shear velocity perturbations appear to be anti-correlated with bulk sound velocity perturbations. On the left is a 3-D image of shear velocity perturbations from 1200 km depth to the core-mantle boundary, determined from model MK12 of Su and Dziewonski using the four gravest spherical harmonic coefficients (a very low-pass filtered image). Negative anomalies (low velocities) are shown in red, positive anomalies (fast velocities) are shown in blue A major negative velocity anomaly under the center of the Pacific is surrounded by a circle of positive velocity anomalies, coinciding with the Pacific rim and associated with subduction. The remnants of cold subducted plates appear at the core mantle boundary and a large upwelling occurs at the center implying a thermal origin for the anomalies: slow is hot, fast is cold.
The picture on the right shows a similar representation of the bulk sound velocity. The color scheme is the same, however the patterns are reversed – a positive anomaly in the center is ringed by negative anomalies associated with the Pacific rim. The anti-correlation of shear and bulk sound velocities in the lower mantle justifies consideration of compositional variations, or some very anomalous ratio of thermal perturbations in the bulk modulus to perturbations in density. The picture shown here was obtained using a combination of waveform (GSN) data and traveltime data obtained from the ISC Bulletin; the work of Masters et al. and of Ishii and Tromp, who confirmed these findings, was based entirely on waveform data collected principally at the stations of the GSN. (Figure provided by Adam Dziewonski, Harvard University).

Seismology, in conjunction with other geophysical and geochemical measurements, can contribute to our understanding of the eruption process. Earthquakes within a volcanic system can provide evidence of an impending eruption, map the pathway of magma through the crust, and provide sources of waves for tomographic studies of the internal structure of the volcano. Tomographic imaging of the 3-D structure of the magmatic plumbing system has been carried out in such locations as the Toba Caldera, the Valles Caldera, Yellowstone, and Kilauea Volcano, providing detailed pictures across several tectonic settings of how magmatic additions to the crust are made. Other examples of important areas of volcano-seismology research include analysis of converted seismic waves, the study of eruption dynamics using seismic and acoustic wave recordings, determination of the state of stress from source mechanisms and shear-wave anisotropy, and the study of harmonic tremor and low-frequency seismic sources (long-period earthquakes and very-long period events, up to 1000s).

Volcano studies provide a natural avenue for interdisciplinary research efforts to investigate the history and current state of volcanoes and calderas. Experiments in such locations are ideal candidates for close coordination with observation campaigns in related fields: igneous petrology, isotope geochemistry, gas chemistry, acoustics, gravity, and geodetic investigations including tilt, GPS, and InSAR. These measurements can be made simultaneously with seismological observations, in some cases across a full volcanic cycle, and, increasingly, in real time.

Next-generation PASSCAL instruments will greatly facilitate volcano seismology studies. New data acquisition systems (smaller, lighter weight, and especially lower power) will significantly improve deployment capability in difficult volcanic terrain. Rugged, low-power, broad-band sensors will improve observations of low-frequency waves from long-period earthquakes and other “exotic” seismic sources. The capability for multiple data streams from a variety of sensors would be extremely valuable, permitting the recording of acoustic, temperature, wind speed and other atmospheric conditions. Telemetry and real-time field processing are essential for monitoring and eruption prediction efforts as well as for changing experimental plans during eruption sequences. The value of seismology as a tool for understanding and managing volcanic hazards will continue to increase as these diverse observations are linked, and as we gain further experience with real-time field processing.



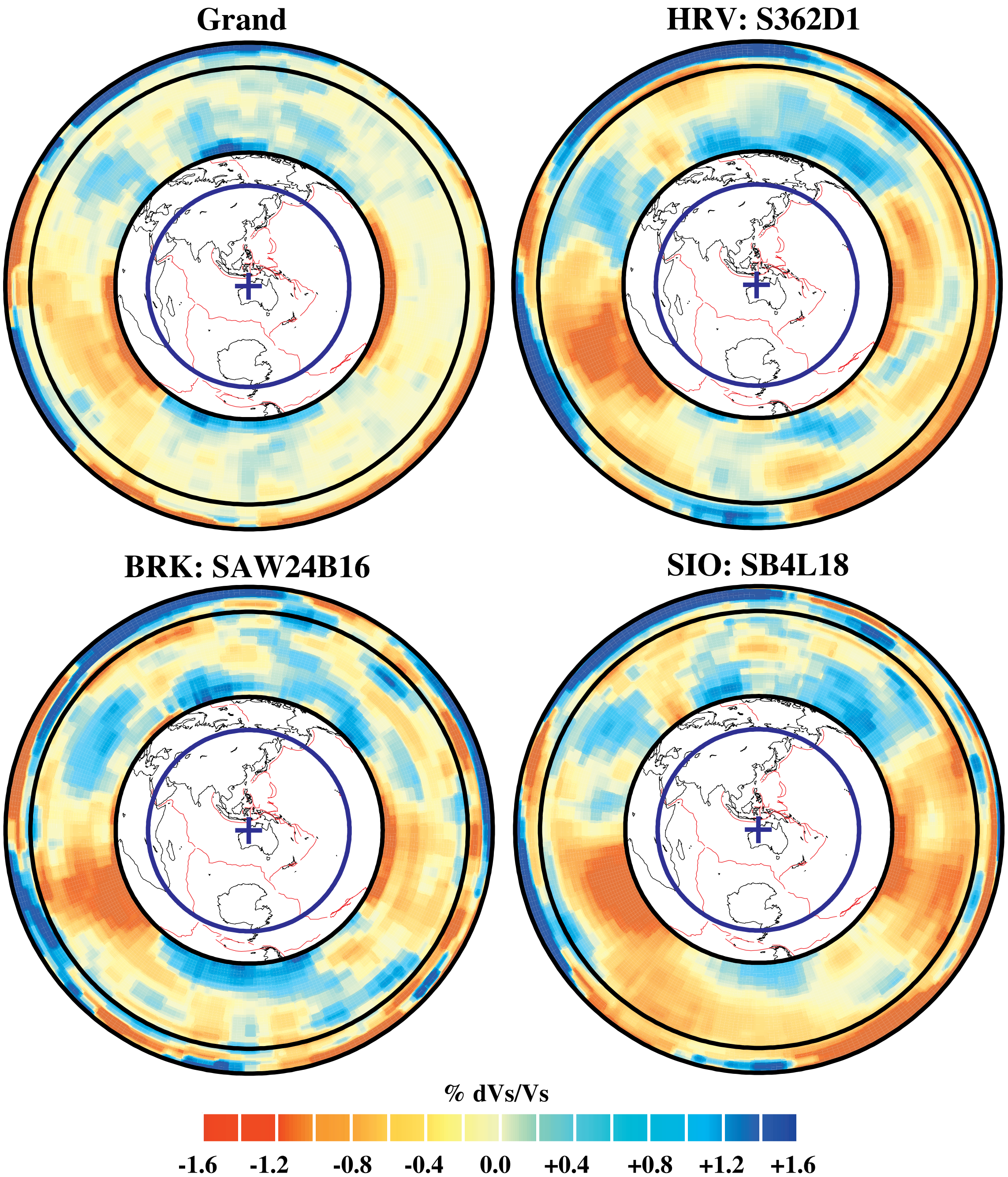
Linking Core and Lithosphere
Comparison of a number of recent tomographic images of the structure of the mantle from the South Atlantic, across southern Africa and into Arabia, shows a tilted low velocity layer extending from the core-mantle boundary to the upper mantle beneath eastern Africa. This anomaly suggests that Cenozoic flood basalt volcanism in the Afar region and active rifting beneath the East African Rift is linked to an extensive thermal anomaly at the CMB more than 45 degrees away. The data used in these tomographic studies come from the GSN and other international networks. (Figure provided by Jeroen Ritsema, Caltech)

Global Tomography and Mantle Convection

Understanding mantle convection is central to a wide range of Earth science topics, from the driving forces of plate tectonics to the longevity of geochemical reservoirs and the overall heat budget of our planet. Seismology has long provided important constraints on models of present-day mantle convection. Recent global and regional tomography models have provided dramatic images of subducting slabs and mantle upwellings, downgoing and upgoing limbs of the convective flow. Variations in seismic velocities indicate density differences and are used by geodynamicists, in combination with gravity data and surface topography, to model convection and estimate the viscosity of the mantle. It is now clear that subducting slabs often penetrate well into the midmantle, and that the 660 km discontinuity is, at best, a partial barrier to mantle flow. New seismic observations of the amplitude and topography of the discontinuities near 410 and 660 km depth are broadly consistent with mineral physics results for the appropriate phase boundaries in olivine. Detailed comparisons are beginning to resolve the chemical and thermal structure of the transition zone. Observations of upper mantle anisotropy, derived from shear-wave splitting and directional travel time variations, are starting to provide new types of maps and images of a mantle fabric related to the flow and strain associated with convection.

IRIS facilities and data have been crucial for the improvements in quality and resolution of mantle tomographic images realized over the last decade. Surface wave observations from the GSN are vital to resolving velocity heterogeneity and anisotropy of the thermal boundary layer in the upper mantle, because in this region travel time data, such as provided by the ISC, do not have adequate depth resolution to address the problem. Higher resolution can be achieved by more closely spaced stations. PASSCAL experiments in a number of regions have been used to probe upper mantle structure and anisotropy. Imaging the plumes that presumably underlie hotspots has proven challenging. Recently, several PASSCAL experiments have delineated apparent low velocity zones beneath hotspots that extend to depths greater than 200 km. This is geodynamically important because while subducting slabs are observed to be the dominant mode of convective downwelling, the amount of upwelling that occurs in the form of mantle plumes, as opposed to passive, broad return-flow upwelling, is still very poorly constrained.

