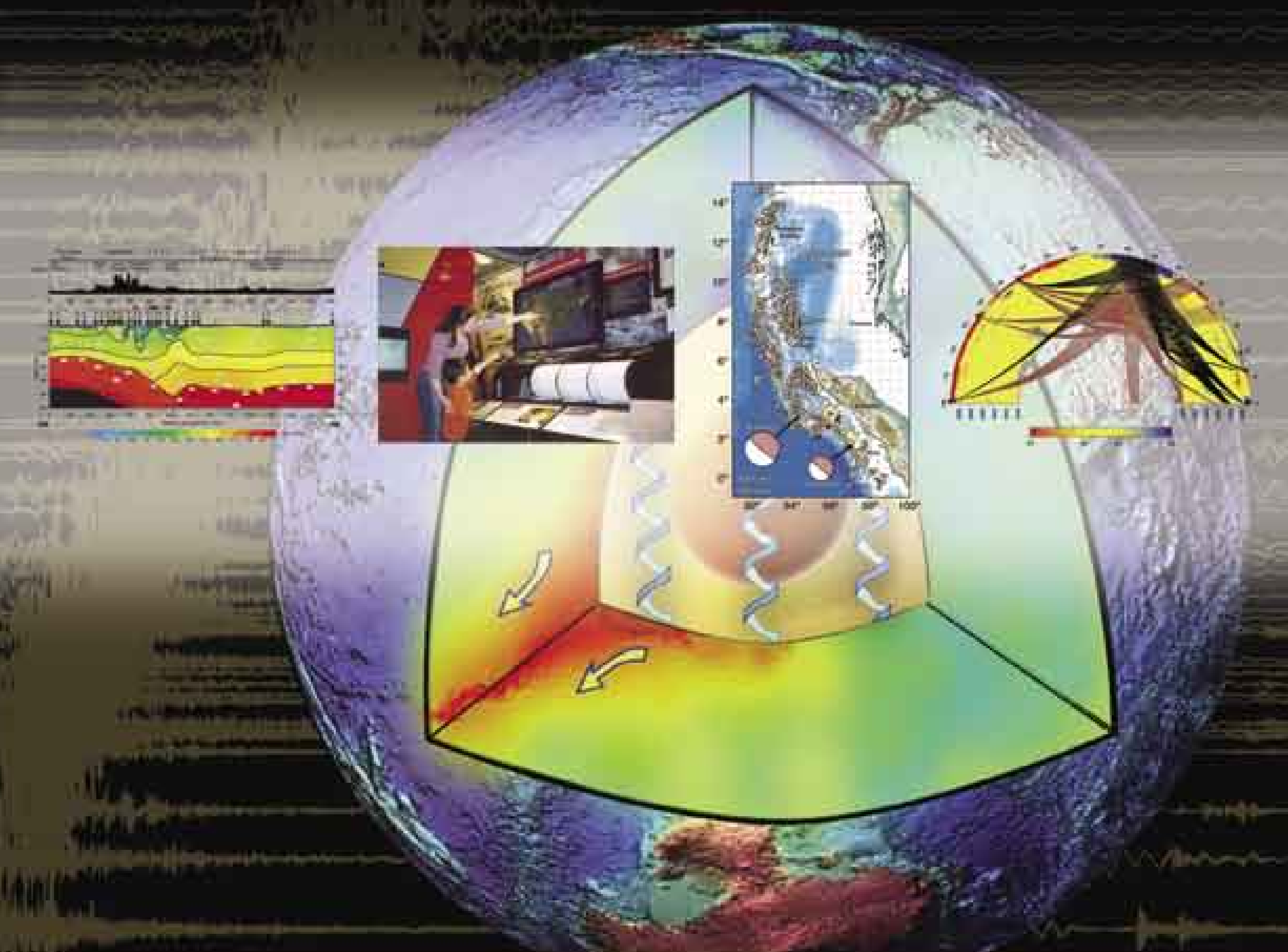
IRIS

Cornerstone Facilities for Seismology and Earth Sciences



Proposal to NSF • 2006–2011

I – Project Description

About the Cover

From the innermost inner core, which influences the evolution of the magnetic field that protects us from cosmic radiation, to the outermost crust, from which we extract resources and where we build foundations for our structures, the cover illustrates recent discoveries about the solid Earth that are enabled by IRIS facilities.

Velocity Profile: A two-dimensional P-wave velocity model running from southern Austria across eastern Slovakia and Poland and into Belarus based on data from the Central European Lithosphere Experiment Based on Refraction (CELEBRATION 2000). CELEBRATION is one of a series of seismic refraction experiments conducted between 1997 and 2003 that were possible only with international cooperation in logistics and data openness that is unprecedented for geophysical field experiments of this type. Together these experiments constitute a network of seismic profiles from Lithuania to Austria. The results have provided new information to resolve questions about mountain building and large-scale crustal deformation that geologists have been studying since the 18th century. (Source: Grad, M, A. Guterch, G.R. Keller, T. Janik, E. Hegedus, J. Vozár, A. Ślączka, T. Tiira, J. Yliniemi, and CELEBRATION 2000 Working Group, Lithospheric structure beneath trans-Carpathian transect from Precambrian platform to Pannonian basin - CELEBRATION 2000 seismic profile CEL05, *J. Geophys. Res.*, submitted, 2005).

Museum Visitors: The IRIS museum display at the Smithsonian Institution's Museum of Natural History captivates audiences of all ages and interests. (Courtesy of Jason Mallett.)

Map of Sumatra-Andaman: Aftershocks for the December 26, 2004 M_W 9.3 thrust, including the, M_W 8.6 thrust on March 28, 2005, show the extraordinary extent of the rupture zone. As the largest earthquake by far, since high-dynamic range, broadband seismometers began to become widespread in the 1980s, this event suggested new analysis methods for rapidly determining the disaster potential of an earthquake, provided new insights about rupture dynamics and tsunami generation, and resulted in unprecedented free oscillation records for studying Earth's deep structure. (Reprinted with permission from Lay, T., H. Kanamori, C. J. Ammon, M. Nettles, S. N. Ward, R. C. Aster, S. L. Beck, S. L. Bilek, M. R. Brudzinaki, R. Butler, H. R. DeShon, G. Ekström, K. Satake and S. Sipkin, The Great Sumatra-Andaman earthquake of 26 December 2004, *Science*, *308*, 1127-1133. Copyright 2004 AAAS.)

Ray Paths: Seismic waves from widely distributed source regions sample the deep mantle en route to the Kaapvaal, Tanzania, and Ethopia/Kenya PASSCAL experiments. Those ray paths shown in red exhibit travel time delays that could not be accounted for with even the best global tomography models from before the time of the experiment, and thus are the basis for discovering the "Africa anomaly," an extraordinary low-velocity region extending 1300 km up from the core-mantle boundary. The thickness, sharp edges, and magnitude of the velocity anomaly show that a reasonable understanding of mantle convection requires consideration of compositional as well as thermal variability. (Source: Wang, Y. and L. Wen, Geometry and P- and S- velocity structures of the "African anomaly," *J. Geophys. Res.*, submitted, 2005).

About this Proposal

This proposal was produced by the IRIS Planning Committee and IRIS staff members on behalf of the IRIS Board of Directors, who represent the full membership of the Consortium, and thus the collective scientific interests of 102 research institutions. The proposal consists of two volumes, including the Project Description, Budget and Program Descriptions in volume 1 and the Review of Accomplishments in volume 2.

The Project Description 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.

The Budget is an explication of our estimates of costs to carry out the activities that are summarized in the Project Description and detailed in the Program Descriptions.

The Program Descriptions are synopses of the core IRIS facilities and the programs that operate them. Each synopsis includes an overview of the development and evolution of the facility and a detailed description of plans and resources requested for the IRIS program.

The Review of Accomplishments is comprised principally of more than 200 one-page vignettes contributed by the research community that have been enabled by IRIS, in most cases through use of one or more of the core IRIS facilities.

Cornerstone Facilities for Seismology and Earth Sciences

The IRIS Proposal

July 1, 2006 – June 30, 2011

Submitted to
National Science Foundation
Division of Earth Sciences
Instrumentation and Facilities Program

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

On behalf of
Board of Directors
and 102 Member Research Institutions
of the IRIS Consortium

August 2005

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Cornerstone Facilities for Seismology and Earth Sciences

Introduction

Earth is an evolving dynamic system of great complexity, with active processes that both sustain and threaten human existence. Whereas the oceans, atmosphere, and near-space environment of the Earth system are relatively accessible for direct sampling and characterization, understanding processes within the planet presents a further formidable technical challenge. The quest to understand Earth's inner workings requires instruments and strategies that can probe the global and local scales of the planet's interior structural and dynamical complexity. Seismology emerged during the past century as a key methodology for understanding Earth, because of all geophysical methods, it provides the highest resolution of the interior. Improving availability of seismic data on global and regional scales has driven discovery after discovery at a pace that continues unabated.

Ensuring availability of high-quality, standardized seismological instrumentation with multi-scale recording capacity is an essential long-term effort that is key to future discoveries and progress in understanding the Earth system. Global observing systems of the highest possible quality, combined with suites of portable instrumentation with broadband or high-frequency sensitivity, are required for diverse research investigations of all regions and depths of the Earth system, as well as for studies of earthquake ruptures and other active dynamical processes that generate elastic waves.

In 1984, IRIS—the Incorporated Research Institutions for Seismology—was founded with NSF support to establish core facilities for acquiring and distributing seismological data. Over the ensuing 21 years, development of these facilities has secured the critical role played by seismology in national and international research in Earth science. The IRIS facilities have embraced a commitment to high-performance in instrumentation quality, data resources, and user services that has established a standard for free and open access to scientific data. These commitments are altering Earth science research, education, and applications in the United States and internationally.

Because seismological data are central to diverse Earth investigations, recognition is growing that IRIS facilities can serve as a cornerstone for Earth science research. In 2005, IRIS expects to respond to over 200,000 data requests and ship over 550 million seismograms comprising more than 11 terabytes of data. These data infiltrate every sector of seismological research around the world, with corresponding increases in the number of publications using IRIS data.

IRIS facilities have impact beyond the confines of research on Earth's dynamical systems. Leadership from IRIS Education and Outreach efforts has exposed large numbers of U.S. citizens to seismological and Earth science information in museum displays, dynamic web sites, and public lecture series. There has been a significant increase in the use of seismology to introduce young students to science and mathematics in addition to the quantification of the dynamic Earth processes. Data from the global seismological facilities are also deeply embedded in the real-time operational procedures of earthquake, tsunami, and nuclear test monitoring systems, in parallel with the research efforts using the same data. It is hard to imagine the loss to science had global seismic data not been readily available in the wake of the devastating Sumatra-Andaman earthquake and tsunami of December 26, 2004. The rapid seismological quantification of the tectonic nature of the event, its rupture process, and energy release has provided unprecedented information about this enormous earthquake that would have been impossible prior to development of the IRIS facilities. A commitment to sustained data

Seismological Discovery at an Unabated Pace

Slow Earthquakes. Systematic analysis of Rayleigh waves reveals large earthquakes that produce no discernible high-frequency body waves, some of which may be ice quakes.

Crustal Basin Structure. New techniques to collect and process high-frequency seismic data have produced great improvements in understanding crustal processes and in microzonation of seismic hazard.

Lithospheric Structure. Receiver functions produced a revolutionary advance in resolving crustal and upper mantle structure models. Developments in migrating receiver functions create a new imaging technique.

Mantle Strain. Studies of anisotropy, including long-period surface waves and splitting of S waves, reveal details of crystal alignments from mantle deformation, reflecting past and present tectonics.

Mantle Temperature. Joint inversions for P and S velocities, together with Q tomography, reduce the ambiguity in attributing lateral differences to temperature or mineralogy.

Post-Perovskite Phase. Details of the geographic distribution of the sharpness and height of an abrupt change in wave speed at the top of the D´´ layer constrain its interpretation as a phase transition.

Evolution of the Core. Analysis of PKP waveforms reveals anisotropy and asymmetry of the inner core, providing new insights on the history of the geodynamo and temperature in the core.

Examples of how IRIS facilities have helped sustain the pace of discovery are described in the section on Research Enabled by IRIS Facilities.

Unprecedented GSN and FDSN recordings of the great Sumatra-Andaman earthquake of December 26, 2004 provided the basis for rapid quantification of the faulting process that produced the devastating Indian Ocean tsunami. GSN data played a critical role in presentations by NSF, USGS, and NOAA to Congress and the media in the wake of the earthquake. Reprinted with permission from Science *308:5725, May 20, 2005. Copyright 2005 AAAS. Cover graphic by S. Lombeyda, V. Hjorleifsdottir, J. Tromp, and R. Aster.*

collection efforts is critical for responding to future devastating earthquakes and for understanding processes occurring in the Earth system on time scales of more than a few decades.

At the same time, we have learned a terrible lesson from the Sumatra tragedy. Earth science did not provide a useful advance warning. Observational systems and real-time analytical procedures were not sufficiently mature to characterize the size of the earthquake and its tsunamigenic potential rapidly in real time. The transfer of real-time scientific results and emergency warning to exposed areas failed utterly. With retrospective benefits from the most complete recording of a giant earthquake ever obtained, however, seismologists, monitoring agencies, and disaster response specialists can now see a clear path to developing the practical systems needed to reduce the risk of such disasters in the future.

In this proposal, we present a plan that will sustain and build upon the established excellence of IRIS facilities. The thematic topics that we put forward in our introduction (see blue boxes) are addressed in our section on proposed activities over the next five years. Innovative efforts that exploit the long reach of IRIS international operations, that meet the challenges of vastly increasing data volumes for active and passive seismological experiments, and that facilitate exciting new approaches to analyzing seismic data are described, along with new directions in public and educational outreach that will engage new generations in the intellectual excitement and challenge of understanding the Earth system.

IRIS – Overview of the Consortium

IRIS is a consortium of 102 U.S. Member Institutions, 2 U.S. Affiliates, 47 Foreign Affiliates, and 11 Educational Affiliates. The Consortium is dedicated to the operation of science facilities for the acquisition, management, and distribution of seismological data. Over the past twenty years, the membership of IRIS has come to comprise virtually all U.S. universities with research programs in seismology, and has incorporated a growing number of educational affiliates and domestic and international partners. Data collected by IRIS are made freely available to, and are widely used by, the global community without restriction for research, real-time monitoring of tsunamis and nuclear tests, and other applications.

IRIS contributions extend far beyond managing facilities. Seismology, always a data-driven field, is also an experimental one. It has become possible for seismologists to perform complex data-gathering experiments unconstrained by the technical or instrumental capabilities of their departments and institutions. Broadening the capacity to perform investigator-driven seismological research has also increased opportunities for seismologists to engage in multidisciplinary projects. Individual seismologists are now freed of the encumbrances of building and maintaining technical support groups and can concentrate on their science and interactions with other disciplines. As a direct result, the seismological community and, arguably, the broader Earth science community, have been strengthened both from the perspective of individual projects and multidisciplinary community-driven

Thematic Topic 1: Facilitating Integrative Earth Science

Leading Earth science questions must be addressed from multidisciplinary perspectives that integrate complementary disciplines, data, and techniques. Integration reduces ambiguity by allowing diverse observations to provide cross-disciplinary constraints, and it also derives from the understanding that our hypotheses are becoming more holistic. Moreover, we are finding that data collected at multiple scales and from both active and passive sources are necessary in many investigations.

How will IRIS enable seismologists and other Earth scientists to initiate and conduct integrative research?

Thematic Topic 2: Facilitating Efficient Operations and Maintenance

IRIS will continue to seek new operational efficiencies in the core instrumentation programs in order to improve data quality, data return, and real-time data retrieval. IRIS also will continue to work toward standardizing instrumentation to reduce maintenance and operating expenses. Support of other NSF science programs, such as EarthScope, is contingent on having a strong and efficient program base. Some further efficiencies require new approaches to educating and supplying resources for the user base.

How can IRIS improve data return, metadata capture, and data quality from portable array experiments?

What are appropriate performance metrics for global and portable instrumentation?

What can IRIS do to assist investigators doing experiments in difficult field environments?

initiatives. In turn, this community activism has fed back directly into the core programs of the NSF Directorate for Geosciences, driving productive new programs in solid Earth sciences.

In parallel, seismology's community culture has been transformed. Throughout its expansion, IRIS has nurtured the principles of transparent, shared governance, free and open data access, and flexible operations that have themselves become cornerstones of the current health and excitement in Earth science. This has changed the world view of many young scientists entering the field, and has paid dividends in developing the grass-roots enterprises that eventually lead to major programs, such as EarthScope. This approach continues to be a model for other community-based initiatives in the Earth and environmental sciences.

The IRIS Consortium has changed the field of seismology by broadening community participation in a transparent and open management structure. Member representatives share information during workshops and governance committee and board meetings, and through community web sites and bulk emails, all of which provide the "virtual critical mass" that allows even smaller geoscience departments to participate in facility governance and to foster their own leading, competitive research programs in seismology. Effective use of the IRIS facilities is assured through community education and training programs at all levels. Educational Affiliates, a new and growing class of association with IRIS, are making IRIS data and the latest research results available to a diverse cohort of undergraduate liberal arts institutions and K-12 educators. Additionally, the large number of international affiliates is a consequence of the leading and sustained role played by IRIS in the development and operation of global seismological networks. IRIS's international credibility is the basis

Thematic Topic 3: Improving User Services

IRIS facilities gather and distribute substantial amounts of raw seismological data and metadata that, increasingly, are being used in ever more sophisticated structure and source-imaging algorithms. The need to field more instruments and process more and larger user requests for data present technical and management challenges. Deploying larger and more complex arrays of portable instruments requires enhanced training and improved documentation. Integrating more sophisticated and adaptive tools into user services will require a coordinated effort among the programs and among users with different computational and technical resources. Working within an integrated scientific framework also presents new challenges.