Weak reflections from the upper mantle discontinuities have been imaged by stacking thousands of GSN seismograms; these images show that the 410 and 660 km



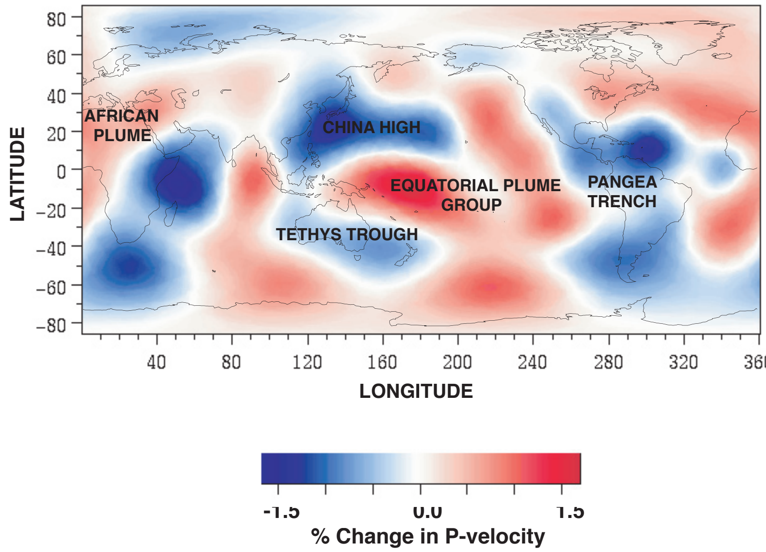
Earth Slices

Slices through four recent models of shear velocity heterogeneity in the mantle. Seismic images such as these provide important constraints on geochemical and geodynamical models of mantle convection. In the images shown here, subducting slabs can be traced well into the lower mantle, suggesting a significant degree of whole mantle convection. The most dominant features in the lowermost mantle are two seismically slow anomalies that are centered beneath Africa and the Central-West Pacific Ocean. These anomalies are often described as the seismic expression of two ascending superplumes. Controversies as to the origin and significance of these mid- and deep-mantle structures will be resolved as models improve, based on data of the highest possible quality from networks such as the GSN.

The models shown here are from Steve Grand at UT Austin, (Grand), Gu et al. at Harvard (HRV), Megnin et al. at UC Berkeley (BRK) and Masters et al. at Scripps(SIO). The Grand model is based on only body wave travel times. The Berkeley model is derived from modeling long period waveforms. The Harvard group uses a mixture of travel time and surface wave data and mantle waveforms and the Scripps group uses travel times, surface wave and free oscillation data. Despite differences in data and analytical techniques, these models have converged considerably compared to the last generation of models less than a decade ago. There is now general agreement that a long-wavelength 3-D reference Earth model is within reach.

A detailed comparison of these models is summarized on the Reference Earth Model web page: http://mahi.ucsd.edu/Gabi/rem.html. (Figure provided by Gabi Laske, U.C. San Diego)

Geography of the Base of the Mantle
Map of the P-wave velocity at the base of the mantle, made using an inversion of GSN PKP-Pdiff data. The strong correlation between this map and the history of Mesozoic and Cenozoic paleosubduction suggests whole-mantle cycling of the lithosphere. While complete imaging of the core-mantle boundary is difficult because the reduced amount of both seismicity and continents in the southern hemisphere, the use of long-range core-diffracted Pdiff data from a global network of seismometers has overcome this handicap. While first-generation tomographic images like this are tantalizing, greater resolution (attained with continued seismic monitoring) will help us better understand the details of the structure and evolution of the deep Earth. (Figure provided by Michael Wysession, Washington University).



discontinuities are ubiquitous features with topographic variations of 20 to 30 km. Receiver function analyses of GSN and PASSCAL data have revealed detailed topography on the upper mantle discontinuities; these variations are surprisingly large at short scales, suggesting that chemical as well as thermal structure may be an important factor in the transition zone. In the mid and lower mantle, seismic tomography results image broad slow regions, in puzzling contrast to convection simulations which typically predict much narrower plumes. In the lower mantle, the anti-correlation of shear and bulk sound lateral variations indicate a complex relationship between temperature and elastic properties of mantle materials.

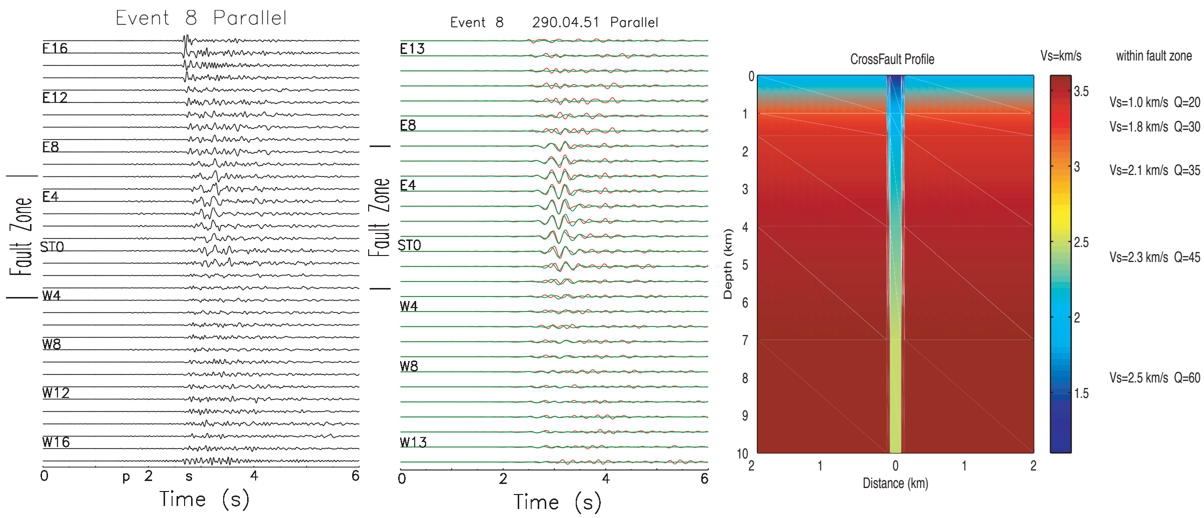
As seismic images and mineral physics results continue to improve, it will become increasingly important to combine these studies into self-consistent models of mantle composition and thermal structure. Advances in seismology will involve bridging the resolution gap between local and regional studies and the global-scale tomography models, as well as objectively integrating diverse data sources, such as surface waves, body waves and normal modes.

IRIS facilities will help address a number of unresolved issues: What is the relationship between deep continental roots and the surrounding convective regime? What role do the transition zone phase boundaries play in mantle convection? Are there compositional boundaries in the lower mantle that may sometimes prevent the penetration of subducting slabs to the CMB? Do plumes originate in the lower mantle, and how important are they in the convective process?

Heterogeneity in the Lowermost Mantle and Core

Many of the fundamental questions concerning the history and evolution of our planet, from core segregation to the genesis of hotspots, are related to the chemical and thermal structure of the deep mantle and core. While seismology provides the most direct images of the deep Earth, a full understanding of this region requires interactions with geomagnetists, geochemists geodynamicists and mineral physicists. For example, there will be continuing challenges to reconcile the geochemical evidence for isolated mantle reservoirs with the increasing seismic evidence for deep mantle convection and to unravel the complex nature of the thermal and chemical boundary layers that exist at the CMB – the boundary that divides the silicate mantle from the iron core.

Increases in the amplitudes of velocity variations in the lowermost mantle, as compared with the rest of the lower mantle, are a robust feature of global tomographic models. Recent studies of smaller regions near the core-mantle boundary using precursors to core phases recorded at both GSN and PASSCAL stations have demonstrated the presence of smaller scale velocity anomalies, including radial and azimuthal anisotropy and ultra-low velocity zones (ULVZs). The global distribution of ULVZs is not yet known, but the continued mapping of such anomalies over the coming decade will help to determine the relationship between these high-amplitude, small-scale structures and the longer wavelength velocity lows, seen in the tomographic images, with which they appear to be associated. Establishing the relationship between the observed long- and short-wavelength heterogeneity will provide important clues to the dynamic behavior of the deep Earth. It will also be important to determine whether the observed anomalies are likely to be the result of strong thermal anomalies, partial melting, or perhaps of chemical heterogeneity. Results constraining the Vp/Vs ratios observed at the scale of the ULVZs have been interpreted to favor either partial melting or compositional variations. PASSCAL experiments designed for deep-Earth studies are revealing a complex vertical structure across the bottom few hundred kilometers of the mantle, analogous to the



Structure inside Faults

Details of the velocity structure and temporal changes in the post-earthquake characteristics of faults can be obtained from high resolution observations of seismic waves trapped within the fault zone. Dense arrays of instruments across the fault using the special set of PASSCAL instruments reserved for RAMP (Rapid Array Mobilization Plan) and the multi-channel PASSCAL recorders are well-suited for these studies.

Left: Fault-zone parallel component seismograms recorded by 36 PASSCAL instruments in a 3-km long line across the rupture zone of the 1992 M7.4 Landers earthquake for an aftershock occurring within the rupture zone at 5 km depth. Middle: Low-pass filtered seismograms (red) show 3-5 Hz fault-zone trapped waves at stations located within the rupture zone. 3-D finite-difference synthetic trapped waves (green) fit observations well. Right: The model used for 3-D synthetics, showing a depth-dependent structure of the Landers rupture zone. (Figure provided by Y-G Li and John Vidale, University of California, Los Angeles)

variations observed in the crust and lithosphere. Further input from geochemists and mineral physicists will be critical for resolving this issue.

In the inner core, a cylindrical pattern of anisotropy has now been confirmed by a variety of seismological methods, but the question of its origin remains unanswered. Recent studies have shown a time dependence in the pattern of core-phase travel time anomalies, with a possible super-rotation of the inner core with respect to the mantle. Splitting functions determined from free oscillations excited by earthquakes occurring over several decades show a smaller time dependence; recordings from GSN stations have approximately doubled the length of time for which this type of analysis is possible. Waveform and travel time studies have shown the existence of lateral variations in velocity, attenuation and anisotropy in the inner core, with some raypaths appearing especially anomalous. All of these observations, as they are confirmed and refined, will place constraints on the poorly known physical processes – maintenance of the geodynamo and the growth and potential convection of the inner core, for example – operating in this most remote region of the Earth.

Future progress in deep Earth seismology will depend, in part, on reconciling the results obtained with global scale studies (e.g., mantle tomography models) with those derived from high-resolution imaging of particular regions (e.g., ULVZ studies). Problems of spatial aliasing inherent in global analyses will be reduced as source coverage improves through long-term monitoring and earthquakes occur in rarely sampled regions. Theoretical advances are needed, as well, to take full advantage of all of the available information in the IRIS waveform archives, including amplitude and polarization data and the scattered energy that arrives between the major phases. Together, advances in data coverage and analysis methods will facilitate rapid progress on a number of fundamental questions: How do large-scale patterns of mantle convection relate to ULVZs, anisotropy, and the thermal boundary layer at the CMB? How important is compositional heterogeneity in the lowermost mantle and how long can geochemically distinct regions persist in the mantle? What do the differing scales of mantle structure tell us about the dynamics and evolution of the deep Earth? What effect does mantle structure have on core processes? What do observations of inner core anisotropy and heterogeneity reveal about the formation and evolution of Earth's core and the energy source for the geodynamo?

Earthquakes, Faults and Deformation

How earthquakes nucleate and seismic ruptures grow are fundamental questions in earthquake seismology. Becuase most large earthquakes do not occur in areas of dense seismographic instrumentation, data from the GSN are often used to determine the characteristics of earthquake ruptures. These studies have typically concluded that in most earthquakes the distributions of slip and stress drop are highly heterogeneous. It is not yet clear to what extent this heterogeneity can be explained in terms of fault properties, including geometrical segmentation, previous earthquake slip, and the random effects of a complex dynamic rupture.

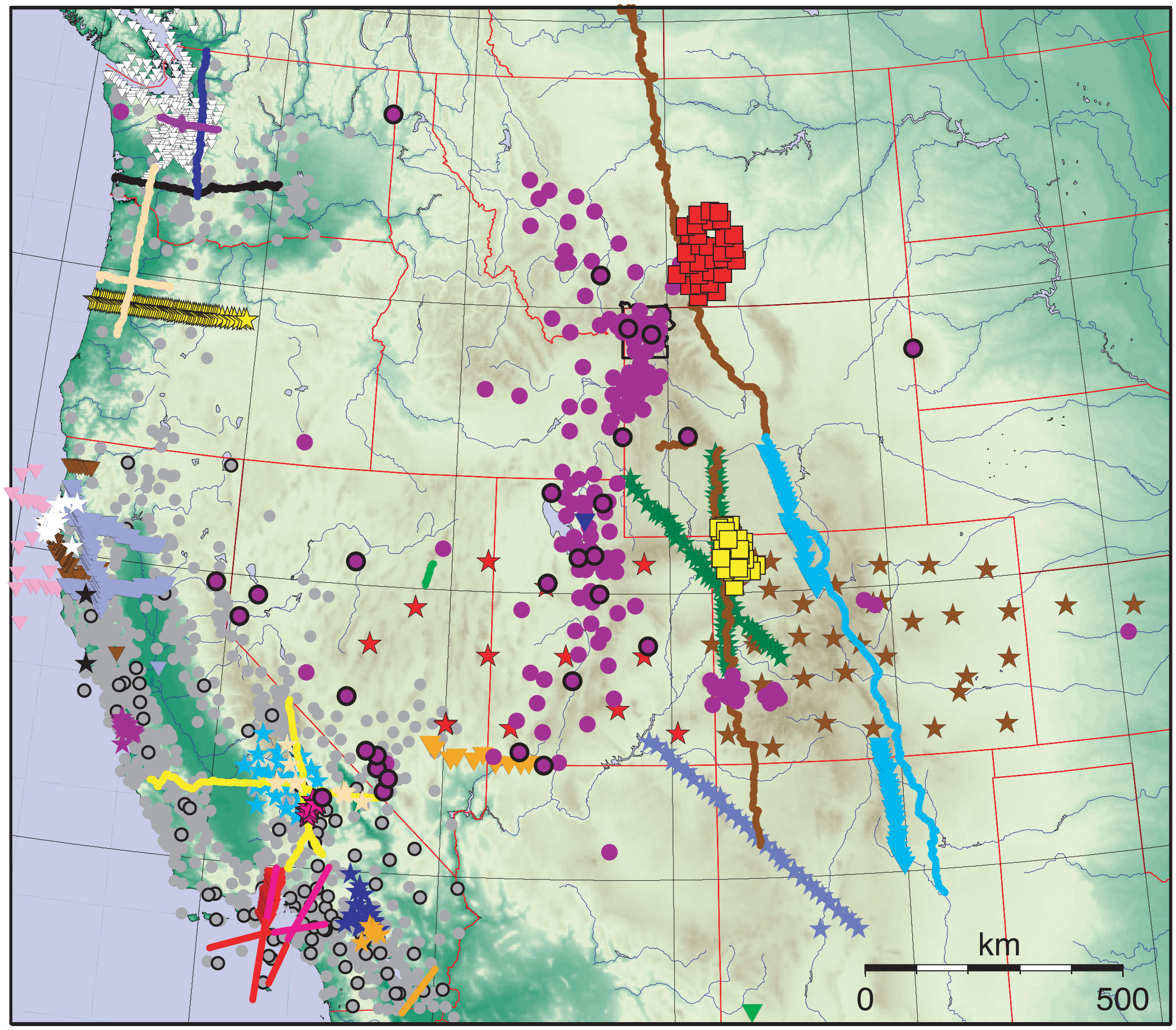
Recent research has highlighted the complex nature of strain release associated with compressional and transpressional plate boundaries and the mechanics of strain partitioning. On a global scale, the GSN provides the data necessary to analyze seismicity in terms of fundamental earthquake parameters, such as location, focal mechanism, and seismic moment. Several PASSCAL deployments have provided similar, but more complete, regional data sets. These source parameters constitute an earthquake strain record for the Earth's crust and mantle that can be used in conjunction with geodetic and geological observations to constrain modes of tectonic deformation, and directly address questions about strain localization and fault interaction.

It is well recognized that the interaction of one earthquake with another may reveal fundamental aspects of earthquake generating processes. Aftershock sequences provide observations of the temporal history of stress migration in a recently stressed (or de-stressed) medium, and current research indicates that relatively simple models of stress triggering based on Coulomb stress calculations can explain some of the aftershocks following some earthquakes; however, negative results are also quite common. The rapid deployment of PASSCAL RAMP (Rapid Array Mobilization Plan) instruments to regions of recent large earthquakes has been very useful for the collection of high-quality aftershock data, and data from future events are likely to further constrain models of earthquake interaction.

Knowledge of the geometry of faults at depth and the detailed structure of faults and fault systems is needed to understand earthquakes and tectonic deformation, and is particularly useful for determining earthquake hazards. Both active and passive source seismology are used to image fault systems on a variety of scales. On a scale of meters to tens of meters, shallow very-high-resolution reflection and refraction imaging has unveiled the recent history of near-surface faulting via the disruption and offset of sedimentary layers. On a scale of tens of meters to tens of kilometers, passive source and active source reflection, refraction and wide-angle reflection profiling have been used to determine large scale morphology of major fault systems, and local and regional velocity heterogeneity within and adjacent to the fault zones. For example, recent seismic investigations have shown that the San Andreas fault in northernmost and in southern California extends through the entire crust, offsetting the Moho. Fault zones are often characterized by heterogeneous seismic velocities in spatially complex patterns, with high velocities likely related to fault asperities and low velocities related to fault gouge and possibly the presence of fault zone fluid. On a somewhat larger scale, the irregular geometries of fault bounded basins and other structures can have significant effects on strong motion amplification and attenuation.

Explaining the nature of earthquakes at great depth within the Earth's mantle remains a challenge to seismologists, geophysicists and materials scientists. How shear failure of an apparently brittle nature can occur under the confining pressures that prevail in the upper mantle has not yet been resolved. The successful recording by GSN and PASSCAL instruments of the great 1994 Bolivia and the 1994 Tonga-Fiji earthquakes allowed the rupture processes of two large deep earthquakes to be imaged in great detail, and these results put new, strict constraints on models that attempt to explain the earthquake process at depth. For example, results from several groups show that the Bolivia earthquake involved rupture on a horizontal plane that cuts across the descending slab. An important implication is that, once initiated, seismic ruptures are not confined to the cold, potentially metastable olivine at the core of the sinking lithosphere. Energy calculations based on seismic records of the 1994 Bolivia earthquake have also been used to argue that melting of mantle material may be an important component of the faulting process. Through studies of multiple earthquakes, it has become apparent that, though similar in many regards, deep earthquakes display a great variability in the details of the rupture process. Continued and improved observations of future deep earthquakes will provide new constraints on any general mechanism for deep seismicity.

Under the National Earthquake Hazards Reduction Program, NSF supports fundamental earthquake studies, research on global seismicity, and earthquake source physics. Advancing our understanding of earthquakes and faults requires substantial multi-disciplinary and inter-agency efforts. IRIS facilities and university research programs are only part of the technical and intellectual resources required to understand the mechanism and hazards of earthquakes. These studies make extensive use of GSN and PASSCAL data. On a global scale, GSN data are key to the determination of Centroid Moment Tensor (CMT) solutions, which, together with the global distribution of seismicity, provide the fundamental basis for the plate-tectonic framework of earthquake hazards. Although regional seismic monitoring networks, and the Advanced National Seismic System will fill the essential long-term monitoring role in major seismically active regions, PASSCAL instruments are a key community resource for carrying out focused studies with dense station deployments. In partnership with the USGS, the lead NEHRP agency in earthquake hazard assessment, PASSCAL instruments have been used in a number of aftershock studies, including 1989 Loma Prieta, California, 1994 Northridge, California, and 1999 Izmit, Turkey.