How will IRIS develop and distribute modern tools for data collection and processing to users with different technical capabilities?

How can IRIS design these tools so that they can provide a structured platform for complementary geophysical data?

Thematic Topic 4: Facilitating Instrumentation Development

Although the IRIS facilities and the approach to operating them are state-of-the-art, there must be new developments in seismological instrumentation to sustain a modern program. Key components of the instrument pool, including the very broadband seismometer used by the GSN, are nearing the end of their useful life. Replacement candidates must be developed and tested. New scientific opportunities in the oceans and in Antarctica are providing instrumentation challenges in component integration and deployment logistics and in modes of operation and coordination with other scientific programs.

What role should IRIS play in the development of instrumentation relevant to its program?

for sharing seismological data across different networks and for serving as a framework for international research collaborations IRIS's global leadership in operating the GSN as an open network, for example, is one of the underlying factors in the rapid development of tsunami early warning systems after the 2004 Indian Ocean disaster.

In these and in other ways described in this proposal, IRIS has provided cornerstone facilities for Earth science research, education, and applications, and the IRIS Consortium has provided a cornerstone framework for self-organization within the community and in the development of national and international partnerships. This has been recognized by recent technical and management reviews of the Consortium. In addition to enumerating the scientific advances supported by the IRIS facilities and its management excellence, these

Thematic Topic 5: Promoting Diversity in Earth Science

Compared to society at large, Americans from racial and ethnic minorities are a disproportionately small fraction of students and professionals in the Earth sciences and in science and mathematics generally. At the highest professional levels, women and minorities remain underrepresented even compared to other scientific fields. This failure to engage many groups aggravates a shortage of students and young professionals being trained to meet the nation's need for Earth scientists.

How should IRIS work with students, educators, and outreach organizations to bring a broader range of students into Earth sciences at all levels?

How should IRIS address the nation's need to improve science and math education at both the K-12 and university level?

Thematic Topic 6: Facilitating International Collaborations

IRIS facilities are global in scope and geographic reach, but the IRIS Consortium presents an opportunity for international collaboration that some believe could be better annunciated and utilized. This could be explored through international observation systems such as the FDSN or GEOSS, through coordinated network development such as AfricaArray or KNET, through training programs for regional network operators in developing countries, and through facilitation of international research and educational collaborations.

How should IRIS facilitate the ability of American academic seismologists to work internationally and engage their foreign colleagues?

How can IRIS set an example for the use of global monitoring networks and the densification of global networks with regional deployments to promote scientific collaboration, capacity building, and hazard reduction in the developing world?

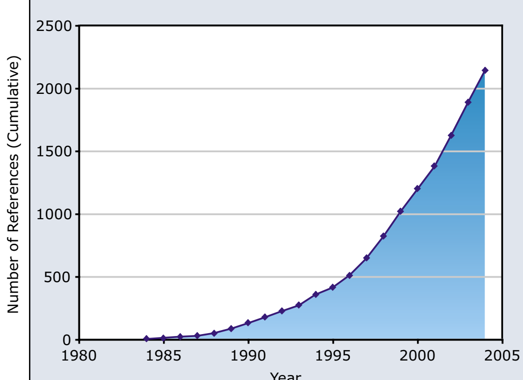
reviews noted ways in which IRIS has been flexible and responsive to community and scientific opportunities and NSF concerns. Specifically, NSF's 2003 review of IRIS management concluded that:

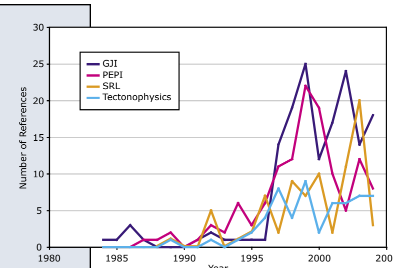
- IRIS has exhibited *outstanding management* of the core facility programs;
- IRIS has *facilitated partnerships* with federal agencies, other large facilities, and international organizations;
- IRIS has demonstrated *successful stewardship* of a large and globally distributed inventory of seismological instruments, seismological experiments, and a very large data archive;
- IRIS has become an *integral part of the seismological community*, making contributions to education and outreach, cyberinfrastructure, and instrument development;
- IRIS has been *responsive to suggested changes* in Consortium management structure.

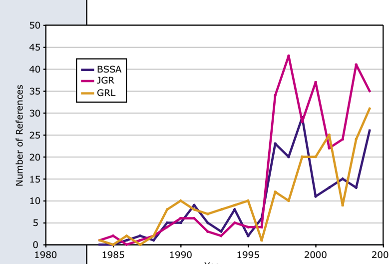
On the basis of these accomplishments, the IRIS Board of Directors is pleased to submit this proposal to renew IRIS's partnership with the NSF for the support of cornerstone facilities for Earth science research, education, and ap-

IRIS Impact as Measured by Published Papers

The ultimate measure of success of NSF's investments in a facility program such as IRIS is the extent to which results based on the use of our resources and data are used in published articles in scientific journals. IRIS maintains a bibliography of IRIS-related publications that has been developed through submission of citations by authors and through a detailed search of key journals. The major Earth science journals shown in the figures on the right have been individually searched to identify articles that reference IRIS or use data from the GSN, PASSCAL, DMS, or E&O programs. More than 2000 articles and abstracts are included in the bibliography for 1984-2005. Three stages are apparent in the growth of publications. Early articles (1984-1987) primarily dealt with descriptions of the nascent Consortium and emerging programs and plans. Early PASSCAL experiments and limited GSN data were the basis for a moderate increase in publications (1988-1995). After 1995, significant expansion of the GSN, completion of a number of PASSCAL experiments and initiation of the DMS archive resulted in a spectacular increase in the rate of publications. This long-term increase in publications is evidence of the value of NSF's decadal investments in the collection and preservation of Earth science data.







plications. We request $89,459,077 over five years to support continuing operations of each of the core programs, to assure the continuing strength and innovation of the core programs, to extend collaborative efforts, and to support expanded functions for Consortium activities. Funding is also requested to maintain and develop new international partnerships, and to fulfill obligations to contribute data for earthquake monitoring applications.

In this proposal we will describe strategies in the following key topics:

- Facilitating integrative Earth science;
- Facilitating efficient operations and maintenance;
- Improving user services;
- Facilitating instrumentation development;
- Promoting diversity in Earth science;
- Facilitating international collaborations;
- Cultivating organizational efficiency.

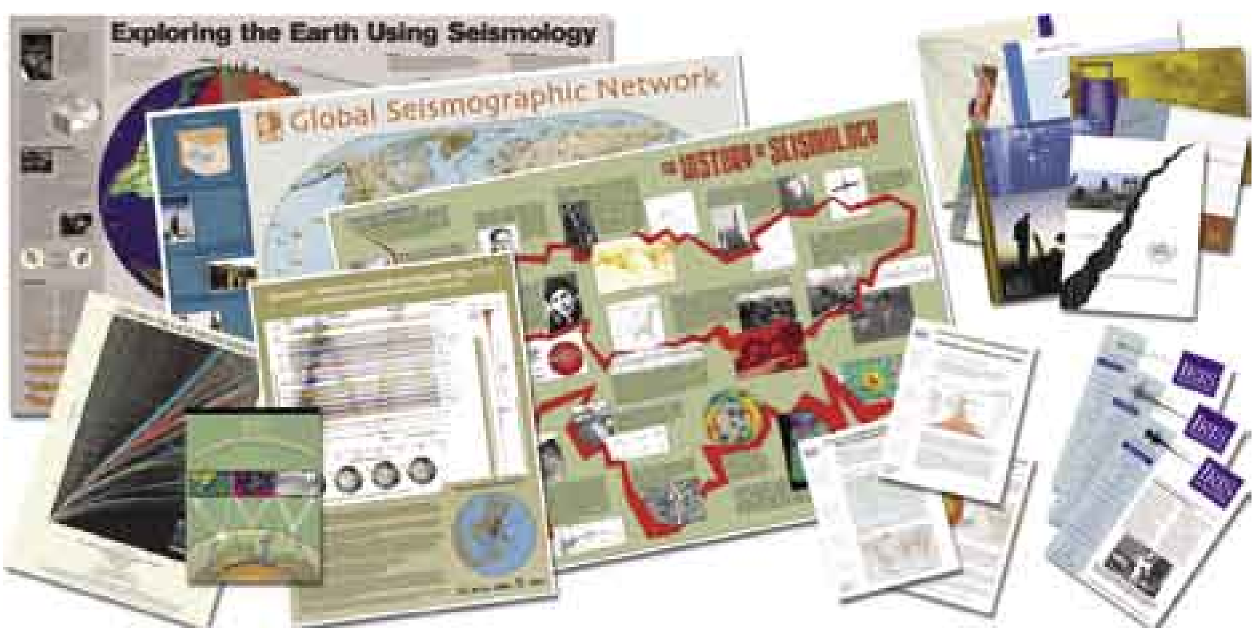
This proposal, which was written with leadership and input from the IRIS membership and contains numerous individual investigator contributions, will show how IRIS intends to achieve these and other goals through a continuation of the open and shared governance that has been a hallmark of the seismological community for two decades.

The cornerstone role of IRIS facilities and the capabilities of the seismological community have been exemplified by the scientific and technical response to the Sumatra-Andaman earthquake and the Indian Ocean tsunami tragedy. Sumatra was a touchstone event, covering all of the IRIS programs and engaging a spectrum of the community from fundamental earthquake source research to natural hazard response and mitigation studies. The earthquake was the largest event ever to be recorded on the Global Seismographic Network (GSN), and one of the largest in the instrumental history of seismology. IRIS data were distributed and used in real time by tsunami warning centers operated by NOAA and by the National Earthquake Information Center (NEIC) of the USGS. Within a few hours of the origin, it became apparent from analysis of IRIS data that the earthquake was

Thematic Topic 7: Cultivating Organizational Efficiency

As IRIS has grown over the past 22 years, the management and governance structure have evolved, with direction of the membership and guidance from NSF, in response to the operational pressures on the facility and the research needs of the community. A continuous process of internal and external reviews, both formal and informal, have helped keep the organization focused on the efficient operation of the core facilities. In addition to ongoing program review by the Board of Directors and standing committees, internal reviews have included review and competition for the PASSCAL Instrument Center in 1994, an assessment of management structure by a Committee of Former ExCom Chairs in 1996, and self studies and strategic plans for the DMS in 2003 and PASSCAL in 2005. In addition to the in-depth review by NSF every five years as part of the renewal of the IRIS/NSF Cooperative Agreements, and annual reviews of business practices by independent auditors, external reviews have included an NSF-mandated review of the GSN in 2002 and an NSF review of IRIS management in 2004. In response to the NSF management review, Consortium membership undertook a major revision of the corporate bylaws in 2004, streamlining the governance structure and creating an elected, nine-member Board of Directors.

How should IRIS continue to engage the community in maintaining and improving its management and technical capabilities?



The Sumatra-Andaman earthquake and the tsunami that it generated led to a disaster that killed hundreds of thousands, disrupted the lives of tens of millions, and set back development across a region that comprises most of humanity. Photos from http://walrus.wr.usgs.gov/tsunami/sumatra05/photos.html.

exceptional in size, and further analysis began to indicate that the earthquake was exceptional in complexity. In fact, preliminary papers already published on this earthquake suggest that entirely new earthquake processes with complex frictional behavior have been detected. In many ways, this was a "design event" for the GSN, and the success of its recording will influence earthquake science for years.

But the Sumatran tsunami was also an immense human tragedy. While we hope that we can learn enough from this earthquake to produce better seismic hazard forecasts, it has become apparent over the past few months that the IRIS facility template has helped inspire international and national efforts to construct earthquake monitoring and tsunami warning systems, and to develop international research capacity through collaborative data exchange. This motivates exploration of new modes of international collaborations for the IRIS membership. IRIS will be part of the follow-on reconstruction and capacity-building efforts by virtue of its international credibility and the activities of individual Consortium members. In this example of IRIS enabling scientific progress, the IRIS framework of real-time data acquisition, quality control, and open data dissemination is being used as a model for designing regional and national networks as part of international tsunami-warning systems. Indeed, many of the new systems will rely on real-time data from GSN stations; in return, new partnerships and international arrangements are reinforcing the international agreements that are already in place and will improve the uptime and performance of the network.

The Sumatra event demonstrates several points.

- Data collections do not arise by chance. Instead, they require a thoughtful community, sustained effort, and properly designed facilities.
- Data from rare events underlay breakthroughs. With just one really great earthquake recorded by modern seismometers, further scientific surprises lie ahead.
- Properly designed and operated research facilities provide data that are also crucial to social imperatives such as hazard reduction and tsunami warning.

If not for the foresight that led to IRIS and for NSF's past and continuing investments, the progress that is now expected from using Sumatra earthquake data would probably have been impossible.

The IRIS Facilities

IRIS's core facilities are organized around the collection, management, and use of seismological data. The facilities comprise the:

- **Global Seismographic Network (GSN)**, a globally distributed network of sensitive, very broadband seismometers that provides high-fidelity data from most stations in near-real time;
- **Program for Array Seismological Studies of the Continental Lithosphere (PASSCAL)**, a portable instrument loan facility that enables individual investigator teams to deploy instruments and acquire data for specific scientific targets for a specified duration;
- **Data Management System (DMS)**, which provides an open, standards-driven framework for management and distribution of data acquired by the GSN, PASSCAL, and other networks and instrumentation;
- **Education and Outreach Program (E&O)**, which provides resources for K-16 teachers, for other formal and informal educators, for research scientists contributing to education, and a framework for outreach to public, professional, and other Earth science communities.

Individual facility programs are coordinated through IRIS Consortium management and governance committees. They have enough flexibility to support cross-cutting initiatives within IRIS and within the IRIS community, in addition to their core functions. The separately funded USArray component of EarthScope, for example, draws on the programmatic strengths of each of the IRIS programs. By the same token, the cross talk among the programs and their operational flexibility allow the community to develop initiatives unconstrained by a pre-existing facility structure. We explore some of these emerging opportunities in following sections. Detailed synopses of the facilities are presented in Program Descriptions. We give a brief summary here.

GSN

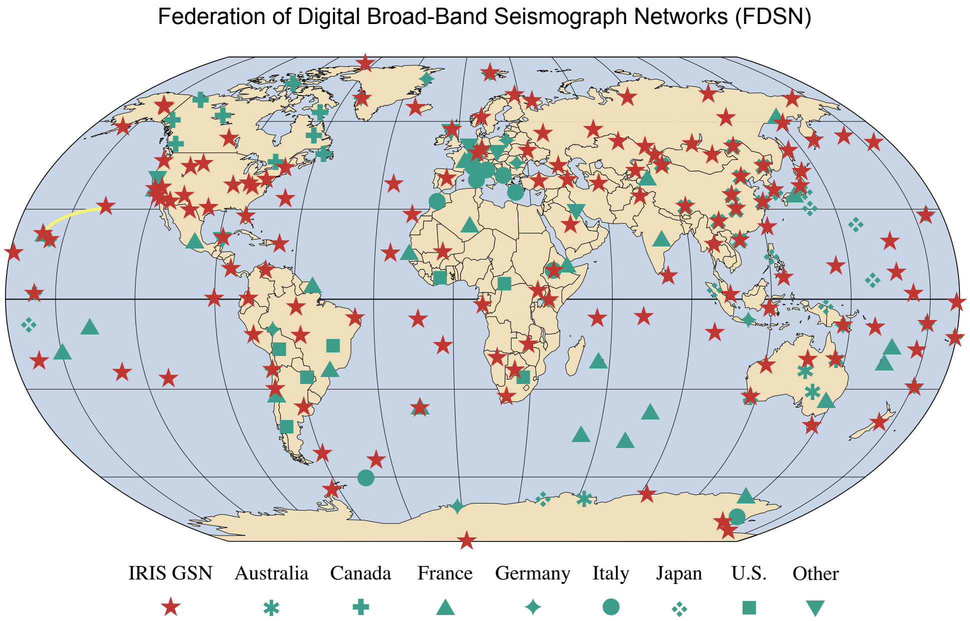
The Global Seismographic Network is a cooperative partnership between IRIS and the USGS, coordinated with the international community, to install and operate a global, multi-use scientific facility as a societal resource for Earth observations, monitoring, research, and education. GSN instrumentation is capable of measuring and recording with high fidelity all seismic vibrations from high-frequency, strong ground motions near an earthquake to the slowest global Earth oscillations excited by great earthquakes. The primary focus in creating the GSN has been seismology, but the infrastructure is inherently multi-use and can be extended to other disciplines.