Selected PASSCAL and related experiments in the Western United States

Experiments using PASSCAL instruments in the Western US have played an important role in recent advances in understanding the structure and evolution of this region of varied and complex continental structure. Colored lines and triangles designate active source experiment sites and colored stars show passive experiments. Circles are regional network stations. This map shows how temporary PASSCAL deployments are complementary to permanent regional networks. The regional networks are optimized for monitoring of seismicity and are concentrated in regions of high activity. PASSCAL experiments can have a variety of experimental configurations.

The stations marked in purple are an excellent example of how real-time telemetry can benefit experiment design and encourage data exchange and multi-institutional cooperation. As described in more detail in the short report in Appendix II (pg. II- 83), stations (purple circles) from a number of permanent regional networks, the USGS National Seismic Network and stations of the PASSCAL broadband array deployed in Montana, have merged in a project to study the structure of the Yellowstone area, the western Rockies and the Basin and Range. A variety of real-time data systems, developed by the USGS, cooperating universities and IRIS, have been combined to form a “virtual seismic network”.

Together with the USGS and regional network operators , we propose to further develop the technologies to support this type of data-sharing. (Figure provided by Frank Vernon and Jennifer Eakins, UC San Diego).

What is proposed

This section provides an overview of the essential components of what is proposed over the next five years and shows how these components are linked in the context of the four themes discussed earlier: higher resolution, long-term observations, high performance, and linking facilities for research and education. In Appendix II of this proposal, we provide detailed descriptions of the core IRIS programs, their current capabilities and 5-year program plans. The budget section provides details on the activities and costs for each program.

The primary building blocks for the core facilities, as outlined in the original 1984 IRIS proposal, are in place – *through NSF investment in IRIS, the seismology research community now has modern digital facilities for recording, archiving and distributing high fidelity ground motion data from permanent and portable stations*. As documented in the preceding pages and in Appendix I, the scientific results based on that investment are impressive and growing. The support requested under this proposal is primarily for the continued operation and maintenance of the core facilities; amortization of existing instruments to protect previous investments; integrative program activities that merge and consolidate the resources of the core programs, especially in areas of telemetry and data communication; and, in the case of PASSCAL, new instrumentation to complete the facility in response to strong pressures for field programs.

Primary Budget Components

The table below presents an overview of the nominal first year budget profile, by core program. The total five-year request, including a inflationary 3% per year increase, is $76.3 million. Year-by-year budgets and explanatory details are found in the budget section of the proposal.

Core Operations

The infrastructure and human resources that provide operational and maintenance support and various user services are an essential component of any facilities program. A substantial portion of the budget for each of the IRIS core programs is for support of infrastructure and personnel at the main facility locations:

- **GSN** – The Global Seismographic Network (GSN) is a cooperative venture between IRIS/NSF and the US Geological Survey (USGS). The IRIS component of the GSN is operated and maintained through IRIS partnership with the IDA group at the University of California, San Diego for support of maintenance facilities and approximately 13 employees. The rest of the GSN is operated by the USGS Albuquerque Seismological Laboratory, and support for O&M is provided directly by the USGS. While the USGS is responsible for support of infrastructure and 37 personnel at the Albuquerque Seismological Laboratory, IRIS provides support for costs related to station enhancements and upgrades. Support is also provided for activities at US universities that cooperate in the operation of GSN stations as part of regional networks. IRIS also supports the charges for ongoing, real-time communication links to GSN stations.
- **DMS** – The Data Management System (DMS) operates through a combined structure of IRIS employees, subawards, and partnerships. The Data Management

IRIS Nominal Year one Budget (in $ thousands)

	GSN	PASSCAL	DMS	E&O	Headquarters and Consotrium
Core Operations	*Core Operations* 2,250	*Core Operations* 2,765	*Core Operations* 2,750	*Core Operations* 500	*Core Operations* 1,475 *Consortium* 375 *Management Fee* 50
Amortization	*Equipment Replacement* 880	*Equipment Replacement* 700	*Replace Mass Store* 200		
Integrative Activities	*Real Time* 200 *Univ Network Coord* 50	*Real-time* 200 *Software* 50	*Real-Time* 300 *Network Coord* 325	*VSN Explorer* 150	
New Resources	*Oceans & Geo Obs* 100 *Station Enhancement* 300	*New Instruments* 1,000			
Total	*3,780*	*4,715*	*3,575*	*650*	*1,850*
				IRIS TOTAL	***$14,570***

Center (DMC) in Seattle is an independent IRIS facility, operated and staffed by 11 IRIS employees, including the DMS Program Manager. The University of Washington serves as a host institution for the DMC, providing local scientific and technical advice and direct access to the Internet backbone. The data collection functions associated with the GSN are part of the DMS responsibility and are carried out through a partnership with the USGS and through a subaward to the University of California, San Diego. Smaller awards to other university groups and consultants are included to support quality control and programming activities.

- **PASSCAL** – The primary maintenance and support activities are carried out through the PASSCAL Instrument Center in Socorro, New Mexico which is housed in a dedicated facility provided by the New Mexico Institute of Mining and Technology. Personnel support for 12 FTE's is provided under subaward to New Mexico Tech. All permanent equipment and most supplies are purchased directly though IRIS. An on-site IRIS Program Manager oversees the activities of the Instrument Center. Subawards also are made to the University of Texas, El Paso for support of portable instrumentation and to the University of California, San Diego for support and development of the PASSCAL Broadband Array.
- **E&O** – The IRIS Education and Outreach Program (E&O) provides the interface between IRIS resources, IRIS facilitated research and the general public. The E&O program enables audiences beyond research seismologists to access and use seismological data for educational purposes. The E&O program acts as a catalyst to stimulate educational activities in the other IRIS programs and with member universities. Funding through this proposal to the Earth Science Instrumentation and Facilities Program will provide support for a Program Manager and a program assistant who will plan and implement activities that encourage the use of IRIS data and resources in the classroom and museums. Teacher training and student internships are carried out in cooperation with member universities. Additional support for specific projects comes from other NSF awards in Geosciences and Education and Human Resources (e.g. Digital Libraries).
- **Management** - IRIS Headquarters is housed in the American Association for the Advancement of Science Building in Washington, DC. A senior management team (President, Director of Planning, Director of Operations, and Business Manager) and staff of five employees provides overall facility and consortium management and support for business activities. In addition, the Program Managers for the GSN and E&O programs also operate from the Washington Office. Costs include: salary and office expenses for the headquarters office; meeting expenses for the Executive, Planning and Coordinating Committees and Board of Directors; accounting and legal consultant services; insurance; publications; Workshops; and other consortium activities.

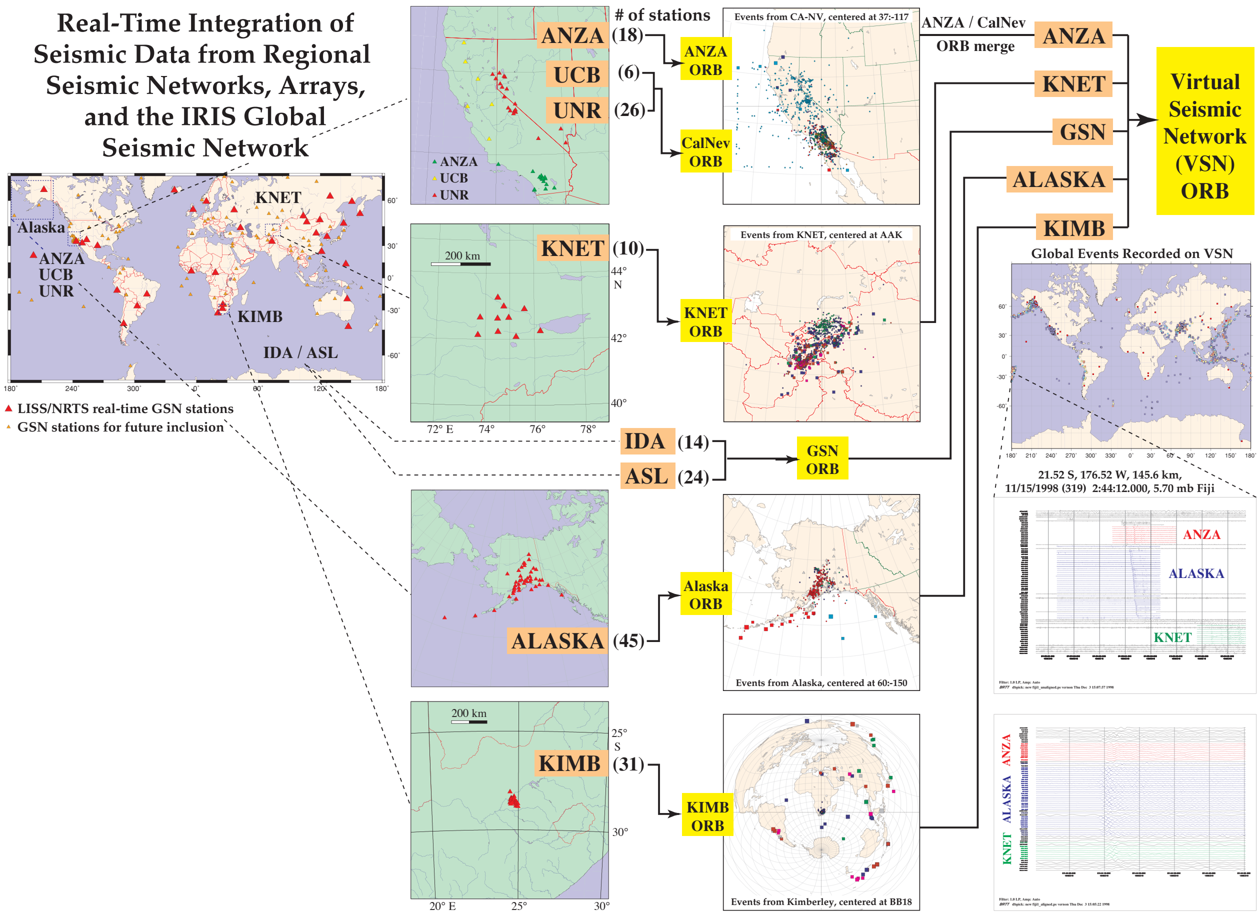
The continued investment in a coordinated, but distributed infrastructure and a competent and responsive staff (whether direct IRIS employees or through subawards) has been a primary resource in the development of the IRIS facilities and are critical to their continued success. To ensure that maximum benefit is derived from these significant investments in infrastructure and personnel, IRIS committees and staff engage in on-going review and assessment of the activities within and between the core programs.