The GSN is the U.S. contribution towards global, uniform, unbiased Earth coverage by a permanent network of broadband, three-component digital stations. GSN is coordinated internationally within the Federation of Digital Broad-Band Seismograph Networks (FDSN), of which IRIS is a

Evolving Facilities

IRIS was founded 22 years ago to address important data needs of American seismologists by creating new instrumentation and data-collection resources and fundamentally changing their mode of operation. At that time, there was no globe-spanning network of modern seismographic stations. Individual universities conducting seismological experiments maintained separate pools of portable instruments and non-uniform databases, and there was no mechanism for sharing digital waveform data among institutions. Rather than wait for an inefficient process to lead to less-than-ideal mechanisms to address these needs, the seismological community created IRIS facilities, enabling great leaps forward in seismology. IRIS facilities have evolved continuously to address new needs and to facilitate further advances. GSN has progressed from isolated STS-1 seismometers at the outset to multiple sensor installations adapted to the requirements at each site, including boreholes in noisy environments. GSN communications has evolved from shipping tapes, to dial-up, to continuous, real-time VSAT transmission. PASSCAL has continually upgraded both sensors and special-purpose data loggers to meet the evolving needs of the research community. In addition, the PASSCAL instrument facility has changed from being primarily an instrument depot to being a central resource for supporting field experiments, including training, field engineer support, and data download facilities. The DMS has adapted to real-time data transmission by integrating data-collection centers, developing software to ingest vastly more data, and introduce automated quality control—all without significant increases in operations staff. In addition, the DMS has taken advantage of the Internet by serving data remotely from online mass-storage devices, and by developing clever ways to cache those data most in demand.

As data quality, data volumes, and processing capabilities continue to grow, there are new demands from seismologists and other scientists using seismic data. IRIS is looking forward to meeting these needs by continuing to evolve. PASSCAL will develop online training and other innovative PI-support products. DMS will participate in cyberinfrastructure/geoinformatics collaborations to facilitate cross-disciplinary use of seismic data. GSN will take advantage of technological development to become more cost-effective, more real-time, and more uniformly distributed—improving coverage in the polar regions and the oceans.



Distribution of stations in the Federation of Digital Broad-Band Seismograph Networks, highlighting the major contribution of GSN to the global coverage, complemented by that of its national and international partners, and a significant number of stations installed and operated jointly by GSN and various FDSN partners.

founding member. The GSN currently consists of 138 stations, most of which have real-time data access. GSN station distribution is designed to complement that provided by other FDSN members. GSN equipment is modular, enabling it to evolve with technology and scientific needs, while meeting the technical standards set within the FDSN. Standardization of equipment and data formats creates efficiencies for operations and maintenance. GSN makes every effort to take advantage of a broad mix of available telecommunication technologies, using public and private Internet links, and dedicated satellite circuits.

A cornerstone of the GSN is free data exchange with the international community. All real-time GSN data are available to anyone in real-time, without restriction, via GSN Data Collection Centers or the DMS.

The GSN is both benefactor and beneficiary of government-university cooperation involving the National Science Foundation (NSF), U.S. Geological Survey (USGS), Department of Defense (DOD), National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA). The GSN provides a foundation for the backbone networks of the Advanced National Seismic System (ANSS) in the United States, and supplies the critical core data for the Pacific Tsunami Warning Center. The International Monitoring System is using data from GSN stations for the Comprehensive Test Ban Treaty. The GSN is an official U.S. observing system component of the Global Earth Observation System of Systems (GEOSS). The GSN serves as a key component of the FDSN global backbone. Primarily operated and maintained through the USGS Albuquerque Seismological Laboratory and the University of California at San Diego, the GSN is augmented by independent national and international affiliate stations and arrays.

The GSN is an educational tool for Earth studies. With the ease of access to data and the blossoming of technology, GSN data are now routinely used in introductory college courses, and high school use is increasing. GSN stations themselves are focal points for international training in seismology. Real-time access to GSN data has led to rapid analysis of earthquake locations and their mechanisms, increasing public awareness of earthquakes as scientific phenomena.

PASSCAL

The PASSCAL facility provides the seismological community with state-of-the-art, low-power, portable seismic instrumentation and advanced field and database management tools in support of investigator-driven seismological experiments worldwide. The keys to PASSCAL's remarkable success as a scientific facility include performance, reliability, and simplicity—of instrumentation, field support, and data management—all of which have made it possible for the university community to routinely undertake large broadband and active-source experiments that would otherwise be dependent on institutional resources.

Scientists write individual or collaborative science proposals requesting PASSCAL instrumentation to agencies including NSF, USGS, DOD, and the Department of Energy (DOE), which are peer-reviewed. PASSCAL currently has a complement of more than 1000 portable, digital seismic recording systems with over 2200 recording channels, comprising approximately 600 3-channel recorders, 400 single-channel "Texan" instruments, and 4 multichannel reflection/refraction systems. An additional 150 Texans will be delivered in late 2005. In addition to the instruments managed by IRIS, PASSCAL provides maintenance support for the 440 Texan instruments owned by the University of Texas at El Paso in return for the use of these instruments in PASSCAL experiments. All of the IRIS instruments are supported by a dedicated staff of 13 full-time personnel at the PASSCAL Instrument Center located at the New Mexico Institute of Mining and Technology in Socorro, New Mexico.

While a basic metric used to measure PASSCAL's progress has been the number of instruments available for use in experiments, the scope of the facility extends well beyond hardware alone. Underlying the hardware pool, PASSCAL maintains an extensive support structure for instrument design, maintenance, field support, software development, and training. PASSCAL operates as a resource for the research community, in effect serving as a "lending library" for specialized seismological equipment, but also providing technical support and user training.

Since the 1984 start of the program, PASSCAL has supported over 500 experiments, leading to a host of new discoveries about the Earth, some of which are summarized in the one-pagers that accompany this proposal. The range of investigations that has been made possible with the PASSCAL facilities has far exceeded those envisioned at the start of IRIS. PASSCAL resources remain fully subscribed for use in peer-reviewed research programs—confirmation of the importance of the PASSCAL facility to the Earth science community. Indeed, despite continued growth in the size of the instrument pool, demand for instruments and technical support continues to exceed capacity. The gap between demand and capacity remains a major concern of the PASSCAL community, where the queue for broadband instruments now exceeds two years.

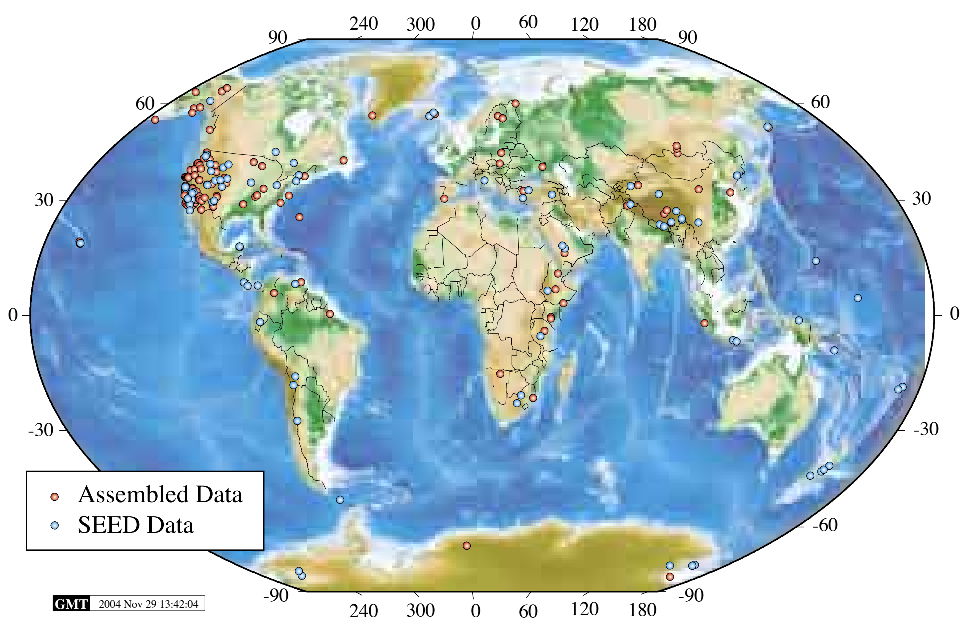
DMS

The primary role of the DMS is to receive, provide quality assurance, archive, and distribute data from the GSN and PASSCAL programs. The IRIS Data Management Center (DMC) plays a key role in the international seismological community, serving as an archive for continuous data for the FDSN. As such, it receives, archives, curates, and distributes data from a large number of permanent seismological networks around the globe that are operated by other national and international agencies and institutions.

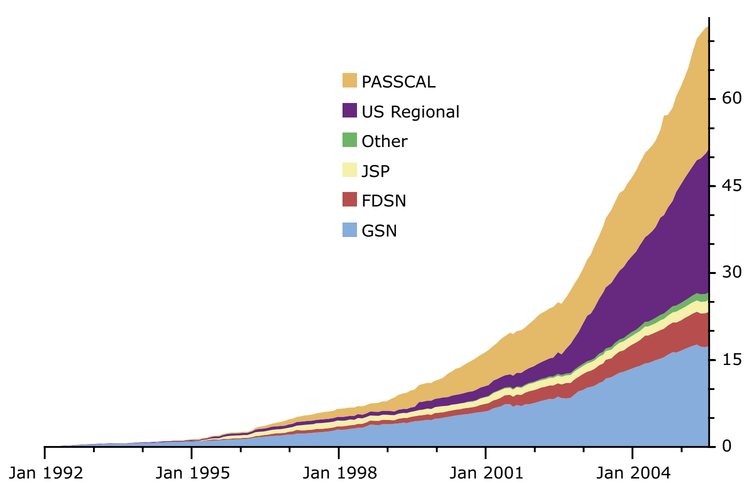
The DMC has also become an important node for archiving data from regional seismic networks in the United States. Of the 18 regional earthquake-monitoring networks supported by the USGS, all have data archived at the DMC. The DMC acts as the de facto consolidating archive for data from regional networks, providing access to the regional data for a broader community. Due to the DMS requirement that data be made available in SEED format with full metadata, these monitoring data can normally be used for research as well as monitoring purposes. Regional network data have now overtaken both PASSCAL and GSN data in terms of the amount of data entering the DMC.

All data collected and archived by IRIS are made available without restriction through its DMC in Seattle, Washington. The DMC houses the primary IRIS data archive, along with associated facilities for real-time data collection, data

PASSCAL Experiment Data at the DMC (1986-2004)



PASSCAL experiments with data in the DMC. In the last 5 years there have been 242 experiments with 235 distinct PIs, representing 65 IRIS member institutions and a total of 105 distinct institutions worldwide.



The DMC's dual sorted archive now exceeds 70 terabytes in size. The GSN and PASSCAL contributions are shown on the bottom and top segments. The most voluminous data are now from U.S. regional networks shown in purple.

base management, and quality control. In addition to developing and maintaining an extensive hardware base, the DMC staff is also responsible for responding to user requests and developing software for a rich suite of user tools and quality-control processes.

By actively developing, supporting, and promoting the open exchange of data based on well-established interchange standards, the DMS has played a key role in ensuring that properly documented data are made available to scientists worldwide, with a minimum of barriers, for use in a wide range of research topics and applied applications.

E&O

IRIS members have increasingly recognized the need to communicate the results of scientific research to the public more effectively, advance science literacy for greater understanding of our rapidly changing and increasingly technological world, and attract more students to study science. To address these issues, in 1998, IRIS created the Education and Outreach (E&O) program to join its existing three core programs. Since that time, the program has grown to 4.5 IRIS staff managing a number of subcontracts and consultant awards, with significant contributions from members of the IRIS community.

A Kipp Academy student engages in a building contest at IRIS Headquarters.

Since its inception, the E&O program has explored the needs of the different audiences it serves and has developed a core program to address those needs. In 1998, the E&O committee convened a conference with representatives from diverse science and science education disciplines, funding agencies, and other Earth science E&O programs to develop a broad vision of how IRIS could uniquely contribute to science education and outreach. The discussions and collaborations that developed during the conference have guided IRIS's E&O efforts ever since and formed the basis for a program plan published in 2002.

The E&O course of action is to provide products and programs for a variety of audiences, including the general public, K-12 students and educators, and post-secondary students at our nation's colleges and universities. At the core of all E&O activities is a focus on the use and explanation of seismic data. Programs range from those that impact large numbers of people for brief time periods (e.g., museum displays, lecturers, teacher training, posters) to those that impact smaller numbers of people through extended interactions (e.g., internships, Educational Affiliates). IRIS's E&O program also looks inward to develop the talent within the ranks of IRIS's member institutions so that all may fully participate in building an education program of national scope and prominence.

IRIS as a Consortium

Consortium activities are an integral aspect of IRIS that complement the more technical activities carried under the core facility programs. Consortium activities include support of the committee structure that ensures shared governance and broad community input to IRIS actions; convening of annual workshops, ad hoc working groups, and committees formed to digest critical issues in a timely manner; and communicating with the membership and the public through the IRIS web site, bulk emails, newsletters, annual reports, and outreach materials. Equally important are the activities the Consortium undertakes on behalf of the community in high-level interactions with other national and international organizations, in exploring initiatives and programs advantageous to the community, in interactions with other scientific and instrumentation consortia, and in the general advocacy for seismology and Earth science within government and international organizations. These activities are carefully monitored (or initiated) by the elected IRIS Board of Directors, which represents the IRIS membership and has fiduciary responsibilities. The Board, in turn, works closely with the program standing committees to ensure that issues specific to core programs are explored in full.

The culture change engendered by IRIS extends beyond the four facility programs. It is now customary for individual seismologists and other Earth scientists to use IRIS as a resource framework for developing new community initiatives, for leveraging individual programs, for identifying international partners, and for meeting educational and outreach objectives of individual projects. IRIS thus enables individual investigators and multidisciplinary groups to meet broader research and educational goals.

One product of IRIS's consortium activities has been the international credibility that IRIS has helped create for U.S. seismology. The IRIS core facilities are global in practice and by definition. The GSN's global scope rests on a foundation of international partnerships and agreements. PASSCAL experiments have been performed on every continent, usually in partnership with local university and government collaborators. The DMS participates in data-exchange agreements with other networks in the FDSN. This global geographic scope translates into international credibility that enables international scientific collaborations on large and small scales. The IRIS membership can leverage the reputation of IRIS to help form new collaborations and partnerships, knowing that the technical infrastructure within the core programs provides a common "language" of standards that can form the basis for solid interactions in collaborative research and education.

Evolving Management Structure

The IRIS governance and management structure is an interface among the scientific community, funding agencies, and IRIS programs. The structure is designed to ensure close involvement of the research community in the development of IRIS facilities, focus scientific talent on common objectives, encourage broad participation, and effectively manage IRIS programs. Community involvement in the governance and management has been key to the success of the Consortium. Each year, over 50 scientists from member institutions participate in IRIS management through its eight regular committees plus ad hoc advisory groups. These scientists work with a professional staff led by the President, Director of Planning, Director of Operations, Director of Finance and Administration, and the four core program managers. IRIS originally governed itself with a Board of Directors comprised of representatives from each of the relatively few founding members. Executive authority was vested in an Executive Committee and appointed presidents who retained their faculty positions at their home institutions. Standing committees were created for each program to maintain community oversight while program managers were responsible for day-to-day activities. As the Consortium grew to more than 100 members and IRIS facilities matured, the "rotator" president was replaced by a permanent full-time position, and the corporate by-laws were revised in 2004 to create a nine-member Board of Directors elected by representatives of the full set of member institutions.

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

Tsunami Risk Reduction and Open Data Policies

GSN data were essential for a rapid recognition of the tsunamigenic potential of the Sumatra December 2004 earthquake. New techniques for quicker and more reliable identification of tsunami potential— rapid determinations of rupture duration and directivity, and finite source slip distributions—depend on GSN instrumentation with both very broadband response (to capture duration of high-frequency shaking as well as surface waves and free oscillations) and great dynamic range (to capture all arrivals of high-frequency body waves, including some intermixed among surface waves). Tsunami risk can be further reduced by "densifying" the GSN with high-capability stations near regions with a greater than average risk of tsunamigenic earthquakes. The USGS has recently been funded to add more stations in the Caribbean, and various international groups are involved in providing new stations in the Indian Ocean. Tsunami warning and research each benefit from free and open data exchange in real time. IRIS continues to foster such data exchange through its own policy for GSN data and its condition of openness in archiving data at the DMC or in using PASSCAL instruments. By insisting on an open data policy for KNET and other stations IRIS helped establish in Central Asia, IRIS has encouraged free data sharing by many countries in that region. IRIS has been effective in opening data access to many stations in Russia and a few stations in China—to the point that China has now announced plans to improve access to data from its next generation, most capable stations.

IRIS has been a lead supporter for open data in international fora for many years. From 1985 to 1995, IRIS participated in meetings of the Group of Scientific Experts to support development of a Comprehensive Test Ban Treaty monitoring system based on open data. Since 1996, IRIS has met regularly with CTBT Provisional Technical Secretariat staff to discuss how an open data policy could improve monitoring. Following the 2004 tsunami disaster, IRIS has been an invited participant in meetings of the Intergovernmental Oceanographic Commission concerning an Indian Ocean tsunami warning system. To broaden support for these positions, IRIS is planning for an endorsement of open data by its international affiliates. Technological obstacles must also be overcome for rapid data exchange to address tsunami risk. IRIS plans to work with the USGS to continue upgrading GSN communications, as well as continue development of data sharing tools such as NetDC.

science and encouraging forefront research.

As a major facilities program for NSF, IRIS works closely with the NSF Division of Earth Sciences to provide the instrumentation and data resources on which NSF-funded seismological research is based. Through a series of cooperative agreements, NSF has provided funding with which IRIS, on behalf of the research community, operates and manages the core programs of GSN, PASSCAL, DMS, and E&O. Because many operational aspects of the IRIS programs are closely integrated with activities at the USGS and other federal and international programs, joint IRIS/NSF coordination with these activities is essential to maintaining an effective program.

As a 501-c-3 non-profit corporation, IRIS provides the legal and fiscal structure through which NSF can interact with IRIS for the stable operation of its facilities, and a mechanism for developing programs and bringing the wishes of it members to fruition. Through its professional staff, committees, and sub-awardees, IRIS provides continuity in institutional and personnel resources for operational and developmental activities.

For its new and significant role as operator of the EarthScope project's USArray, IRIS has built upon and expanded the existing core programs. Management and implementation of the various elements of USArray, separately funded from the core operations, are carried out by distributing responsibilities among the existing program managers and new deputy program managers, with additional staff as required to carry out the expanded activities. A new position, Transportable Array Manager, is responsible for the largest individual component of USArray, and works in concert with the PASSCAL and DMS program managers. A USArray Project Manager and IRIS Director of Operations are responsible for internal coordination between programs and for overall management and reporting to the EarthScope Facilities Office and NSF. A USArray Advisory Committee provides overall advice that complements the roles of the IRIS program-specific standing committees.

Multiple-Use Networks

IRIS partners with the USGS to operate the GSN and, in turn, the USGS uses data from the GSN to monitor earthquakes worldwide. This is a continuation of the long-standing practice in seismology of promoting multiple uses of seismological networks. In addition to supporting the USGS earthquake-monitoring mission, GSN data are used by organizations monitoring nuclear test ban treaties and by NOAA to trigger tsunami alerts and warnings.

The underlying technology supporting this utility is the open availability of data in real time from the majority of IRIS stations, and the agreements among different parties to adhere to data archive and management standards. By working with mission agencies to promote this interoperability, IRIS provides its members with the framework to complement their basic research endeavors and explore applications to problems such as earthquake hazard risk reduction and treaty monitoring. The United States thus benefits from this facility interoperability.

In these multiple-use applications, the GSN often serves as the "backbone" or fiducial network for other, more densely distributed, network deployments. As long as the denser networks meet open data exchange and interoperability standards, the infrastructure in place for the GSN provides the mechanism for integrating real-time data as needed for particular monitoring problems. In this way, some less-developed nations with high earthquake or tsunami risk have been able to develop national networks and contribute their data to the DMS for both application and research purposes. The availability of these new data through the DMS then becomes a factor in promoting additional basic research collaborations with the host countries. The relationships with the IRIS-related Kyrgyz and Kazakh national networks are two specific examples. Recent collaborations with AfricaArray and the national network in Malaysia are encouraging and opportunities will be pursued, in collaboration with FDSN, for enhanced interactions with Saudi Arabia, Egypt, India, Iran, and Afghanistan. There is even an operational benefit: when host countries treat the GSN as a backbone for their national systems, there is often additional support for GSN operations and maintenance, relieving IRIS of some of the marginal costs of global coverage.

EarthScope and IRIS

IRIS played a key role in the early development of the concepts underlying USArray, and is now conducting USArray as a project on behalf of the EarthScope project. From the outset, the vision for USArray has been defined in the context of building upon the range of IRIS infrastructure to provide efficient and effective operation of USArray. Every IRIS element is contributing to USArray, with GSN coordinating the Backbone Network in collaboration with the USGS, PASSCAL coordinating the Flexible Array and Transportable Array efforts, DMS providing data archival and distribution functions for all of USArray as well as portions of the Plate Boundary Observatory (PBO) and San Andreas Fault Observatory at Depth (SAFOD) data sets, and E&O participating in USArray station siting outreach and contributing to EarthScope E&O efforts. In addition, the DMC will participate in the development of much of the IT infrastructure for EarthScope. Significant resources will be focused within the EarthScope project to develop an Integrated Data Access System (IDAS). The DMC is already heavily involved in a variety of EarthScope developments and will be involved in the IDAS as well, such as developing a web-services-based infrastructure for managing data products. The success of EarthScope, USArray in particular, thus depends on the continued health of the IRIS core programs.

The community has endorsed the ability of IRIS to carry out this project, particularly regarding the technical capacity and human resources to quickly transfer what the community knows about instrumentation, portable array operations, and data management into practice in fulfilling its obligations to EarthScope. Similarly, the integration of the USArray program within IRIS and the IRIS management and governance structure has meant that the community has come to participate in the operation of USArray through IRIS. It is no surprise that IRIS has been able to call upon its members in order to scale up its core functions to support EarthScope. The size and complexity of USArray should not obscure the fact that it is essentially a facility operation based on protocols and practices that have been well vetted over two decades by IRIS and its membership. IRIS is thus able to move the best ideas of the community into USArray operations.

It is important to recognize that while IRIS receives new funding to conduct USArray, the budget for IRIS's distinct core functions has not increased; in fact, over the past two years of overall NSF budget austerity, there were reductions in IRIS funding. IRIS's scientific goals and technical objectives described in this proposal are complementary to those of the USArray project; this is particularly evident in the global and international efforts. IRIS has increased its staff and community organizations to accommodate the USArray project, but this has been done as efficiently as possible, with sharing of overall responsibilities for USArray efforts. On balance, this approach has been especially beneficial to EarthScope; many efficiencies have been achieved relative to establishing a completely new structure.

With the advent of EarthScope, a question that naturally arises is whether USArray subsumes most of the domestic PASSCAL field programs so that PASSCAL becomes, at least temporarily, an overseas operation. A review of twenty years of past and planned experiments supported by PASSCAL shows that the program has continually served a balance of in-country and overseas projects at a variety of scales, and that for the foreseeable future, PASSCAL will be an important player in U.S. field-based seismology. Almost since its inception, international-based programs have been an important element of PASSCAL, with large international field programs constituting 30-60% of all major experiments the PASSCAL Instrument Center (PIC) supports. In the United States, however, programs continue to be supported at a variety of scales. Some examples include major field efforts in Alaska and the Pacific Northwest, Rapid Array Mobilization Program (RAMP) deployments following earthquakes of a variety of sizes throughout the United States, site and explosion-source characterization studies, small-scale tests of novel seismological applications, and frequent class uses of PASSCAL equipment. All of these U.S.-soil deployments should continue concurrently with USArray, or even increase to the extent that USArray fosters a broadening of interest in continental United States problems. Given the focused and geographically moving nature of USArray, we also anticipate a continued role for large-scale PASSCAL experiments in the continental United States, collaborating with and expanding research envisioned as part of the EarthScope/USArray science plan.

The benefits to IRIS of conducting the USArray project have included participation in an exciting major new venture in the Earth sciences and in active engagement of IRIS members in EarthScope research and activities. In some cases, new technical innovations arising from USArray will also be beneficial. For instance, the DMS expects that the technologies developed for EarthScope, such as the product management system, will also be applied to other products at the DMC. Collaborative work with EarthScope will benefit the E&O program in the development of new educational products such as video products for large-scale audiences (e.g., through the Discovery Channel or National Geographic).

A very important benefit to the seismological community from USArray would be to have USArray flexible array systems available for general use on a non-interference basis during times that they are not being used on experiments directly funded by EarthScope. IRIS is prepared to work with NSF and the research community to establish instrument-use policies that maximize the benefit of the combined IRIS/PASSCAL and EarthScope/USArray portable instrument pools in supporting NSF-funded research projects. The primary goal would be to ensure that the valuable resource of USArray instruments, both the 200 broadband instruments and the 2000 short-period "Texans," do not sit idle for extended periods while non-EarthScope projects are required to wait for access to the already over-subscribed pool of PASSCAL instruments. Conversely, it would be useful to have the PASSCAL Texans available to complement USArray instruments for deployment in large-scale active-source EarthScope experiment. The five-year plan for acquisition of PASSCAL instruments in this proposal, and the associated budget, assumes that appropriate arrangements can be established for joint use of these instruments.

Research Enabled by IRIS Facilities

This proposal for continued NSF funding derives its ultimate justification from the scientific research enabled by IRIS facilities. As the fifth in a series of five-year proposals requesting significant NSF resources for seismological facilities, it is very reasonable to question whether the scientific return continues to justify sustained support. Fortunately, intense research activity and progress across a vast span of Earth science efforts provide a compelling testimonial to the continuing value added by IRIS facilities. In this section we highlight recent advances and discoveries about fundamental properties of the Earth system over the past five years that have built upon IRIS facilities in various ways. The five-year time scale for preparing IRIS renewal proposals intrinsically emphasizes how much of a difference five years makes in terms of our overall understanding of the Earth system from core to crust and from microseisms to massive earthquakes. The numerous one-page vignettes in the Review of Accomplishment (Volume 2) are all contributed by users of IRIS facilities, and provide a rich and detailed tapestry of scientific progress cascading from NSF's investment in IRIS.

Lowermost Mantle and Core

Earth's deepest regions appear to hold the key to understanding many processes of fundamental importance for the evolution of the Earth system. The mechanism by which the planet's magnetic field is generated and how it evolves over time, the thermal evolution of the planet following accretion and large impacts, and the chemical cycling of material in the interior all require detailed understanding of the structure at great depth, which only seismology can reveal. This leads the seismological community into strong interactions with geomagnetists, geochemists, geodynamicists, and mineral physicists in an interdisciplinary endeavor to understand the deep Earth system.

The most remote place in Earth is the inner core, a 1221-km radius sphere of solid iron that is growing progressively over time as the core cools. No one anticipated the complexity of the inner core that has been revealed by seismological studies or the importance of this deep region for constraining Earth's thermal evolution and geomagnetic history. Discoveries of the past few years include refinement of earlier models of anisotropic structure of the inner core to include an "inner" inner core (a very small central sphere of solid iron with anisotropic properties that are distinct from the overlying shell of younger inner core). The outermost layer of the inner core was recognized to be heterogeneous a few years ago, but the fact that the pattern of heterogeneity involves large-scale hemispherical differences in structure has been demonstrated recently, including hemispherical patterns of isotropic heterogeneity in the outermost 300 km of the inner core. The presence of these large-scale patterns is baffling, challenging dynamicists and mineral physicists to account for the observations with models involving coupling of the core and mantle dynamic regimes. Super rotation of the inner core has been further studied intensively, with recent estimates converging on a smaller (but still positive) value than the initial estimates.

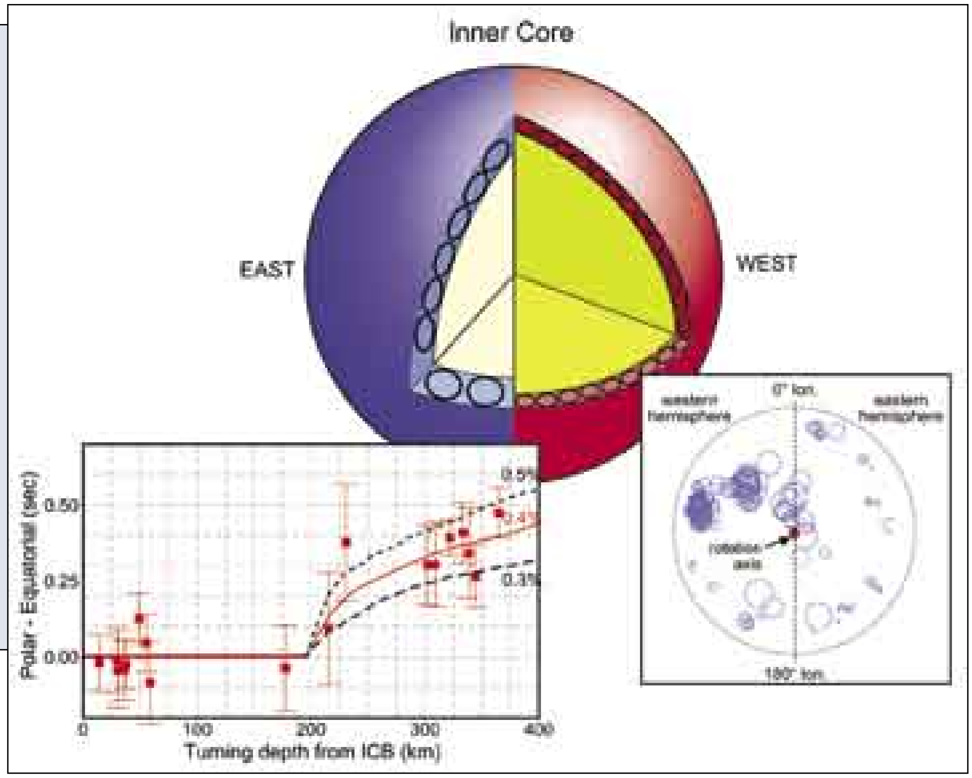
The seismological observations of the inner core, derived from a combination of GSN, PASSCAL, regional network, and ISC observations of core phase arrival times and waveforms, have prompted extensive analysis of high-pressure/high-temperature properties of iron, including mechanisms for developing macroscopic anisotropic fabrics. The rate and mechanism by which the inner core is growing (freezing) over time is the key geodynamic problem, but this is coupled to the energy budget for the geodynamo over time (release of light alloy components upon freezing at the inner core boundary is a major source of buoyancy for driving long-term outer core convection that generates the magnetic field). The presence of an inner core appears to exert a stabilizing influence on the axial dipole and stability of the magnetic field, which should also have varied with time along with inner core growth. Initiation of inner core growth thus serves as a key constraint in mantle thermal evolutionary models and overall heat budget of the planet; high estimates of heat flow through the core-mantle boundary (CMB) imply a very young inner core, but this may be at odds with paleomagnetic observations of ancient geomagnetic field. Data from the IRIS facilities are thus driving research in areas well removed from seismology.

While the outer core appears to be less seismologically complex than the inner core due to its low-viscosity fluid state, as data accumulate there are increasing indications of structural complexity at the base of the outer core and just below the CMB. These regions are likely to be active dynamic environments where chemical and thermal differentiation are occurring associated with the progressive cooling down of the core. Relating seismological features to geomagnetic secular variation and variations in planetary rotation has been an area of significant work in the past few years. Efforts to resolve whether there are any seismically detectable lateral variations between distinct dynamic environments within and outside the axial cylinder are continuing, but as yet the issue is still open.

Seismological investigations of the core-mantle boundary region have revealed remarkable complexity in the structure of the lowermost mantle, extending results available five years ago significantly. Massive coherent regions of low shear velocity beneath the Central Pacific and southern Africa/southern Atlantic/southern Indian Ocean regions previously suggested by mantle tomography models have been

Inner Core Discoveries

Analysis of seismic waves from GSN, PASSCAL, regional networks, and other stations has revealed that the inner core has a heterogeneous, anisotropic structure. Unusual hemispherical patterns in travel times of core phases have been resolved along with anisotropic behavior for paths diving into the interior. An innermost region of distinct anisotropic fabric also appears to exist. Future deployments of stations at high latitudes are of great importance to constraining inner core structure. (Figure provided by Ken Creager, University of Washington, and Lianxing Wen, Stony Brook University.)



revealed to have very abrupt lateral boundaries by studies of GSN and PASSCAL data sets accumulating in the southern hemisphere. These large low shear velocity provinces have only minor compressional velocity anomalies, indicating anomalously high bulk velocity material; normal mode studies suggest that they have relatively high densities. Thus, early characterization of these regions as “superplumes” has been cast in doubt; these appear to be chemical anomalies with uncertain thermal structure. Possible explanations include concentrations of ancient material with geochemically enriched components that may resolve the geochemical requirement of an isolated reservoir, or replenishing accumulations of delaminated oceanic crust swept into piles over the history of subduction to be sampled by plumes and giving rise to distinct chemistry of ocean island basalts.

Other seismological attributes of the lowermost mantle include ultra-low velocity zones (ULVZs) and seismic velocity discontinuities that were mapped using new imaging methods developed for seismic arrays and concentrations of stations such as those being deployed by IRIS for the EarthScope project. With improved resolution and spatial sampling as a result of expanded instrumentation and duration of deployment, the seismic results are motivating extensive mineral physics experimental and theoretical investigation of lower mantle phase equilibria and elastic properties. The discovery in 2004 of a phase change that occurs in magnesium silicate perovskite, the most abundant mineral in the lower mantle, may account for observations of seismological features detected in the lowermost 300 km of the mantle. The geodynamic role of this phase transition may be very significant. Seismologists, geodynamicists, and mineral physicists are coordinating closely on this topic now.