Upgrade and Replacement of Previous Investments

One of the advantages of modern digital technology is that much of the equipment is modularized and amenable to gradual upgrade and replacement at the level of individual components. As technology evolves, disks can be upgraded with new devices that are higher capacity, more reliable, and more energy efficient, or replaced with telemetry. Timing systems in all IRIS instruments have already been upgraded to receive GPS time. Most new generations of hardware are smaller and lower power, so that in addition to improved data quality, upgrades usually lead to reduced cost and increased ease of use.

Now that the GSN is essentially complete, a significant component of the hardware costs requested for the GSN will be used to develop a badly needed pool of parts for replacement and upgrade. With more than $18 million invested in GSN equipment (including seismometers, data acquisition systems, power subsystems, clocks, telemetry and ancillary equipment) at over 100 remote sites, it is inevitable that components fail because of age, lightning and power surges, harsh physical conditions, etc. A regular program for replacement of aging components is needed to maintain the network and protect NSF's investment in these seismological observatories. This proposal requests funds to amortize replacement of GSN hardware at approximately 5% of capital costs per year. We note that this is about half of the normal business standard of 10% capital replacement costs per year.

The hardware infrastructure at the Data Management Center is also based on modularized components. There is a continual downward migration of computers and disk resources within the DMC architecture, with newer, more advanced hardware being incorporated for critical high-end processes, as older equipment migrates to lower levels. The major hardware element at the DMC is the multi-terabyte mass store system. The current device was purchased in 1998 with support from the NSF Major Research Instrumentation program, the W.M. Keck Foundation and SUN Microsystems. The current mass store will reach the end of its planned life expectancy in two years. An expanded mass store will be necessary to meet existing archival



Virtual Seismic Network

Starting at the end of 1998, a feasibility test has been conducted for real-time data integration from multiple, disparate, seismic networks. Data from the IRIS GSN, the PASSCAL Broadband Array (deployed at that time in Kimberly, South Africa), four US regional networks (Universities of Alaska, California at Berkeley and San Diego, and Nevada, Reno), and the Kyrgyzstan National Broadband Network were integrated into one common data processing system. Data latency, even for the Kyrghyz network, was typically measured in seconds and data recovery was well in excess of 90%. Processing included standard real-time functions of data assembly, automated phase picking, event location, and display of event location and magnitude information. This test demonstrated that over 150 seismic stations from seven different primary data collection centers could be accessed through the Internet and processed in real-time using one SUN Ultra 60 workstation. (Figure provided by Frank Vernon, U.C. San Diego).

requirements and to support new data acquisition programs. The anticipated cost for this upgrade of approximately $1M is budgeted in this proposal as installments of $200K/year over five years. In negotiation of final funding arrangements under a new Cooperative Agreement, we will request that this be funded as a single item in the second year, since, unlike the amortization of GSN and PASSCAL equipment, the mass storage device will be a one-time replacement of a single component.

Especially for the portable instruments used by PASSCAL, we are entering a phase where the simple mechanical aging of equipment in a harsh operational environment results in decreased performance and failure. The average age of the PASSCAL field systems is approaching eight years. All of the instruments have been shipped numerous times to remote locations, often involving multiple trans-shipments via less-than-ideal modes of transport. As a result, the instruments now require more intensive maintenance between experiments, a costly and time consuming exercise with an inventory of over 600 instruments. In this proposal, we request funds to replace the more vulnerable and key hardware components (data acquisition systems and seismometers) of the existing PASSCAL field equipment inventory. The request is based on amortizing the existing capital costs at approximately 5% per year. Where appropriate, old components will be "retired" to less rigorous use, for example in permanent installations or for educational purposes.

Addition of New Resources

The GSN has reached the number of instruments required to provide uniform global coverage of the continents and part of the oceans. The DMS has established the core infrastructure required to handle the types and quantities of data being produced by IRIS data sources. For GSN, the additional resources, beyond core operations and amortization, requested under this proposal primarily consist of incremental improvements and maintenance of the current facility to provide enhanced capability in areas such as telemetry, additional geophysical sensors at GSN stations and cooperation in the development of ocean bottom stations.

PASSCAL has been extremely successful in stimulating the development of instrumentation that has revolutionized the way in which seismic data are collected in portable field experiments. While there is widespread support for the quality of the instruments and the support that PASSCAL provides, the PASSCAL facility remains significantly below its original design goals of 1000 field systems with 6000 channels. The pressure of instrument demand from funded NSF projects clearly shows a pressing need to expand the number of field systems. The existing PASSCAL pool of instruments is in near-constant use and there is a two-to-three year waiting period to fill requests for broadband instruments to be used by funded projects. In this proposal, we place a high priority on adding new equipment to increase the instrument base of portable PASSCAL field systems. As described in more detail in the PASSCAL program and budget sections, an investment in new equipment of $1M per year for five years will complete the PASSCAL facility, with a complement of over 1000 short period instruments for active source and microearthquake studies and 500 instruments for long deployment, passive source studies.

Integrated Activities

As the IRIS programs mature, we seek to encourage opportunities for expanded interaction and integration between programs. Long-term deployments of portable broadband instruments blur the distinction between the PASSCAL and GSN programs. Using common formats and tools for data access means that researchers can make requests to the DMS without concern for the original source of the data. These interactions not only enhance the data resources and technical capabilities available to the research community, but they also can lead to efficiencies in operation. Many of the software tools and telemetry techniques now being developed to enhance real-time data collection find application to both GSN and PASSCAL. It is anticipated that the next generation of field hardware – including seismometers and data acquisition systems – will increasingly involve components that can be used in both permanent (GSN) and portable (PASSCAL) programs. These IRIS efforts to encourage integrated data collection and distribution will also have important impact on other developments in observational seismology – e.g. the USGS Advanced National Seismic System (ANSS), regional and national networks in the US and abroad, and the USArray component of EarthScope. More complete integration of IRIS data collection and distribution services – "from sensor to desktop" – will also benefit users outside of the research community, including mission-oriented activities such as the reporting of earthquakes by the USGS National Earthquake Information Service and regional centers, the monitoring of nuclear test-ban treaties by US and international agencies, and the use of seismology in education and public outreach.

Telemetry and enhanced resources for real-time data communication and distribution are themes that run through all of the IRIS programs. The GSN and PASSCAL are the primary data producers of the IRIS facilities. From the user's perspective, the GSN operates in a passive mode (with data emerging from an independently operated network of stations) and PASSCAL in an active mode (with direct PI involvement in the siting and operation of stations). Through standards developed and established across the IRIS facilities, there is growing opportunity to integrate data from diverse sources, both within IRIS and from other national and international facilities. When accessing data from the IRIS DMC, archival data from PASSCAL, GSN, the FDSN and regional networks can be merged in a single request. As technologies for global communication become more common, it will be possible to create a personal "Virtual Seismic Network" (VSN), merging data in real-time from regions of special interest for research and teaching.

While real-time analytical techniques may lead to new research discoveries based on real-time data, a primary reason for pursuing these developments, from a facility perspective, is decreased operation and maintenance costs and improvements in data quality. A GSN with full and continuous telemetry will be less reliant on operator intervention and failure-prone mechanical disk drives. Any problems in station operation will be quickly identified, improving total network performance. One of the major costs of operating a PASSCAL experiment is the servicing of disks, often in remote and expensive-to-reach field locations. In anticipation of universal Internet access and emerging satellite technology, even in remote foreign locations, PASSCAL is experimenting with various technologies, including radio, cell phone and satellite, to allow researchers to bring data from field locations directly to their desktop.

Real-time data collection also has advantages in hazard reporting and ineducation and outreach. The USGS National Earthquake Information Service routinely incorporates real-time data from the GSN in its location and reporting of national and global earthquakes. The Pacific and Alaskan Tsunami Warning Centers use real-time GSN data in monitoring and evaluating earthquakes for tsunamis.

The Spring/Summer, 1999 issue of the IRIS Newsletter featured a series of articles on "Planet Earth On-Line" and introduced the concept of the "Virtual Seismic Network", which draws on a number of developments in real time data collection that have emerged from the GSN, PASSCAL, DMS and related programs. A recent test, involving collaboration between IRIS, USGS, regional networks and individual experiments, has demonstrated both the feasibility and utility of the VSN concept. Over the next five years, a major direction for IRIS will be to implement the VSN concept as an integrative activity between all programs. Telemetry will be extended as an integral part of all GSN and PASSCAL data collection efforts. Real time data distribution will be enhanced through the DMC, and the E&O program will bring to the classroom and museums the excitement of real time observations of "the pulse of the Earth".