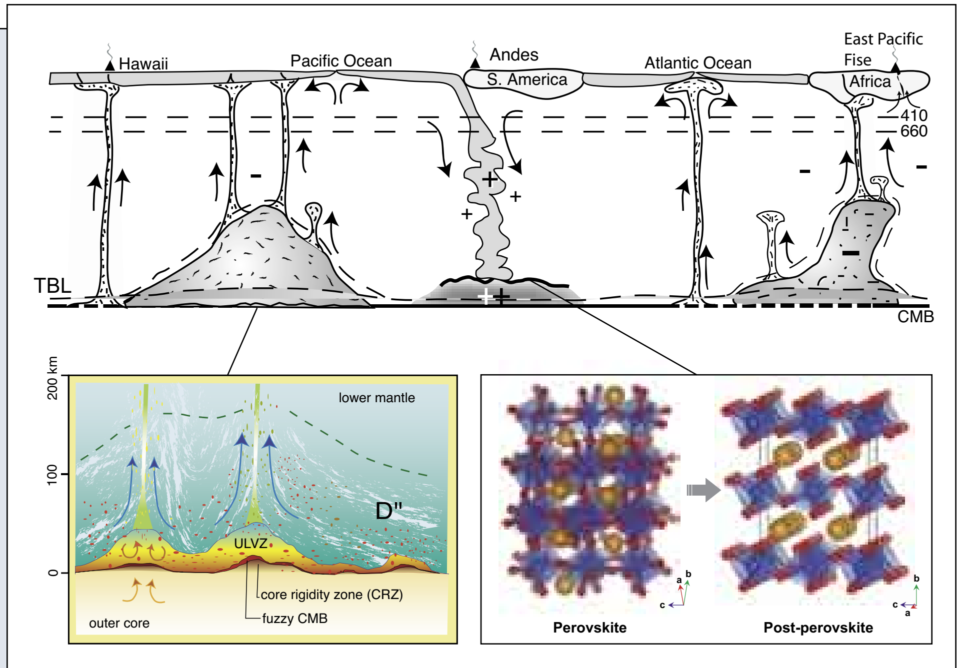
Future progress in understanding the very deep Earth system will require improved data coverage, efforts to reconcile long wavelength structures with fine-scale features resolved on regional scales, application of new imaging methods that exploit increasing data volumes and station density, application of new 3-dimensional wave propagation algorithms, and continued close interdisciplinary coordination on formulating testable hypotheses about the deep dynamical system. Many of the activities identified in this proposal directly address these needs. For example, deployments of new stations in Antarctica, Africa, at ocean observatories, and in the context of USArray, will provide improved coverage of the deep mantle and core, even while primarily intended for studies of shallower structure. Enhancing community interactions between the IRIS Consortium and CIG, COMPRES, and CIDER are also key elements of this undertaking, necessary for meeting the computation, experimental, and interdisciplinary engagement requirements.

Mantle Dynamics

One of the central research topics of Earth science is understanding the configuration of mantle convection, as this governs the nature of plate tectonics and the long-term evolution of the planet’s interior. A five-year update on the seismological contributions to mantle dynamics reveals extensive

Deep Mantle Discoveries

Seismological investigations of the boundary layer at the base of the mantle are revealing complex structures as dramatic as those in the lithospheric boundary layer. Seismic wave data from GSN, FDSN, PASSCAL, and regional networks are contributing to mapping out the complex structures, which include large, low-shear velocity provinces (also see proposal cover figure). Observations of these velocity discontinuities in the deep mantle have motivated mineral physics experiments, which lead to the discovery of a phase transition in magnesium silicate perovskite that yields a post-perovskite phase. (Figure provided by Thorne Lay, University of California, Santa Cruz.)



progress and discovery within the framework of striving to understand the circulation of material in the mantle. Global seismic tomography has long been a centerpiece of IRIS-related research accomplishments; three-dimensional images of large-scale mantle structure have resulted from compilations of global seismic data, with GSN and PASSCAL data available through the DMS playing a central role. Research in this field has continued unabated, and today's generation of global models is pushing the critical envelopes of improved spatial resolution and increasingly sophisticated characterization of anisotropic and attenuation structures throughout the mantle. This is one of seismology's first-order contributions to the understanding of mantle convection. While there has been recent progress in the imaging of downwelling regions near subduction zones, perhaps the highlight of the past few years has been the rapid progress in characterization of upwelling regions enabled by improved global coverage of seismological data sets.

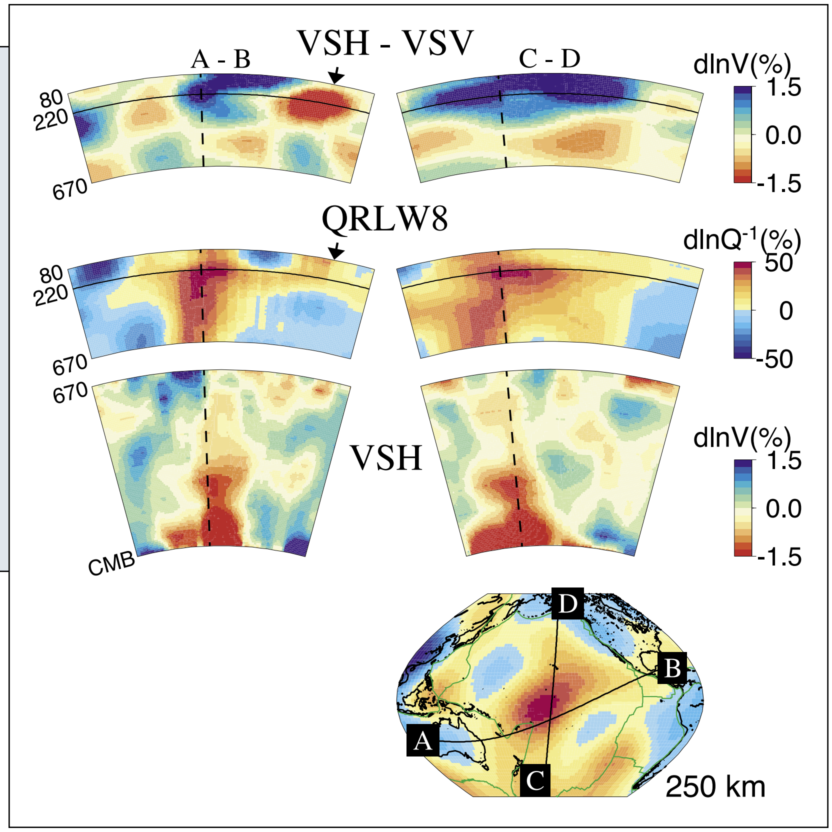
Recent images of low-velocity regions with large vertical extent beneath major surface hotspots have fueled discussion about the scale and heat transport of thermal plumes from the lower mantle. A very diverse Earth science community is involved in the study of hotspot volcanism, and it is fair to say that seismology plays a pivotal role in assessing whether mantle plumes are present or not. Tomographic images and mapping of upper mantle discontinuity perturbations and shear wave anisotropy in the vicinity of major hotspots are areas of intensive research, with continuing debate about the extent of mass transport across the transition zone. Coordinated efforts among seismologists, geodynamicists, and mineral physicists are now commonplace in studies of mantle upwellings, and there is improving mutual understanding of the contributions and limitations of each discipline participating in this effort. While the debates remain intense at present, it is clear that seismological imaging of the interior continues to be an essential element in making progress. IRIS facilities and GSN and PASSCAL data will continue to be critical to improving the seismological quality and resolution of images of mantle upwellings.

Even while evidence for deep-seated origins of surface hotspots has mounted, so too has evidence for the transition zone serving as an impediment to flux of material between the upper and lower mantle. There are significant changes in the spectrum and distribution of heterogeneity across the 650-km seismic discontinuity in the latest generation of mantle tomography models, along with evidence for large-scale accumulation of high-velocity materials in the transition zone beneath downwellings. Although the overall relationship between lower mantle heterogeneities and regions of subduction in the upper mantle revealed in earlier work persists, simplistic models of ready penetration of downwelling slabs into the lower mantle have largely fallen out of favor. Extracting additional information from the seismic wave fields using amplitude and shear-wave splitting information combined with advanced 3-dimensional waveform modeling is one of the current frontier areas for understanding the fate of subducting slabs and their role in geochemical cycling of material in the mantle.

Investigation of upper mantle discontinuities using GSN and PASSCAL data sets and other international seismic data accessible through the DMS is another area of intensive re-

Velocity, Attenuation, and Anisotropy Tomography

Global and regional imaging of material properties in the mantle based on GSN, FDSN, and PASSCAL data is providing increasingly sophisticated models of upper mantle anisotropic properties (top), upper mantle shear wave attenuation (middle), and whole mantle shear velocity (bottom). Relationships among these properties are reducing the ambiguity of interpretation of thermal and chemical causes. (Figure provided by Barbara Romanowicz, University of California, Berkeley. Reprinted with permission from Romanowicz, B. and Y. Gung, *Science* 296(5567):513-516, 19 April 2002. Copyright 2002 AAAS.)



search. Recent observations of low-velocity zones and multiple reflections from the vicinity of major transition-zone discontinuities has stimulated mineral physics and geodynamical investigations of likely phase transitions with new levels of complexity such as inclusion of hydrous phases and consideration of local water saturation and partial melting. The implications of variable reflectivity of P waves and S waves from the transition zone are being pursued, strongly guided by seismic observations. With increasing volumes of data from continental-scale networks, new methods for imaging scattering structures in the upper and lower mantle are being applied, relaxing the requirement of horizontal layering typical of earlier seismic analysis procedures.

The progress in seismological modeling is closely paralleled by progress in mineral physics theory and experimental constraints on upper mantle materials. Progress toward self-consistent models of thermal and chemical structure is being made, but an appreciation of the overall complexity of the volatile rich upper mantle is challenging seismologists to more fully characterize the structure in terms of heterogeneity, anisotropy, and attenuation. The ability to do so is largely data-constrained; continued accumulation of data from observatories and portable deployments continues to be a fundamental requirement.

Lithospheric Structure and Dynamics

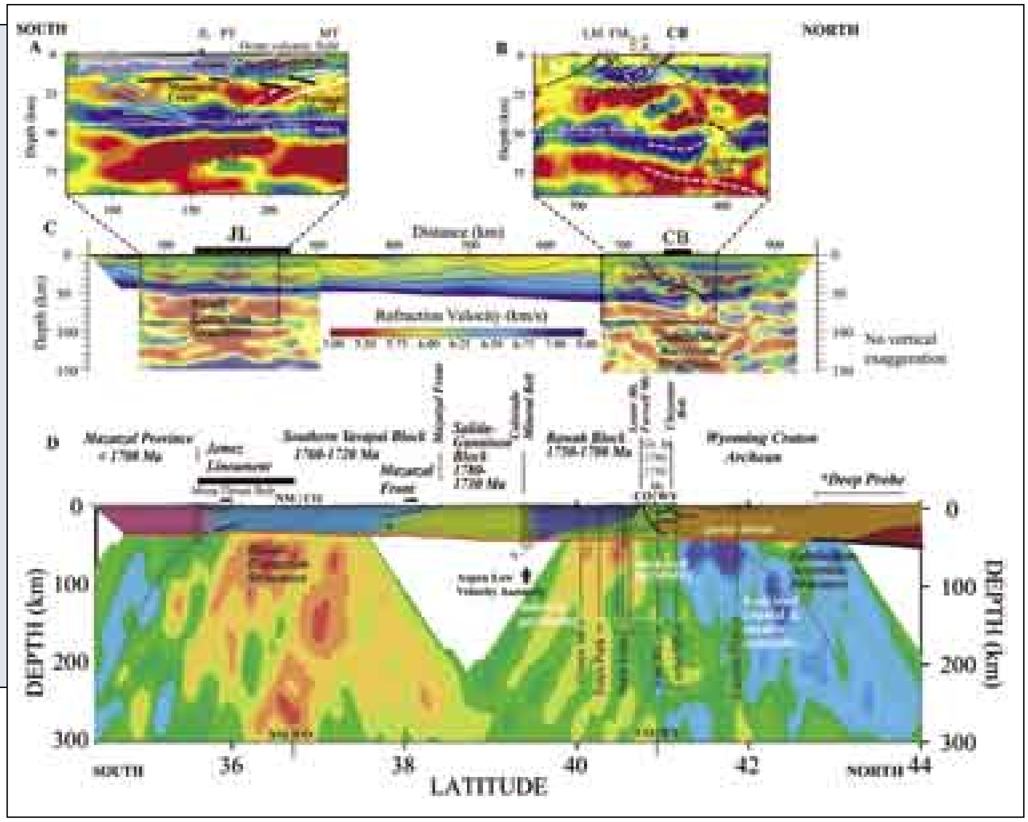
Earth is the only terrestrial planet undergoing plate tectonics, the long-term operation of which will continue to shape the planetary surface upon which we live. The continents record our planet's geologic history, while the present-day oceanic lithosphere reveals the ongoing thermal and chemical nature of the convective system. The continents and oceans provide humankind with all of our hydrologic, biomass, mineral, and most of our energy resources. Thus, characterization of lithospheric structure and dynamics is one of the central efforts of Earth science, from both practical and the intellectual viewpoints, spanning the discipline and bringing seismological results to central relevance for many different research topics.

Numerous seismological approaches contribute to investigations of oceanic and continental lithosphere, and increasingly their transition zones, drawing upon GSN, PASSCAL, and other data sources such as FDSN, ocean-bottom seismometer (OBS) deployments, and pools of additional international instrumentation. Indeed, many PASSCAL experiments are now cooperative ventures involving developed and developing nations. The various data types provide a continuum of scales of resolution from which we gain understanding of complex lithospheric dynamics and Earth history. IRIS facilities are designed to span the suite of instrumentation needs for probing the lithosphere at various spatial scales from the sparse (but global) coverage provided by the GSN, to high-resolution seismic reflection profiling of the upper tens of meters of the near surface with both active and passive source array experiments.

The large-scale framework for lithospheric studies is provided by global tomography and continental-scale studies using large data sets of body waves and surface waves recorded by GSN and PASSCAL instruments. On a global

Multiband Imaging of Lithospheric Structure

High-resolution imaging of lithospheric structure of the Jemez Lineament in New Mexico is being enabled by PASSCAL data processed with combined reflection, refraction, and receiver function migration approaches. Such imaging is revealing relationships between crust and mantle deformation and is allowing integrative interpretation with geological, geochemical, and geothermal information. (Figure provided by Alan Levander, Rice University.)



scale, the upper 250 to 400 km of the shear velocity variations in the Earth are now well imaged at scales of 1000 km and longer, with regional studies bringing the resolution down to 200 to 500 km. This scale highlights the contrasts between oceanic and continental lithosphere, and the differences among Archean cratons, their Proterozoic girdling belts, Phanerozoic mobile belts, and currently tectonically active regions of the continents and their margins. PASSCAL experiments address the finer scales, 0.1 to 500 km, examining the crust and mantle structures of the transitions between oceans and continents, Archean cratons and mobile belts, stable crust and rift zones, as well as determining details of deformation in seismogenic zones through highly detailed microearthquake location. Seismological images are increasingly combined in multidisciplinary investigations with petrological studies of xenoliths, age-dating, geochemical signatures, mineral and petrophysical data, heat-flow measurements, geodetic observations, and balanced structural geology cross sections. Together they identify lithology, estimate lithospheric thermal structure, reveal the nature of deformation in mountain building, and relate the mechanical coupling of the continental crust and lithospheric mantle to the underlying mantle flow system. Similar multidisciplinary data sets are incorporated into models of evolution of oceanic lithosphere from melting processes near the ridge to hydrothermal and conductive cooling as the plate spreads, to deformation and recycling of material in subduction zones. They are used to assess the role of progressive chemical differentiation of material that passes through the ridge and subduction zone thermo-chemical factories. These studies also form the current state of the art in unraveling Earth's dynamic 4.5 Gyr history as preserved in continental landmasses.

High-resolution imaging of the lithosphere requires dense deployments, and a host of international PASSCAL experiments have touched all continents during the past five years. The finer-scale active and passive investigations image structures associated with specific geologic processes, such as lower-crustal upper-mantle delamination, subduction erosion, melt migration, fold and thrust development, and the strain rate and thermally dependent transition from brittle to ductile behavior in the lithosphere. Seismological studies have continued on all of Earth's great orogenic plateaus, such as Tibet, the Altiplano-Puna in South America, and the western United States. In Tibet, surface-wave tomography, regional phase attenuation, shear-wave splitting, and receiver functions are being merged with other geological and geophysical observations to investigate crustal deformation, regional metamorphism, and uppermost mantle control on plateau evolution. Evidence of significant partial melting of the middle crust, and possibly the lower crust, as well as the presence of melts or other fluids concentrated at the base of the upper crust has emerged in a region having extensive crustal heterogeneity at all scales. These observations support interpretations of deformation concentrated in a semi-fluid middle crust, which would accommodate the ongoing continental collision. Investigation of young continent-continent collision in eastern Turkey is being undertaken to address the early phases of evolution of a structure such as Tibet.

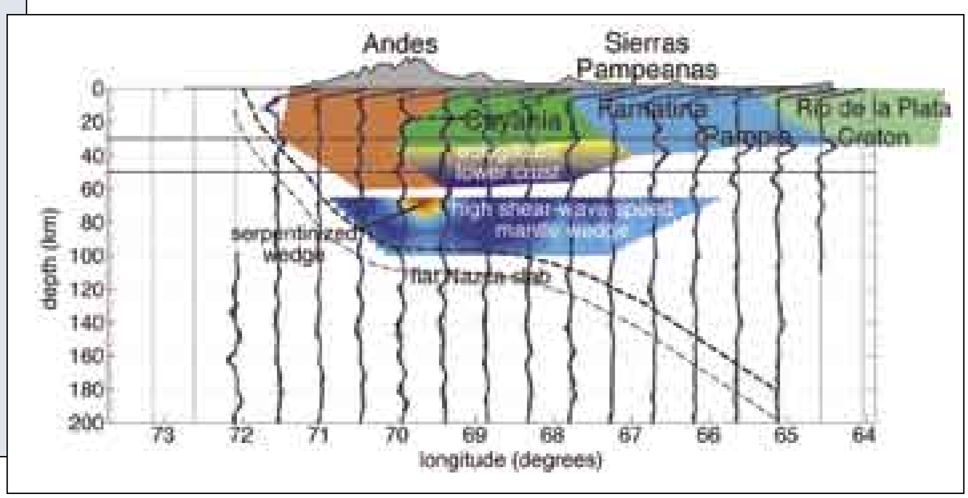
Numerous PASSCAL experiments over the past five years have addressed lithospheric processes in the western United States. Several investigations have focused on plateaus and their peripheries, in particular, detailed investigations of the evolution of the southern Rocky Mountains and the Jemez Lineament, the Rio Grande rift, the northwest Basin and Range, the Yellowstone hotspot, and the southern Sierra Nevada. There have also been extensive investigations in the Cascadia forearc region to assess earthquake hazards. These efforts have also been multidisciplinary, attempting to unravel the history of continental construction, including the details of the mantle convection system, crustal evolution during continental rifting, the secular variation of crust and mantle structures resulting from hot spot volcanism, and the crust-mantle consequences of lithospheric delamination. In many instances, geodetic measurements or analysis of geochemical signatures of xenoliths were studied in combination with the seismic images to explore the details of particular crust-mantle processes.

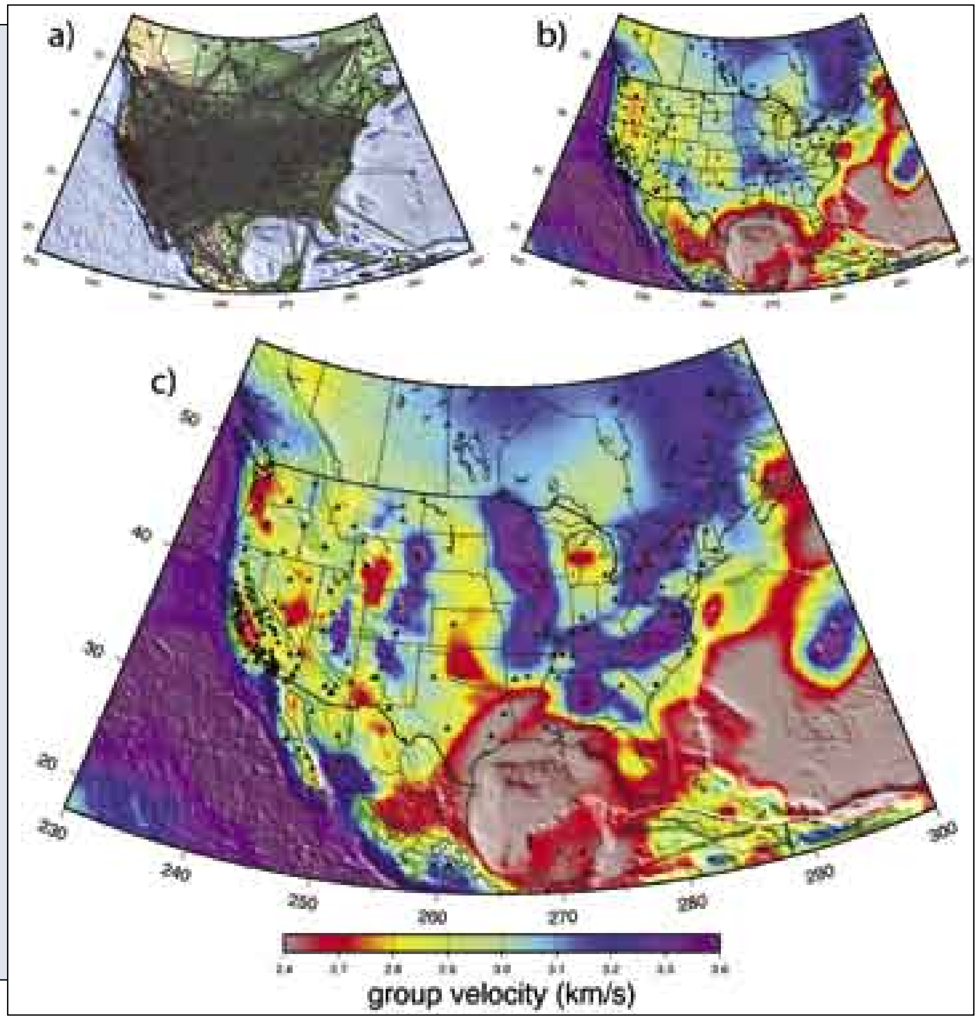
From the forearc of the Cascadia subduction zone (illuminated by the SHIPS project in Cascadia), inland to the CANOE transects across northwestern Canada, 4 billion years of geologic history are traversed, extending from a modern subduction zone to a region built in the Archean and subsequently accreted to during the Proterozoic. Highly detailed seismic images are driving geodynamic simulations to discern the difference between thrust-stacking models and differentiation-in-place models for stabilization of cratons. The thickening of crust—from 30 km beneath the Basin and Range to 50 km beneath the Rocky Mountains and Great Plains, and its consequences for upper mantle structure, continues to be a focus of investigation. Receiver function migrations and travel-time tomography are being brought to bear on this transition. Underplating and crustal melt injection are locally involved in parts of the Rockies and Basin and Range, whereas on the southwestern periphery beneath the southern Sierra Nevada, lithospheric foundering involving garnet-rich crustal material appears to be occurring. Seeking an understanding of why the northwestern Basin and Range has very thin crust despite little crustal extension, has been the focus of active- and passive-source seismology experiments, low-temperature geochronology, Ar-Ar geochronology, and geologic mapping. The thick crust of the Colorado Plateau and Southern Rocky Mountains has evaded the localized thinning concentrated under the Rio Grande rift, which has low shear wave velocities extending down to at least 150 km depths. High-resolution reflection, refraction, and migrated receiver function imaging of the Jemez Lineament suggests that Proterozoic suture zones originating during continental accretion provide crustal ascent routes for basaltic magmas arising from extensive modern melt systems in the upper 150 km of the mantle. Large-scale deformation and thermal rejuvenation of the lithosphere in the apparent wake of the Yellowstone hotspot is the focus of several investigations of travel times, shear-wave splitting, and receiver functions. These regional studies reinforce the impression of enduring multiscale deformation occurring throughout a diffuse Pacific-North American plate boundary. Seismology provides only a snapshot of structure related to a geologic process. Investigations of various stages of delamination in other areas, such as Romania, and thrust stacking or subduction structures under Scotland, central Europe, and the Tien Shan, will further address the question of stability and evolution of continental lithosphere.

Eastern Africa continues to be a target for PASSCAL deployments due to the opportunity to observe active continental disruption via mantle-controlled continental rifting. Studies of seismic wave velocities and attenuation in the upper mantle under Tanzania, Kenya, and Ethiopia are explor-

Cross-Disciplinary, Multiple-Experiment Data Analysis

Several types of data analyses from the PASSCAL experiment CHARGE, including receiver functions and mantle S-wave tomography, together with information from diverse Earth science studies, were used to answer geodynamically driven questions about subduction chemistry and dynamics of the Nazca Plate in the Sierras Pampeanas region. (Figure provided by Hersh Gilbert, University of Arizona.)





Ambient Noise Inversion

Innovative processing of background noise signals reveals coherent surface wave signals that can be exploited to resolve crustal heterogeneity on very fine scales for all seismic station deployments, including GSN, PASSCAL, ANSS, and regional networks. Coverage from "rays" along paths between seismic stations (upper left) is dense and nearly homogeneous across the most of the United States, especially compared to coverage from the ideal situation for classical studies, which requires earthquakes aligned with paths between a pairs of stations to correct for phase at the sources. Thus, a dispersion map for 16 s period Rayleigh waves obtained using ambient noise signals (bottom) suffers less from numerical smoothing and shows more short wavelength features than a dispersion map based on teleseismic earthquakes (upper right). (Figure provided by Michael Ritzwoller, University of Colorado.)

ing the interaction between an ascending plume and continental lithosphere. Global tomography in this region appears to trace the plume back to the core-mantle boundary, far to the southwest near the southern Mid-Atlantic Ridge. This is an excellent example of mantle influence on the crust arising from deep-mantle processes hundreds of million years ago. P-wave tomography reveals strong velocity variations between 150 and 400 km depth beneath Ethiopia, with low velocities shifting to the west beneath Kenya and dipping westward beneath the Tanzania craton. Increasing the number of permanent stations in Africa will enable major enhancements in the large-scale imaging for Africa, which serves as a context for these regional investigations.

There is also increasing appreciation of the remarkable complexity of the subduction factory, particularly for the role of volatiles in the mantle wedge and how they affect the mineralogy, melting processes, and deformation. Studies of seismic-wave arrival times, shear-wave splitting, receiver functions, and attenuation have been conducted in Cascadia, Alaska, Japan, Costa Rica, New Zealand, Chile, Izu-Bonin, Tonga, and the southeast Caribbean. The strong heterogeneity and complex geometry of subduction structures in these regions prompt the development of new and efficient imaging techniques and migration procedures (Kirchhoff, plane wave, and Generalized Inverse Radon Transform depth migrations). From the subduction beneath central Alaska (which maintains a very shallow dip and is frequently not accompanied by arc magmatism), to regions of flat slab beneath Central Chile and Argentina (where thickened crust extends 200 km east of the Andes mountains), to Middle American subduction zone (where along-strike changes in the subducting slab appear to affect coupling and volcanism), a wide variety of subduction environments are being investigated. The Denali region in Alaska is particularly interesting as it is one of Earth's few 6000 m peaks associated with transpression and the site of a Mw 7.9 event in 2002. Notions of a serpentinized mantle wedge developed from high-resolution teleseismic migrated images in Cascadia have been applied to subduction environments elsewhere, with the importance for seismic coupling and maximum earthquake size being assessed. The potential onset of subduction along the eastern seaboard of North and South America is also the subject of both active and passive seismic investigations, including estimating seismic velocity heterogeneity, identifying the lithosphere and asthenosphere boundary, shear-wave splitting, and assessing crust mantle coupling.

Crustal structure and heterogeneity is now even being resolved from seismic noise. Innovative analysis of ambient seismic noise, using methods referred to as "daylight" or diffuse wave imaging, allows high-resolution determination of short-period surface wave dispersion across regional networks. This technique is yielding unprecedented maps of crustal heterogeneity determined from both permanent and temporary seismic deployments. Coupled with receiver function depth migrations of teleseismic signals, there is now the prospect of extending the framework characterization of lower crust and uppermost mantle structure down to the 5 to 10 km scale, within which high-resolution active experiments can define detail at the scale of geological processes.

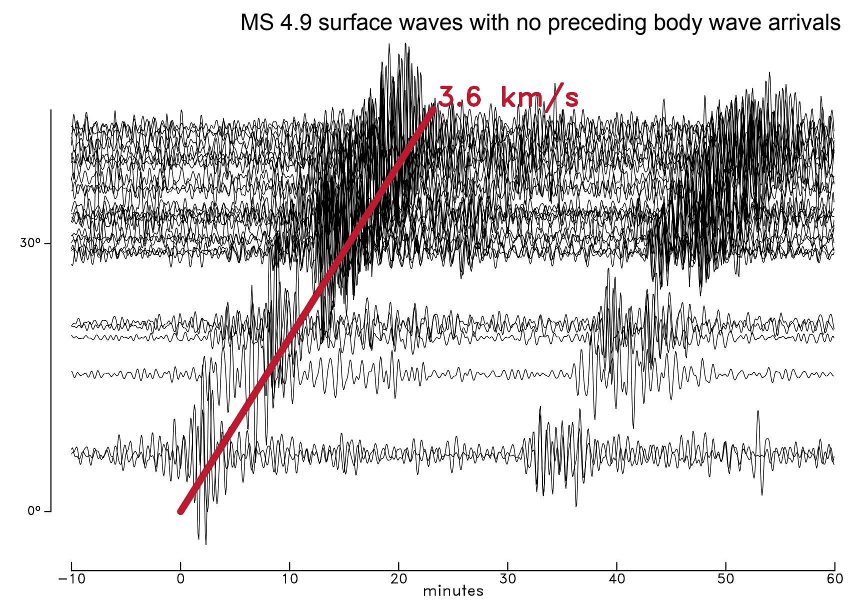
Looking to the next five years, one can confidently anticipate a steady flux of results on all scales of lithospheric investigation. These results will come from the slate of scheduled PASSCAL deployments around the globe; the infrastructure development underway to support experiments in polar environments; the innovative use of expanding data sets for migrations, scattering analysis, and ambient noise analysis; and analysis of global- and regional-scale observations for complex aspects of material properties such as anisotropy and attenuation. The fundamental problems of lithospheric evolution and dynamics cannot be addressed in any single region or by using any single data-collection strategy. Moreover, the crust and mantle are closely linked and the processes involved are multi-scale. For example, mantle forces drive crustal response in compressional environments; crustal inputs modulate mantle structure and melting in subduction zones; and crustal phase changes drive delamination events with surprising consequences for both the crust and mantle. Only by sustaining a global perspective, and exploiting data collection in diverse tectonic environments that are at different stages of evolution, can we hope to the solve major problems of continental evolution, including interaction of plate tectonics with the deeper mantle circulation system, hotspot volcanism, crustal thinning and thickening, and related processes that govern the geologic history of the continental crust.

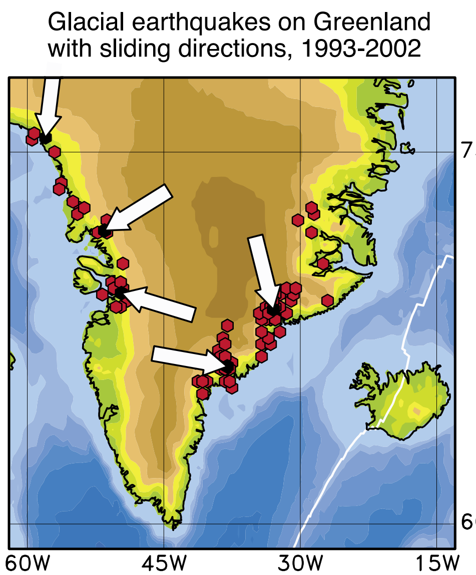
The diversity of instrumentation in the PASSCAL pool provides a rich facility for investigations that span a wide range of areas of Earth science. In addition to fundamental studies of evolution of the origin of Earth's lithosphere, PASSCAL experiments, especially with Texans and multichannel instrumentation, also play a vital role in a wide variety of more pragmatic, high-resolution studies. PASSCAL investigators are identifying the location of groundwater resources; mapping the flowpaths of subsurface contaminants that threaten water supplies; complementing trenching evidence with reflection seismic interpretations in paleoseismic studies of historic great earthquakes; mapping basin structure and response, especially in urban areas of seismic risk; and using sequence stratigraphic principles to corroborate sedimentation rate changes associated with paleoclimatic change.

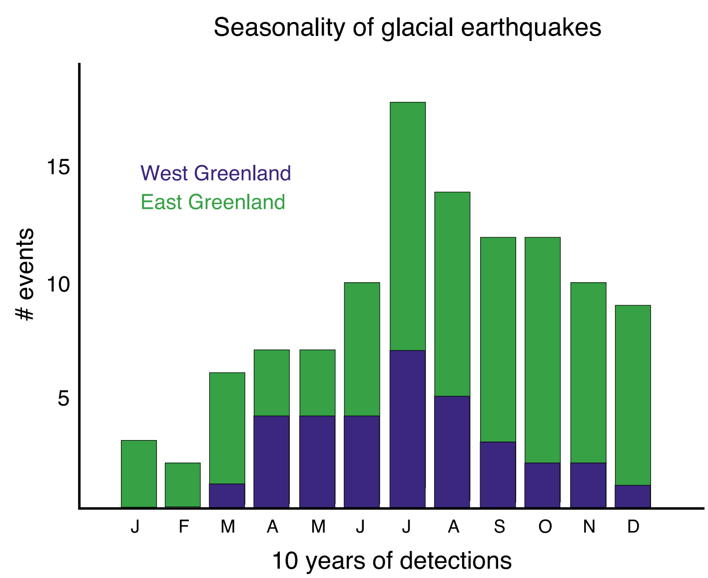
Earthquake Faults and Ruptures

The science of earthquakes—understanding the processes by which earthquakes nucleate, how ruptures grow and how they arrest, and how stresses evolve before, during, and after earthquake occurrence—is one of the fundamental topics of Earth science. Seismology plays an obvious and important role in studying these phenomena; the elastic waves radiated during fault sliding provide key information about the process. Observation of elastic waves for all scales of earthquake processes has long been a driver of seismological instrumentation capabilities, motivating robust calibration, high dynamic range, and adequate bandwidth. The global occurrence of earthquakes mandates global deployments of seismometers for scientific investigation and monitoring, but the multi-scale nature of earthquake processes further motivates flexibility of instrument deployment for local densification near faults; borehole deployments to gain fidelity of the recordings; and long-term operation to assess background interseismic behavior, coseismic behavior, and postseismic behavior. IRIS has designed its facilities to accommodate those needs for earthquake research that are not met by established monitoring operations of the USGS or other agencies.