Related Programs

While our proposal focuses on the IRIS facilities, there are other seismology and Geoscience initiatives currently underway. IRIS participates in each of these programs through the exchange of data, the coordination of siting for new instrumentation, and the long-term planing and oversight. Other existing and proposed programs in observational seismology that interact directly with IRIS facilities include:

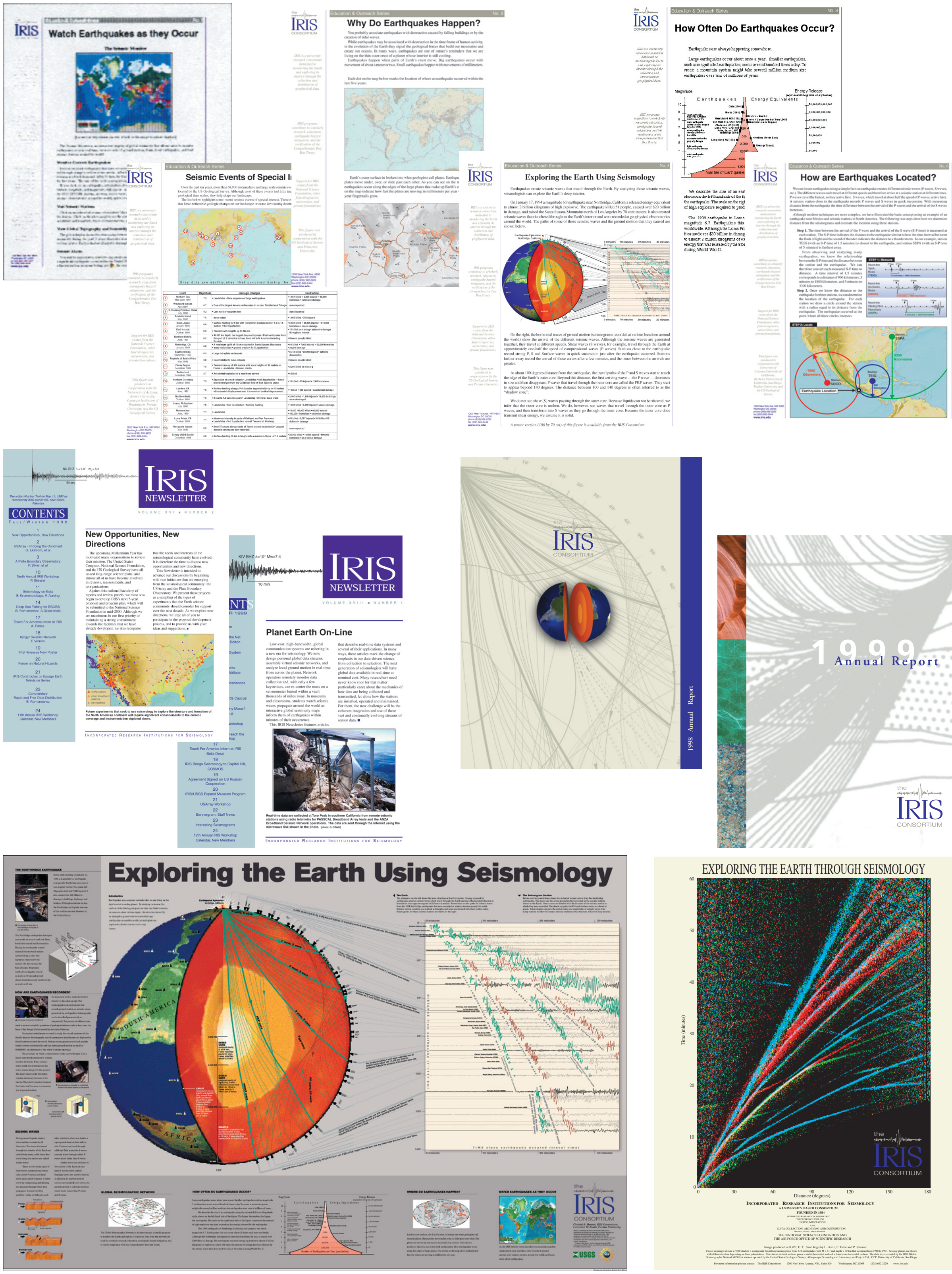
USArray, a component of **EarthScope**, is designed to systematically map the deep structure of the North American continent at high resolution using a transportable array of broadband instruments over an 8 to 10 year period. USArray is being proposed as part of EarthScope (which also includes the San Andreas Fault Observatory at Depth, the Plate Boundary Observatory and InSAR) through the Major Research Equipment (MRE) account of the National Science Foundation. When funded, it is proposed that the USArray part of EarthScope will be operated by IRIS. All USArray data will be archived and distributed through the IRIS Data Management System. USArray funding, however, will not support or offset costs included in this proposal for the IRIS core programs.

The **Advanced National Seismic System (ANSS)** is an initiative of the US Geological Survey and operators of local seismic networks to upgrade and improve US capabilities to monitor local and regional earthquake activity, especially the strong motions associated with large events. The goals and strategy of this proposed program are different from those of USArray. USArray focuses more on systematic coverage to coherently map Earth structure through portable instrument deployments. ANSS focuses primarily on urban hazards. The ANSS networks will not be operated by IRIS, although IRIS may have a role in coordinating data access and archiving data.

The **International Monitoring System (IMS**) includes a network of 170 seismic stations, whose locations and specifications were negotiated as part of the Comprehensive Nuclear Test-Ban Treaty. The network is designed to provide a baseline global coverage of possible nuclear testing for all nations party to the treaty. Over 50 IRIS stations are designated for participation in the IMS. IRIS also receives data from the other IMS stations. In addition to providing stations for use in the IMS, IRIS works to ensure that all seismological data related to the monitoring of the Comprehensive Nuclear-Test Ban Treaty are openly available. IRIS receives no funding from the IMS for the operation of IMS-designated GSN stations.

The **Enhanced Atomic Energy Detection System (AEDS)** Network is a network designed to meet US national security requirements defined in a Presidential Decision Directive for monitoring compliance with the Comprehensive Nuclear Test-Ban Treaty. Although the enhanced AEDS network and the IMS network share common stations, the AEDS network is designed to provide additional coverage of nuclear testing

IRIS Publications



IRIS Publications
IRIS produces a range of publications both for educational purposes and for program planning and development. IRIS posters and one-pagers are designed to answer common questions about earthquakes and seismology, and to complement the educational resources of the IRIS websites and museum displays. The Newsletter, which is organized around topical issues, highlights emerging opportunities for seismology. The Annual report serves as a summary of IRIS activities and program status.

Program Implementation

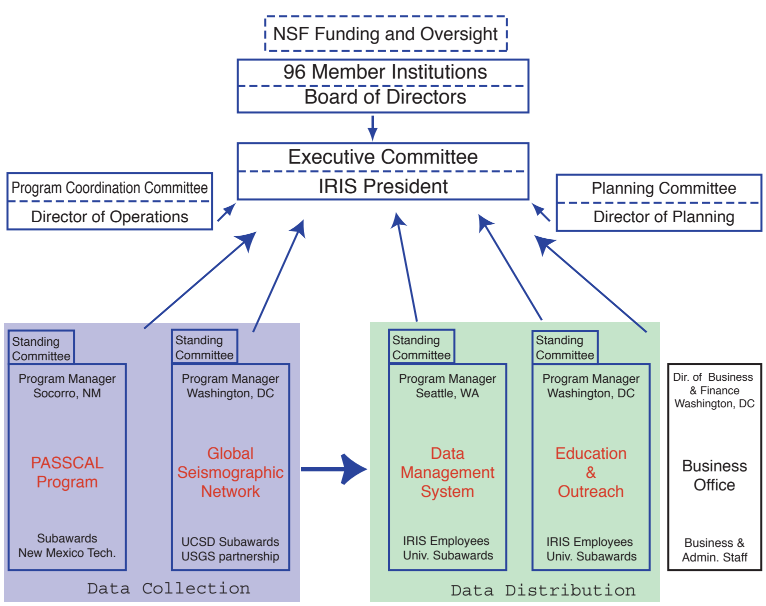
Consortium Governance and Management

The IRIS governance and management structure is an interface between the scientific community, funding agencies and the programs of IRIS. The structure is designed to ensure close involvement of the research community in the development of IRIS facilities, to focus scientific talent on common objectives, to encourage broad participation, and to effectively manage IRIS programs. Community involvement in the governance and management of IRIS has been a key to the success of the Consortium. Each year, over 50 scientists from more than 30 research institutions participate in the management of IRIS through seven committees, five subcommittees, and a series of *ad hoc* advisory groups. These scientists work with a small professional staff consisting of the President, Director of Planning, Director of Operations, Business Manager, and four Program Managers to administer IRIS programs.

IRIS is governed by a Board of Directors consisting of representatives from each of the 96 member institutions. Operational policies are set by a seven-member Executive Committee elected for rotating three-year terms by the Board of Directors. The Executive Committee, in turn, receives information and advice from a series of advisory Committees. The Planning Committee develops new initiatives and coordinates IRIS research activities with related programs in fields such as earthquake hazard mitigation and nuclear monitoring. The Program Coordination Committee integrates activities such as telemetry and software development that cross-cut the individual programs. Four separate Standing Committees provide detailed oversight of the four core programs: the Global Seismographic Network (GSN), the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), the Data Management System (DMS), and the Education and Outreach Program (E&O). It is the role of all appointed Committees to develop recommendations for the Executive Committee, which in turn, evaluates and acts upon such recommendations on behalf of the Board of Directors.

In addition, the President and the Executive Committee appoint special advisory committees and *ad hoc* working groups for specific tasks. Four subcommittees of the IRIS Executive Committee have special responsibility in areas of: 1) budget and finance (whose members work with the IRIS business manager) 2) meetings and publications, 3) membership and 4) legal affairs.

The Executive Committee meets at least twice per year to review the status of IRIS programs, prepare and approve annual budgets and develop long-term program directions. Each of the four Standing Committees meets twice per year to review program-specific activities and makes recommendations for improvements and future developments. Chairs of the Standing Committees participate in Executive Committee meetings on a non-voting basis.



Facility Management

IRIS management is under the direction of a full-time President, appointed by the Executive Committee. Senior staff consists of a Director of Planning, a Director of Operations, four Program Managers and a Director of Business and Finance. In addition to senior personnel, the total IRIS staff consists of five support staff at Headquarters in Washington DC and eleven technical staff at the IRIS Data Management Center in Seattle, Washington.

Participation

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

Geoffrey Abers, Boston University	DMS, PAS
Duncan Agnew, University of California	GSN
Keiti Aki, University of Southern California	PAS
Shelton Alexander, Pennsylvania State University	EX*, DMS**
Charles Ammon, Saint Louis University	GSN
Don Anderson, California Institute of Technology	EX
Charles Archambeau, University of Colorado, Boulder	JSP
Milo Backus, University of Texas, Austin	DMS
Jeffrey Barker, SUNY Binghamton	EO
Susan Beck, University of Arizona	GSN
Harley Benz, US Geological Survey, Golden	DMS, GSN
Jon Berger, University of California, San Diego	JSP, GSN
Eric Bergman, US Geological Survey, Denver	GSN
Gregory Beroza, Stanford University	GSN
Tom Boyd, Colorado School of Mines	SEC
Gilbert Bollinger, Virginia Polytechnic Institute	SEC, PAS
Larry Braile, Purdue University	EX, PAS**, EO**, COCOM
Tom Brocher, US Geological Survey, Menlo Park	PAS
Rhett Butler, University of Hawaii	GSN
Ray Buland, US Geological Survey, Denver	GSN
Alan Chave, Woods Hole Oceanographic Institution	GSN
Ken Creager, University of Washington	DMS
Robert Crosson, University of Washington	DMS
F.Anthony Dahlen, Princeton University	GSN
Paul Davis, University of California, Los Angeles	PAS
Peter Davis, University of California, San Diego	GSN
Diane Doser, University of Texas, El Paso	PAS
Doug Dreger, University of California, Berkeley	GSN
Ken Dueker, University of Colorado, Boulder	PAS
Adam Dziewonski, Harvard University	EX**, GSN**, PCOM
Göran Ekström, Harvard University	DMS, JSP, GSN**, EX*, COCOM**
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	EX, DMS, EO
Fred Followill, Lawrence Livermore National Laboratory	PAS
Don Forsyth, Brown University	GSN**
Clifford Frohlich, University of Texas, Austin	DMS
Kaz Fujita, Michigan State University	GSN
Lind Gee, University of California, Berkeley	SEC, EO
Freeman Gilbert, University of California, San Diego	EX
Peter Goldstein, Lawrence Livermore National Laboratory	DMS
Steve Grand, University of Texas, Austin	GSN
Michelle Hall-Wallace, University of Arizona	EO
Egilll Hauksson, California Institute of Technology	PAS
Tom Heaton, California Institute of Technology	GSN
Donald Helmberger, California Institute of Technology	GSN
Tom Henyey, University of Southern California	PAS
Eugene Herrin, Southern Methodist University	GSN
William Holt, SUNY Stony Brook	DMS
Heidi Houston, University of California, Los Angeles	GSN
Eugene Humphreys, University of Oregon	EX, PAS
Bob Hutt, US Geological Survey, Albuquerque	EO
David James, Carnegie Institution of Washington	PAS
Lane Johnson, University of California, Berkeley	DMS**, GSN**
Roy Johnson, University of Arizona	PAS**, COCOM
Arch Johnston, University of Memphis	EX
Thomas Jordan, University of Southern California	EX
Hiroo Kanamori, California Institute of Technology	GSN, EX
Randy Keller, University of Texas, El Paso	EX*, COCOM**
Monica Kohler, University of California, Los Angeles	DMS
Glenn Kroeger, Trinity University	EO
John Lahr, US Geological Survey, Denver	EO
Charles Langston, University of Memphis	GSN, JSP
Thorne Lay, University of California, Santa Cruz	EX, GSN
Jonathan Lees, Yale University	DMS
Art Lerner-Lam, Lamont Doherty Earth Observatory	JSP, GSN, PAS
Alan Levander, Rice University	EX*, DMS**, COCOM
Peter Malin, Duke University	PAS, DMS
Stephen Malone, University of Washington	DMS, EX
Kurt Marfurt, University of Houston	PAS
Robert Massé, US Geological Survey, Denver	GSN
Guy Masters, University of California, San Diego	EX
Tom McEvilly, University of California, Berkeley	EX**, GSN, COCOM
Susan McGeary, University of Delaware	SEC
George McMecham, University of Texas, Dallas	PAS
Robert Mellors, San Diego State University	EO
Anne Meltzer, Lehigh University,	PAS**, EX**, COCOM, PCOM
William Menke, Lamont Doherty Earth Observatory	PAS, DMS
Robert Meyer, University of Wisconsin	PAS
Kate Miller, University of Texas, El Paso	PAS
Brian Mitchell, Saint Louis University	TRES, GSN
Bernard Minster, University of California, San Diego	JSP, DMS
Walter Mooney, US Geological Survey, Menlo Park	PAS
John Nabelek, Oregon State University	DMS, PAS
Keith Nakanishi, Lawrence Livermore National Lab.	DMS, JSP
Guust Nolet, Princeton University	EX, EO
Bob North, Geological Survey of Canada	GSN
Emile Okal, Northwestern University	GSN
David Okaya, University of Southern California	PAS, DMS
John Orcutt, University of California, San Diego	EX**, DMS, PCOM
Tom Owens, University of South Carolina	PAS, EX, DMS
Jeffrey Park, Yale University	EX**, SEC, JSP
Gary Pavlis, Indiana University	TRES, DMS, EX, PAS**, COCOM
Robert Phinney, Princeton University	PRES, EX**, PAS**, JSP
Thomas Pratt, University of Washington	PAS
Paul Richards, Lamont Doherty Earth Observatory	JSP**, EX*, DMS
Steve Roecker, Rensselaer Polytechnic Institute	PAS
Barbara Romanowicz, University of California, Berkeley	GSN**, PCOM, COCOM
Larry Ruff, University of Michigan	DMS
Selwyn Sacks, Carnegie Institution of Washington	PAS
Martha Savage, Victoria University of Wellington	DMS
Susan Schwartz, University of California, Santa Cruz	DMS**, COCOM
Peter Shearer, University of California, San Diego	EX
Anne Sheehan, University of Colorado, Boulder	GSN
Paul Silver, Carnegie Institution of Washington	EX**, PAS, JSP
David Simpson, Lamont Doherty Earth Observatory	PRES, PAS, JSP
Stuart Sipkin, US Geological Survey, Golden	GSN
Robert Smith, University of Utah	EX, PAS.PCOM
Stewart Smith, University of Washington	PRES, JSP**
Sean Solomon, Carnegie Institution of Washington	GSN**
Seth Stein, Northwestern University	EX
Brian Stump, Los Alamos National Laboratory	JSP, PAS
Fumiko Tajima, University of California, Berkeley	DMS
Toshiro Tanimoto, California Institute of Technology	DMS
Steve Taylor, Los Alamos National Laboratory	DMS
Ta-laing Teng, University of Southern California	EX, GSN
George Thompson, Stanford University	EX
Clifford Thurber, University of Wisconsin, Madison	EX, PAS, SEC
Anne Trehu, Oregon State University	PAS**, EX
Rob van der Hilst. Massachusetts Institute of Technology	DMS
Frank Vernon, University of California, San Diego	PAS, JSP
John Vidale, University of California, Los Angeles	EX
Terry Wallace, University of Arizona	EX**, GSN**, DMS. PCOM**
Douglas Wiens, Washington University	EX, GSN
Richard Williams, University of Tennessee	TRES, PAS
John Woodhouse, Oxford University	DMS
Robert Woodward, US Geological Survey, Albuquerque	EO
Francis Wu, SUNY Binghamton	DMS**
Michael Wysession, Washington University	GSN, SEC
George Zandt, University of Arizona	PAS

EX = *Executive Committee*
DMS = *Data Management System*
EO = *Education and Outreach*
GSN = *Global Seismographic Network*
PAS = *Program for Array Seismic Studies of the Continental Lithosphere Committee (PASSCAL)*
JSP = *Joint Seismic Program*
COCOM = *Coordinating Committee*
PCOM = *Planning Committee*
TRES = *Corporate Treasurer*
SEC = *Executive Committee Secretary*
PRES = *President*
****** = *Chair*
***** = *Vice Chair*

Operation of all other IRIS facilities are carried out under subaward to IRIS member universities. Each of the four core programs have a standardized management and oversight structure consisting of a Program Manager and Standing Committee, but each program operates through its own unique combination of direct employees, subawards, and partnerships. Although IRIS has only 24 full-time employees on its payroll, more than 80 full-time scientists and technicians are involved, through subawards and in cooperation with the USGS, in the operation of IRIS facilities and support of IRIS programs.

Program Planning

The primary mechanism for IRIS support has been a series of five-year Cooperative Agreements between IRIS and the National Science Foundation. These awards are based on proposals, such as this one, which review the current state of the facility and outline the goals for activities for the next five years. Both the IRIS proposal and the annual program plans and budgets are developed through a systematic process designed to distill the collective scientific interests and priorities of close to 100 research institutions.