The past few years have seen an evolution of earthquake science, embracing the laboratory-based notions of state- and rate-dependence of rock friction, along with the recognition of short- and long-range stress interactions between faulting events. The occurrence of the great Sumatra-Andaman earthquake dramatically reinforced notions of fault-zone heterogeneity and variable time scales of rupture processes on faults. The massive data set from GSN and FDSN stations for the Sumatra earthquake combines with extensive geodetic, hydroacoustic, T-phase, infrasound, and geological observations to provide our first opportunity to analyze the detailed process of a truly massive earthquake. And, as one might expect for a 1300-km-long rupture, all those observations, which sense different aspects of the rupture process, are revealing a complex process with variable rupture velocity, slip ranging from 0 to 30 m on the fault plane, and time scales of sliding ranging from seconds to an hour or more. Yet, even as the analysis proceeds, the fundamental issues of what causes slip and stress heterogeneity on faults, and the extent to which geometrical segmentation and variations in hydrologic condition, material properties, and residual stress from prior events control the rupture process remain with us. Advancing understanding of the nonlinear dynamical system of individual faults and fault systems requires sustained seismological observations on many scales; this is the precise need that IRIS facilities continue to fill.







Exotic Source Detection

Seismic waves excited by processes distinctive from standard earthquake faulting can be detected and characterized by analysis of continuous recordings using global search algorithms. Here GSN and FDSN surface wave signals generated by glacial sliding events in Greenland are detected and the sources quantified despite the absence of short-period body wave signals. Earthquakes with unusually long source process time can be detected by similar methods. (Figure provided by Goran Ekstrom, Harvard University.)

In many ways, IRIS facilities and the IRIS Consortium have been preparing for the Sumatra-Andaman earthquake since the first stations of the GSN were installed. The design goals of the GSN were created with the objective of capturing great events in real time, on scale, with high dynamic range, and with ultra-broad bandwidth. Largely, these goals have been met. Additionally, the data from GSN stations have become integral to the earthquake monitoring missions of United States and international agencies, illustrating the dual use of a facility deployed for fundamental research purposes. This dual use has been supported by the IRIS commitment to the free and open exchange of data in real time, a commitment underlying each of the IRIS facility programs.

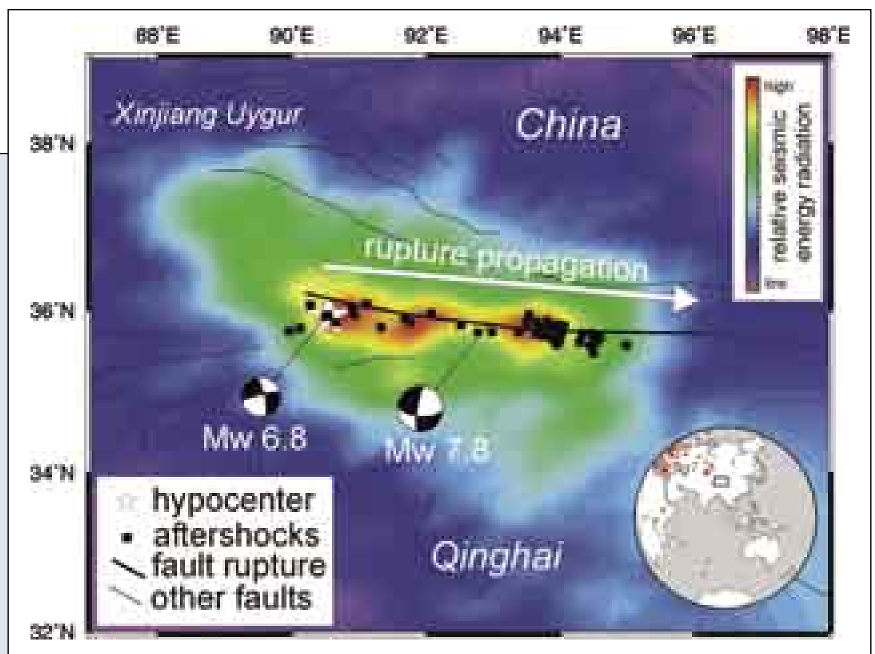
The GSN recordings of the Sumatra-Andaman earthquake will yield benefits in the basic science of earthquake rupture and tsunamigenesis. But, a somewhat unanticipated benefit has been the degree to which affected countries and regional organizations are looking to IRIS facilities as models for the backbone of regional tsunami early warning systems. At a time when global Earth observation is receiving renewed attention across the Earth and environmental sciences, the IRIS model of a research-driven facility serving multiple users has great resonance.

Although observations of the Sumatra earthquake encapsulate the complexity of earthquake faulting in a megathrust environment, recent strike-slip faulting earthquakes further reveal our limited understanding of faulting processes in general. The past five years brought the long-awaited rupture of the Parkfield segment of the San Andreas Fault, probably the most intensively studied fault zone on the planet. And yet, when the earthquake occurred, more than a decade outside of the original prediction window, the rupture surprised many by nucleating and propagating differently than expected, with northward rupture propagation. The largest earthquake to strike American territory since 1964 involved strike-slip faulting on the Denali fault in an event that both demonstrated the success of the Alaskan pipeline's engineering design, but also produced mysteries by inducing seismicity across the Basin and Range province many fault lengths away. A large strike-slip fault in northern Tibet ruptured with a large segment apparently failing with a rupture velocity faster than the shear velocity; this is, perhaps, the best documented example of supersonic rupture yet. A large rupture in the mid-Indian Ocean appears to have a source duration of more than a minute, but with most moment release concentrated late in the rupture. Coupled faulting on parallel transform segments in the Pacific Ocean has also been documented. The largest swarm of earthquakes yet recorded involved strike-slip and normal faulting in the Andaman back-arc basin, a burst of activity that followed the great Sumatra-Andaman thrust event. These observations, all subjects of detailed investigation using GSN data, reinforce the importance of long-term observations of earthquake processes for basic scientific research aside from the monitoring and hazard perspectives.

PASSCAL deployments along subduction zones have continued to play critical roles in characterizing fault-zone geometry and aftershock behavior. Deployments along Central America reveal complex along-strike variations in the depth range of the seismically coupled interface. Simultaneous observation with continuous GPS measurements are contributing to efforts to establish procedures for mapping the up-dip and down-dip transitions to non-slipping portions of the plate interface. Similarly, observation of episodic creep events in Cascadia accompanied by increase in seismic tremor have prompted a whole new class of coupled geodetic and seismic deployments to constrain deformation processes down-dip of the seismically coupled interface.

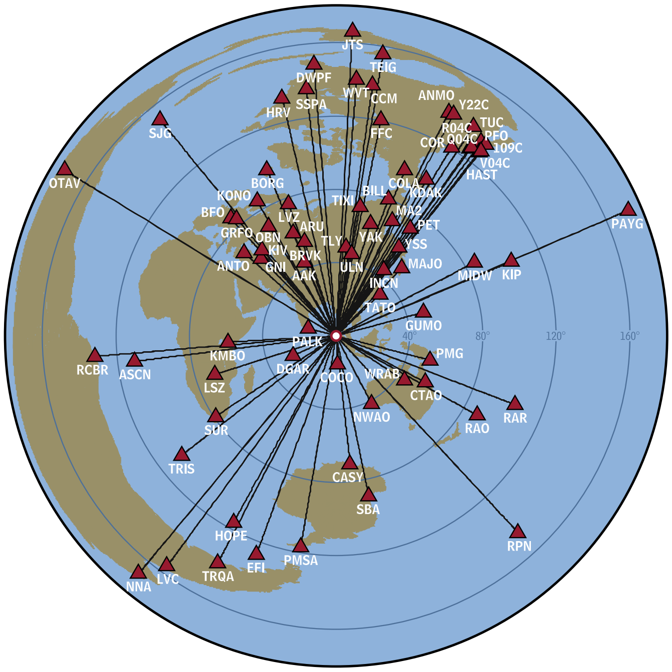
One of the most basic of seismological practices, locating earthquakes, has undergone rapid advances in the past five years, exploiting large earthquake waveform data bases such as those provided by the DMS. Cross-correlation of waveforms and new methodologies for relative event location have revealed far greater occurrence of earthquake clustering and earthquake lineaments than had ever been recognized. Remarkable aspects of earthquake faulting are emerging that had been obscured by event mislocation. These developments prompt new strategies for locating events that require having massive databases online and available for comparison with signals from new events. Some of the strategies for the DMS development in the next five years will abet this new direction in earthquake location research.

Availability of continuous seismic recordings also plays a key role in new research efforts to characterize the steady vibration of the Earth induced by coupling among the atmosphere/ocean/solid Earth systems. The potential for constraining statistical attributes of otherwise difficult to characterize oceanic circulation systems is leading seismology into new interactions with communities that have not previously used



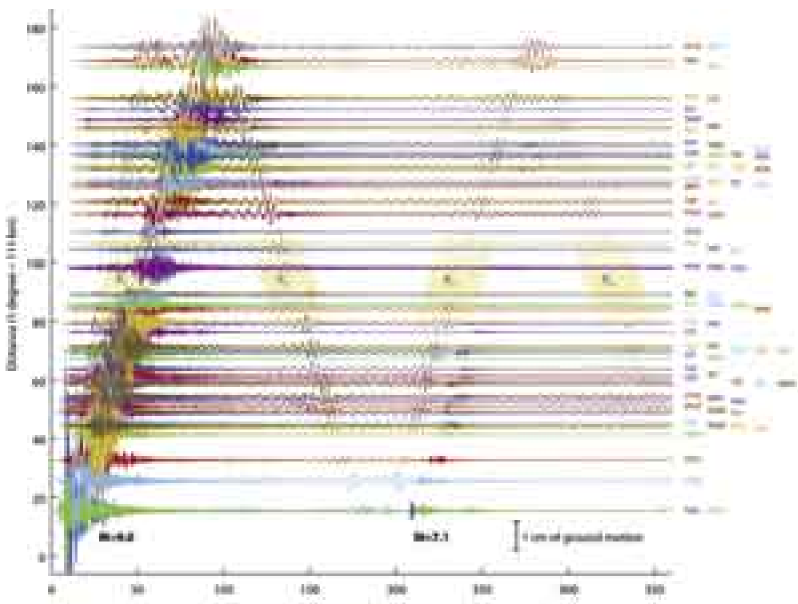
Supershear Rupture

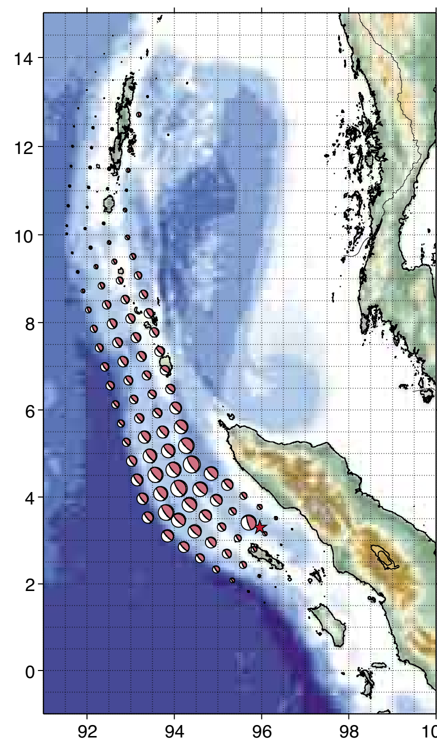
GSN, FDSN, and PASSCAL data provide critical information for analyzing rupture process of large earthquakes. For some events, like the Kokoxili (Mw=7.8) earthquake of northern Tibet, surprising aspects of the rupture are revealed by both broadband and short-period recordings, in this case an interval of the faulting that ruptured with higher velocity than the crustal shear velocity. The occurrence of a supershear velocity rupture for large strike-slip earthquakes reveals attributes of the faulting process that are now also being investigated in laboratory experiments. (Figure provided by Kris Walker and Peter Shearer, University of California, San Diego.)

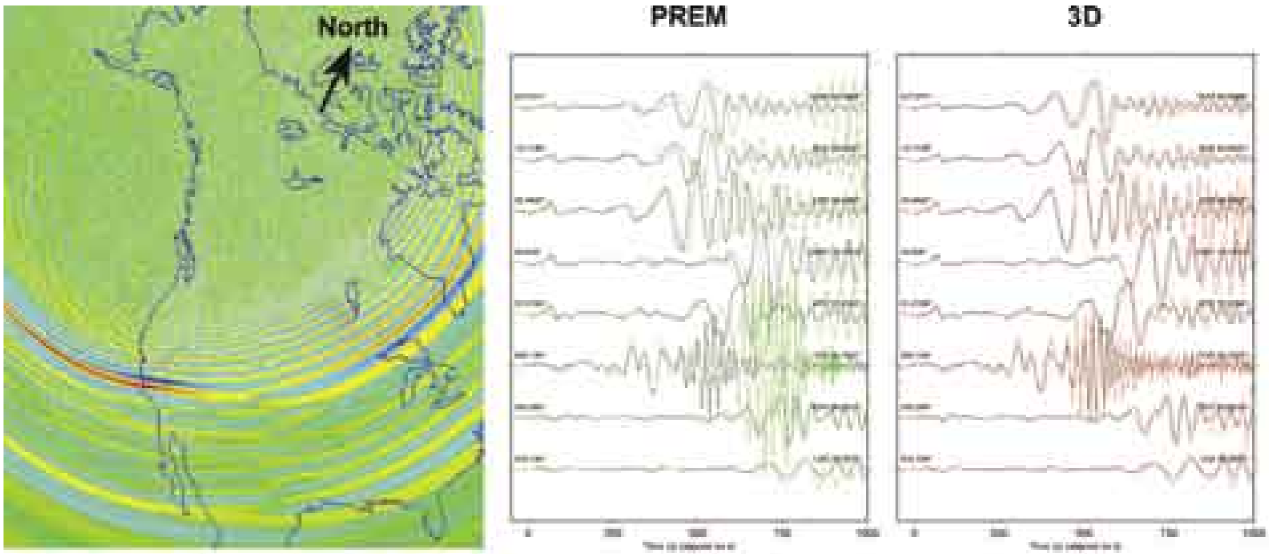


Great Earthquake Vibrations

The December 26, 2004 Sumatra-Andaman earthquake produced global seismic vibrations captured by the GSN and FDSN stations; providing by far the best data set ever for a great earthquake. Many of the GSN signals are used routinely in operational efforts of the USGS National Earthquake Information Center and the NOAA Pacific Tsunami Warning Center. These real-time data were critical for rapid characterization of the earthquake's size. The same data have been used in subsequent analyses of the rupture process, aftershock events, and investigations of Earth structure. (Figures [left top and bottom] provided by Rick Aster, New Mexico Institute of Mining and Technology. Figure [bottom right] provided by Hong Kie Thio, URS Corporation and Charles J. Ammon, Pennsylvania State University.)







Full Wavefield Simulations

For the past 20 years seismologists have been developing three-dimensional aspherical models of mantle velocity structure based on analysis of GSN and FDSN data. Calculation of the response to models of earthquake ruptures in these 3-D structures is now possible using large computer clusters and advanced wave propagation codes. This example shows Spectral Element Method computations of complete ground motions for the 2002 Denali earthquake, compared to ground motion recordings from GSN stations. It also shows the improvement obtained by using a 3-D tomographic model compared to even the best 1-D reference models. The ability to closely match the complete wavefield with tomography-based models is allowing the development of entirely new strategies for quantifying earthquake rupture processes. (Figure provided by Jeroen Tromp, California Institute of Technology.)

seismological observations. Numerous efforts are also underway to exploit the increasing distribution of seismic observations to quantify microseism origins, identifying and locating storm systems and other processes that produce what is usually derided as “background noise.” Systematic processing of continuous records also reveals unexpected sources, such as glacial sliding events. These events radiate seismic waves that are predominantly long period, and hence not located in standard earthquake bulletins. Research using GSN and PASSCAL recordings plays an important role in developing techniques for characterizing different types of sources, for example, distinguishing among quarry blasts, rock bursts, and mining collapses. Such advanced source-characterization capabilities are essential for monitoring of nuclear testing treaties.

Determination of the presence and geometry of faults at depth and the *in situ* properties of the fault zone is an essential step in both fundamental earthquake science and in seismic hazard assessment. Active and passive PASSCAL experiments in urban areas are essential complements to surface geological investigations. High-resolution investigations are needed for detecting blind thrusts and other earthquake-capable structures, as well as for investigating site effects associated with basins, topography, and geologic structures. Steeply dipping faults present serious challenges to seismic imaging, but progress has been made, notably on the San Andreas Fault near Parkfield, by using combinations of surface and borehole sensors and migration schemes designed to retain information about steeply dipping structures. PASSCAL deployments have played a key role in analysis of guided waves within fault zones, which provide sensitivity to fault zone properties at depth.

Under the National Earthquake Hazards Reduction Program, NSF supports fundamental earthquake studies, research on global seismicity, and investigations of earthquake source physics. The IRIS facilities comprise only one component of this multidisciplinary effort, but GSN and PASSCAL data are an essential element. GSN data are extensively used in the determination of centroid moment tensors and in earthquake rupture studies for events around the world. PASSCAL instrumentation is used in many focused studied that address Earth structure and fault-zone environments that contribute to earthquake science well beyond regional network data. DMS databases and pathways to global data sources abet research on earthquake science both nationally and internationally. Overall, IRIS facilities can legitimately be viewed as a major NSF contribution to earthquake science.