In developing each year's priorities and budgets, the IRIS Committees continually review program operations and management. For example, a review of the IRIS management structure by an *ad hoc* committee of former Executive Committee chairs led to the formation of the IRIS Planning and Program Coordination Committees. A competition for the IRIS Data Management Center resulted in the Center being moved from an interim location at the University of Texas to its current location at the University of Washington. A competition for the PASSCAL Instrument Center lead to the consolidation of the previous two centers at Stanford and Lamont to a single new location at the New Mexico Institute of Mining and Technology. The GSN was reviewed in 1990 with a published "Technical Plan" and went through an extensive internal audit in 1996. The GSN was reviewed again in 1998 when the White House Office of Science and Technology Policy appointed a special panel of the National Science and Technology Council to evaluate the GSN in the context of other global networks. The DMS Standing Committee is currently conducting a self-study to review the appropriateness of work now being done by the DMS and to recommend future activities. The E&O program has actively sought guidance from the seismological and education communities, and various components of the E&O program, including teacher workshops and the summer internship program, have been assessed through questionnaires, personal interviews and participant evaluations.

Fiscal and Audit Controls

IRIS is a 501(c)(3) non-profit corporation, incorporated under the laws of the State of Delaware in 1984. The Consortium is governed by By-Laws, which have been updated and reviewed by action of the Board of Directors. A 501(c)3 corporation is limited under US tax laws as to the type of fiscal, legal and political activities in which it can engage. In addition to internal management and governance oversight, IRIS is required, as part of its Cooperative Agreement with NSF, to undergo annual external audit of finances and business practices. Office of Management and Budget (OMB) Circular A-133, "Audits of States, Local Governments, and Non-Profit Organizations," requires non-Federal entities that expend $300,000 or more in a year in Federal awards to have an audit conducted in accordance with the Circular. Since 1992, Arthur Andersen has been performing A-133 audits of IRIS and issuing their independent auditors' reports on IRIS financial statements, and compliance and internal controls related to Federal programs. Arthur Andersen reported no findings or questioned costs as a result of audits of IRIS under the current Cooperative Agreement.

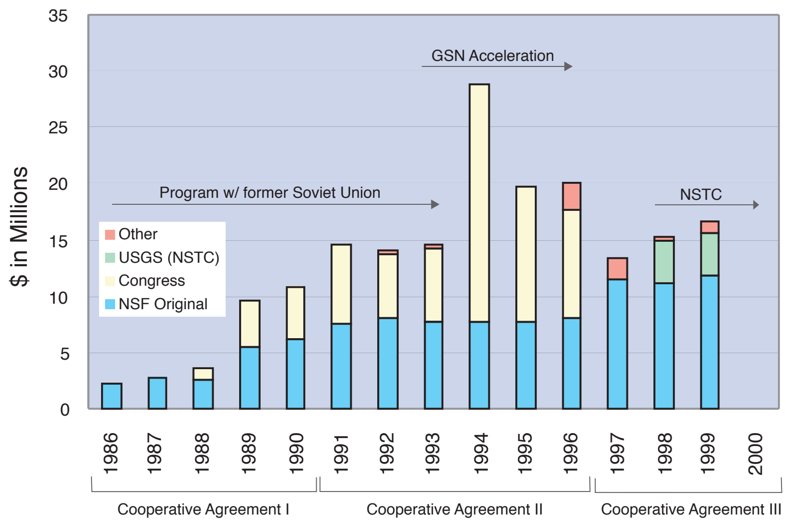
IRIS also is responsible for an inventory of equipment, with a total value of more than $25 million, which has been purchased for IRIS facilities with NSF funds. Title to all equipment remains with the National Science Foundation, but IRIS tracks and maintains complete inventory of all permanent equipment items.

Community Activities

The Consortium activities include meetings of the Executive Committee, the Planning Committee, and the Program Coordination Committee. It also includes the development of topical workshops, the annual IRIS workshop, the IRIS Newsletter, other publications, and membership services. Interactions with the broader IRIS membership take place at an Annual Board of Directors meeting, a three day Annual Workshop and miscellaneous special purpose workshops. The membership is kept informed of IRIS activities through publication of a Newsletter and Annual Report and through an extensive web site with access to various facilities and services.

In addition to program oversight and administration, the Consortium also serves the role of an on-going forum for exchanging ideas, setting community priorities, and fostering cooperation. To enhance this role, IRIS engages the broader Geoscience community through its Newsletter and workshops. The Newsletter, which is widely distributed without charge, is organized around topical issues that highlight emerging opportunities for seismology. The annual workshop is used to assess the state of the science, introduce IRIS programs, and provide training. Through a student grant program, young scientists attend the workshop at little or no cost, and become introduced to the programs and services of the Consortium.

The Fall/Winter 1998 IRIS Newsletter, "New Opportunities, New Directions", for example, featured articles on USArray and the Plate Boundary Observatory



1986-1990 - First Cooperative Agreement. NSF provides funding for program planning and development.

Standards, specifications and prototypes were developed and tested and the IRIS core facilities were established.

1991-1995 - Second Cooperative Agreement. NSF provides core funding of $8 million per year.

NSF funding was used to expand the GSN (beginning with upgrades of existing IDA and USGS stations), purchase PASSCAL instruments, and establish the DMC.

1988-1993 - Congress provides $29 million (over six years) for a joint program with the Soviet Union.

Following the Natural Resources Defense Council's success in gaining permission to install temporary seismic stations in the Soviet Union, IRIS approached the Soviet Academy of Sciences to install GSN stations throughout this previous inaccessible area of the world. Congress provided funding to IRIS through the Department of Defense for developing a joint program with the Soviet Union. Congress declared the IRIS project a "program of special congressional interest".

1994-1996 - Congress provides $42.5 million to accelerate installation of the Global Seismographic Network in time for the signing of the Comprehensive Nuclear-Test Ban Treaty.

Following the 1990 review of the Nuclear Nonproliferation Treaty, pressure for a Comprehensive Nuclear Test-Ban Treaty (CTBT) began to mount within Congress. Congress recognized that the Global Seismographic Network could contribute to the CTBT monitoring system. Congress provided IRIS (through NSF) with $42.5 million over three years to accelerate the installation of the GSN for treaty monitoring. Over 50 GSN stations were eventually included within the treaty as part of the official monitoring system. According to the Chairman of the Congressional Budget Committee "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."

1996-2000 - Third Cooperative Agreement. NSF increases core support for IRIS by almost $4 million per year ($11.4 million) following a review by a special panel of the National Science and Technology Council.

Beginning in FY97, NSF included "nuclear monitoring" in their budget justification as part of IRIS' mission and enhanced the IRIS budget request in response to the new requirement. The Director of the NSF and the Director of the USGS described IRIS as "a blueprint for scientific programs that not only advance our understanding of the physical world, but also address the needs of our society."

1998-2000 - The USGS established a new $3.8 million budget line for the Global Seismographic Network following a review by the NSF/USGS convened panel of the National Science and Technology Council.

The USGS uses GSN data for the developing reports from the National Earthquake Information Center, and those reports, in turn, are used by various national and international agencies for earthquake response. Within its budget justification, the USGS also states that many of the GSN stations are part of the official monitoring system for the CTBT, and that the entire GSN contributes to the United States' independent capability to monitor the treaty.

that became integrated into EarthScope, the NSF's Major Research Equipment account request for fiscal year 2001. The Spring/Summer 1999 Newsletter "Planet Earth On-Line" presented a series of articles on real-time data access and processing methods that are now being integrated into IRIS operations. Results from the 1999 IRIS Workshop were used to set the science priorities highlighted in this 5-year proposal. Meetings at the 2000 workshop are already beginning to identify some of the scientific priorities for the USArray regional deployments.

As a large consortium, IRIS also serves as a representative for the Geoscience community. IRIS staff and Committee members serve on White House Committees, State Department Advisory Boards, US Geological Survey panels, and testify before Congress. Such broad interactions raise the profile of Geoscience and provide a direct societal return from the federal investment in IRIS. Such interactions also result in a practical benefit to seismology by creating opportunities to leverage funding.

In addition to representing the interests of the Geoscience community, IRIS also serves the complementary role of providing information about science policy matters to the scientific community. In other words, we strive not only to increase the scientific literacy of policy makers, but also the political literacy of scientists. Through featured newsletter articles and electronic mail announcements IRIS educates the scientific community on the state of federal programs that effect scientific research and education. As a result of this "feed-back" to the scientific community, many IRIS members have become more engaged in debates on topics ranging from arms control verification and hazards reduction to the development of national science priorities.

Evolution of IRIS Funding

IRIS programs have been built through a combination of strong NSF support for core program activities; financial and "in-kind" partnerships with universities, government agencies and international network operators; and augmented funding based on unique opportunities for multi-use applications. In particular, significant program funding, in addition to the core support from NSF, has come from special appropriations by members of Congress and the Administration who recognized the value of expanding IRIS facilities into multi-use systems that serve not only academic research, but also earthquake hazard mitigation, nuclear test monitoring, and education.

As a result of IRIS's expanded mission, we now have a broad base of support that extends beyond academic research. Following a review by the National Science and Technology Council, conducted at the request of NSF and USGS during our last Cooperative Agreement, the NSF provided increased funding to IRIS. In addition, the US Geological Survey developed a new budget line to help support the Global Seismographic Network. The Department of Defense is also working with IRIS to provide data from non-IRIS stations that are part of the International Monitoring System for the Comprehensive Test Ban Treaty.

While IRIS has benefited, and continues to benefit, from these additional funding sources, none of them are sustainable without the strong support from NSF for the core IRIS facilities. NSF's funding has allowed us to develop and maintain facilities at the highest technical level, thus making them attractive for use by other agencies and groups. The support from other organizations, in turn, has allowed us to expand our facilities beyond what we could accomplish with NSF funding alone. Although we now have responsibilities beyond our own particular data needs (for example, IRIS must also take into account the needs of the nuclear monitoring and earthquake hazards community), we have more facilities, the facilities are more sustainable, and we benefit directly from the development that occurs within those other communities.

The history of IRIS funding (see box) clearly shows how NSF support has been leveraged in the development and enhancement of IRIS programs By making the resources available for other applications, IRIS has broadened the base of support for its programs, making them more sustainable and creating new opportunities.