The Next Five Years

Over the next five years, IRIS plans to support groundbreaking research in seismology, and in Earth sciences more generally, by innovative development and continued operation of its four core programs: GSN, PASSCAL, DMS, and E&O. Much as these programs were envisioned twenty years ago as the infrastructure needed for genuinely novel advances in seismology, so now these programs collectively provide facilities to enable further progress in mitigating natural hazards, in sustainable development of our society and economy, and in satisfying our innate curiosity about Earth.

This section summarizes the activities proposed to advance the governing themes of this proposal, and identifies new initiatives for the Consortium and each of the four core IRIS programs. Additional details can be found in the individual program descriptions later in this proposal and in the budget section. In most cases, the budget structure assumes that the activities proposed will be supported through direct core funding from the Instrumentation and Facilities Program of the Earth Sciences Division, as the primary source of funding for IRIS. In some cases, only partial support is requested with the intent of leveraging funding from other potential sources. In all cases, IRIS is prepared to work with NSF to develop alternate and/or complementary support to maximize the return of the NSF investment to advance observational seismology.

The Roles of a Cornerstone Consortium

From its launch, the primary goals of IRIS have been to establish facilities to deploy and operate a global seismographic network, to provide quality portable instrumentation for temporary deployments, and to archive and manage the collected data. These facilities are now mature and integral to the conduct of Earth science research. The centrality of the facilities to Earth science requires this core functionality to continue. But it also generates opportunities to leverage and build upon their success.

In the next five years, IRIS will leverage this cornerstone position to achieve new efficiencies and capabilities in the core programs, enable transformative scientific collaborations, strengthen existing institutional partnerships, enable new partnerships and initiatives, and contribute to efforts to improve diversity in the Earth sciences. IRIS will also provide the resources and framework for its members to develop new science education tools, partners, and programs, responding to fundamental NSF objectives in science education. By ensuring the strength of its cornerstone position, IRIS will also contribute to the domestic and international programs for global geophysical monitoring, and natural hazard risk reduction.

Transforming Earth Science Through Multidisciplinary Integration

Many questions in Earth science are now holistic, and answering them requires a systems approach combining multidisciplinary perspectives with the assimilation of data across disciplinary boundaries. Integration reduces ambiguity by using complementary observations and modeling to provide cross-disciplinary constraints. With IRIS providing cornerstone facilities and capabilities, seismology has secured a role as a central discipline for integrated studies of Earth processes.

Seismologists make contributions to integrative Earth science by being able to target diverse geologic structures, scale lengths, and regions of the Earth, as needed, with the appropriate combination of instruments and passive or active sources. When the capabilities of different instruments and experiment configurations are well understood, they can be brought to bear as part of the suite of techniques and observa-

Engaging Earth Science Communities

Through IRIS, the seismological community has embraced fundamental ways of working—including free, open data access and shared pools of instruments—that have shaped the science for the better. The IRIS model has been so successful that it has served as an example for the organizational structure of other geoscience communities.

Some organizations, such as UNAVCO, COMPRES, GEON, OBSIP, CIG, and EMSOC, are comprised of scientists from other disciplines who see the benefits to seismologists from shared facilities, such as the PASSCAL instrument pool and the DMC, and have formed consortia or evolved their structure to develop analogous facilities for their own disciplines.

Some programs, such as EarthScope, have components that build on the strong base of IRIS facilities and the broad consensus approach (USArray), but have been extended to include other disciplines (PBO and SAFOD). These efforts are able to start off more quickly and on a larger scale by building on existing capabilities rather than by starting from scratch.

Smaller programs with more tightly focused interests, such as AfricaArray, might have difficulty justifying some of the facilities that they would require, but find that they can make use of IRIS facilities to progress rapidly towards their own goals.

Together with other geoscience infrastructure programs, IRIS provides data that benefit research centers with complementary goals and overlapping membership, such as SCEC and CIDER.

tions needed to explore Earth systems. In turn, the need to understand systems at different scales and in different locations drives improvements to seismological techniques and IRIS facility operations.

The workings of the PASSCAL program illustrate IRIS's ability to facilitate integrative research. The capabilities of PASSCAL instruments and the potential science that can be done with them are well known within the seismological community: different combinations of instruments and deployment topologies can be combined to explore different parts of the frequency-wavenumber spectrum for well-defined geological and geodynamic targets. With this understanding, seismological experiments can be tuned to the hypothesis, rather than be restricted to the resolution offered by permanent stations or fixed networks. Over the history of the PASSCAL program, Earth scientists in complementary disciplines have also come to understand the capabilities of the PASSCAL instrumentation, and have been able to propose innovative instrument deployments designed to address problems, rather than pose questions that can be addressed within instrumental constraints.

IRIS also enables integrative science by explicitly reaching out to other disciplines and communicating the capabilities of the facilities and the potential of the science that can be done with them. To encourage disciplinary cross-talk, IRIS makes a point of inviting scientists representing other Earth science disciplines to give keynote addresses at each annual workshop. For example, the last several workshops have explored the integration of satellite geodesy with seismology to study new classes of Earth tremor; the constraints posed by mineral physics and petrology to study the deep mantle; and combined seismological, geodetic, and petrologic studies of volcanoes. Other sessions have shown how ultra-high-resolution deployments can address problems in soil hydrology and pollutant dispersion.

IRIS further contributes to integrative Earth science by disseminating comprehensive open and standardized data management solutions and working with ongoing projects in information technology. For example, the DMS works with the Southern California Earthquake Center-Information Technology (SCEC-IT), Geosciences Network (GEON), and Digital Library for Earth System Education (DLESE) groups, among others, in exploring some of the application frontiers in information technology support for Earth science research and education. The DMS also practices an open-door policy in working with other groups collecting geophysical data, offering insights and help in modern data management and, in many cases, physically archiving the data.

One outcome of these discussions is that the IRIS model of a community-based consortium with open governance and standards-driven data acquisition and management is proving attractive to a number of continuing and nascent initiatives in community organization. In areas such as hydrology, infrasound, and ocean observation, IRIS has been both a literal and figurative model for other organizational efforts. In some cases, the investments that IRIS has made in data and instrument management have provided useful starting points for other communities trying to self-organize around diverse technologies for Earth observation. In providing formal and informal mentoring, IRIS also promotes eventual integration for scientific research.

In the next five years, IRIS will continue to expand its open-door policy supporting integrative research by taking concrete steps to work with other national and international scientific communities in areas of data acquisition and data management, and in the support of individual and collective scientific initiatives.

Encouraging Participation of Underrepresented Groups

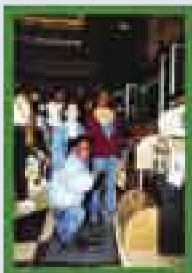
Encouraging individuals from diverse backgrounds to participate in seismology, and in the Earth and physical sciences generally, is one of the goals of IRIS overall and the E&O program in particular. Approaches include establishing and strengthening partnerships with programs and organizations already serving underrepresented groups and targeting these groups to include them in greater numbers in new and existing activities. The E&O program is expanding outreach to underrepresented groups throughout its teacher training, museum, and affiliate programs.

Examples of Consortium-wide activities include encouraging minority students to participate in internship programs and highlighting diversity at our annual workshops. The workshop in 2004 included a plenary presentation about underrepresentation and posters from institutions with successful Opportunities for Enhancing Diversity in the Geosciences (OEDG) programs to show IRIS members what others are doing to encourage diversity. AfricaArray, which is supported by each of the IRIS core programs, is planned to include collaboration with IRIS on teacher workshops and semester-long opportunities for African-American undergraduate students to work with the program in Africa. The Spanish translation of the E&O one-pagers and posters, including the recent Sumatra-Andaman Islands poster highlighting the GSN, help in the effort to engage Hispanic students. The USArray siting outreach program has made special efforts to engage minority groups, such as the multi-year project with Navajo Nation in anticipation of deploying stations in Arizona. Finally, IRIS has a track record of participation of women in its governing bodies, including its Board of Directors, at a proportion above that for tenured faculty members in the Earth sciences.

Innovating on the Base: Incorporating Community R&D in Core Operations

The core facilities have achieved success by maintaining efficient and science-responsive operations. But a crucial driver of IRIS activities is the community input it receives on

Serving Diverse Learners



A continuum of diverse learners is exposed to seismology and related science topics through the E&O Program. Green frames: Exhibits, developed in partnership with the USGS, are on permanent display in large urban centers including New York City and Washington, D.C. Blue frame: Each year students from Key Academy visit IRIS headquarters to supplement their geoscience curriculum with activities lead by IRIS staff. Red frame: Since 1998, 52% of IRIS undergraduate interns have been female while a ~10% were minorities. The program includes a targeted effort to recruit applications from minority-serving institutions. Additionally, IRIS partners with UNAVCO to facilitate the RECESS internship program, which provides extended support for underrepresented students throughout their undergraduate careers. The program is modeled after and shares facilities with the highly successful SOARS program. Yellow frame: The E&O Program has committed to a systemic professional development effort with the high school district in Yuma, Arizona where the student populations is ~70% Hispanic. Large urban districts are invited to send teachers to participate in regular IRIS workshops at no cost. Purple frame: The E&O program regularly brings issues of diversity to the IRIS community to raise awareness and highlight successful efforts to engage a diverse audience.

how to achieve greater efficiencies, provide better services to the user community, and optimize performance. This feedback ensures that new initiatives are inaugurated with community support, and problems with new hardware, software, and facility operations are noted and quickly corrected. It also makes available to IRIS a spectrum of ideas and community-based innovation that may be incorporated into the facility more broadly. This is one mechanism by which IRIS “innovates on the base.”

The combination of community innovation and IRIS data management is enabling individual seismologists to analyze vastly greater amounts of data than even a few years ago. This is a consequence of several factors, including hardware upgrades, increased communications bandwidth, and improvements in user data search and processing software. An example that will be explored by the DMS in the next five years is SOD (Standing Order for Data), whereby users can make requests from the DMC contingent on the waveforms or earthquakes satisfying user-defined, and possibly complex criteria. Another project that will be explored is coupling computational cycles close to the data archive so that, for example, data requests can be accompanied by the computation of synthetic seismograms for user-specified Earth models.

The increase in quantities of instruments in the PASSCAL pool is driven by scientific demand for longer deployments of more instruments in varying configurations. The PASSCAL program is responding in the next five years by focusing on new user services for field operations and the eventual placement of data in the DMS archive. For example, as a result of community innovation, PASSCAL will further develop and integrate new software tools for increasing the efficiency of field operations by making the recording of metadata more efficient and reliable, and thus increasing the effective rate of data return.

The availability of such large amounts of data and the ability to process, organize, and manage them efficiently is one of the key factors promoting convergence of observation, theory, and computation in fields such as geodynamics, Earth structure studies, and earthquake source science. IRIS is providing an organizing framework to make the community aware of efficiencies in every corner of the science through workshops, newsletters, and incorporation of new methods into processing tools available to the community through the DMS and the PASSCAL Instrument Center.

Efficient data distribution is reflected in the ratio of staff at the DMC for data request servicing versus those for new user services and other tasks. Over the past two decades, the DMS has developed scalable solutions for automating the data retrieval process, thus freeing staff from answering routine requests and enabling them to spend more time on new user functionality. In the next five years, this automated capability will continue to expand as the DMS takes advantage of web services and automates the responses to ever more complex data requests.

The GSN innovates on the base by standardizing to commercial off-the-shelf hardware, thus reducing O&M requirements, increasing reliability and data return, and decreasing the chance of unanticipated problems. The GSN also will innovate on the base by working with other international networks, such as the FDSN and the International Monitoring System (IMS), to optimize the collection of broadband seismological data for a variety of research and operational purposes.

Partnerships in the Poles and Oceans

The IRIS program framework is an effective platform for extending the reach of IRIS instrumentation to difficult data acquisition environments. This will meet scientific objectives by beginning to close the gaps in global coverage in the GSN and in the feasibility of remote PASSCAL deployments. For example, in the next five years, IRIS will leverage opportunities to provide ocean coverage by working with the Ocean Research Interactive Observatory Networks (ORION) and Integrated Ocean Drilling Program (IODP) to instrument preexisting ocean bottom boreholes. IRIS will also work with the Ocean Bottom Seismometer Instrument Pool (OBSIP) to provide a small set of broadband ocean bottom seismometers for special development and science programs. In the Antarctic, the special requirements of extreme cold deployments will require community research and development and the incorporation of technical improvements into the instrument base. There are also special requirements for field deployment personnel and logistics that will be explored with NSF's Office of Polar Programs (OPP).

Leveraging Domestic and International Partnerships

Science is an important driver toward globalization, if not a globalizing force in its own right. The global scope and geographic reach of IRIS facilities and the science they support are forward-looking components of the increasing internationalization of science and the increasing importance of science and technology to developing countries. In the next five years, IRIS will articulate and incorporate community objectives in promoting international scientific collaborations, and in substantively linking the scientific community to sustainable development and natural hazard risk reduction. Developing links will require leveraging the IRIS cornerstone position to forge new domestic and international partnerships.

There are many reasons to use the cornerstone position of the IRIS facilities to increase national and international leveraging opportunities in the next five years. In part because of its existing international credibility, IRIS is in a unique position to participate in the growing globalization of geophysical networks, but the geographic scope must be accompanied by a coherent international approach. By promoting a truly international and collaborative approach to global network development, IRIS will: (1) enable the community to develop additional international research collaborations; (2) increase

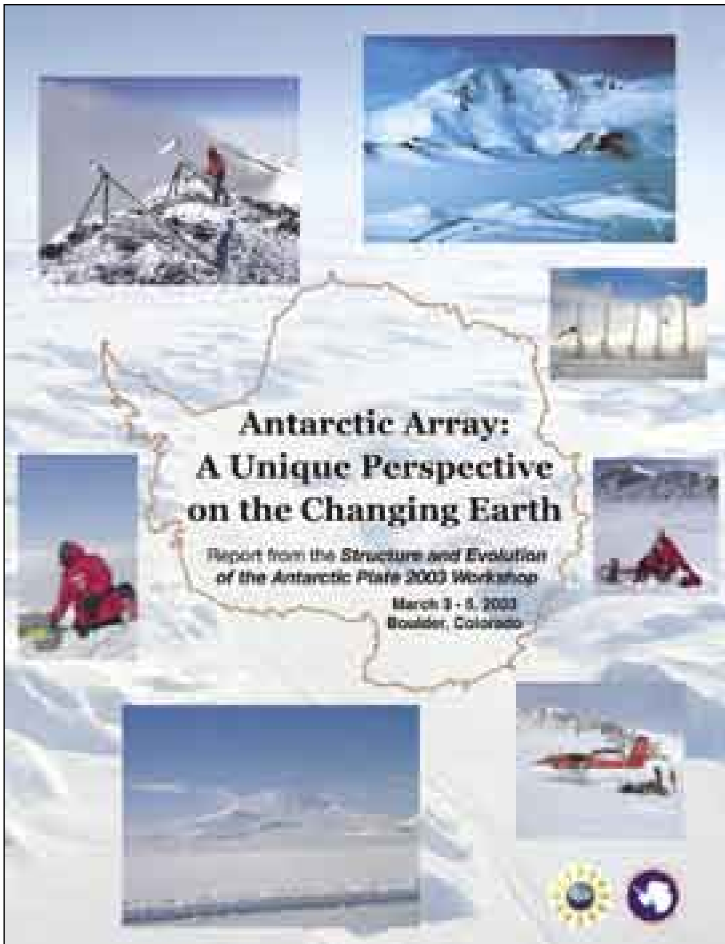
Interagency and International Partnerships

Interagency

- Joint operation of GSN with USGS.
- Joint purchase of PASSCAL instrumentation with DOE.
- Working with OCE on on-shore/off-shore experiments.
- Jointly deploying H20 and other long-term ocean sites.
- Working with OPP and UNAVCO on polar instrumentation.
- Archiving PBO and SAFOD data at DMC.
- Sustaining active-source explosion capabilities with the USGS.
- USArray "Permanent Array" to build ANSS Backbone.

International

- A founding member of the FDSN and established the first FDSN continuous data archive.
- IRIS member institutions form numerous ad hoc partnerships every year to carry out PASSCAL experiments worldwide.
- Serve as an archive for data from permanent seismic networks in more than 120 countries and from SEIS-UK experiments.
- Developed NetDC and DHI, and support their operation at data centers around the world.
- Support activities at the Moscow IRIS Data Analysis Center.
- Support activities at the Kazakh National Nuclear Center that enable transmission of data from the Kazakh seismic network to the DMC.
- Contributed instrumentation and technical advice to build the Kyrgyzstan Seismic Network.
- Contributed retired instruments and data services to AfricaArray.
- GSN station operations are based on partnerships with academic and governmental agencies in 59 countries.
- Partnered with Japan, France, Germany, Italy, Mexico, and Australia, who provided seismic equipment for the joint GSN stations within their networks.
- Maintain GSN Affiliate relations with station operators in Germany, Botswana, and Singapore.
- Partnered with Japan to purchase and install telemetry at GSN stations in the Pacific Ocean.
- Operate seismic stations used by the IMS as part of its auxiliary network.
- Share use of the IMS Global Communications Infrastructure to telemeter continuous GSN data.
- Initiated a series of UNESCO-supported international workshops on managing data from seismological networks.
- Support international station operator training workshops for GSN stations.



IRIS Engagement with Antarctica Initiatives

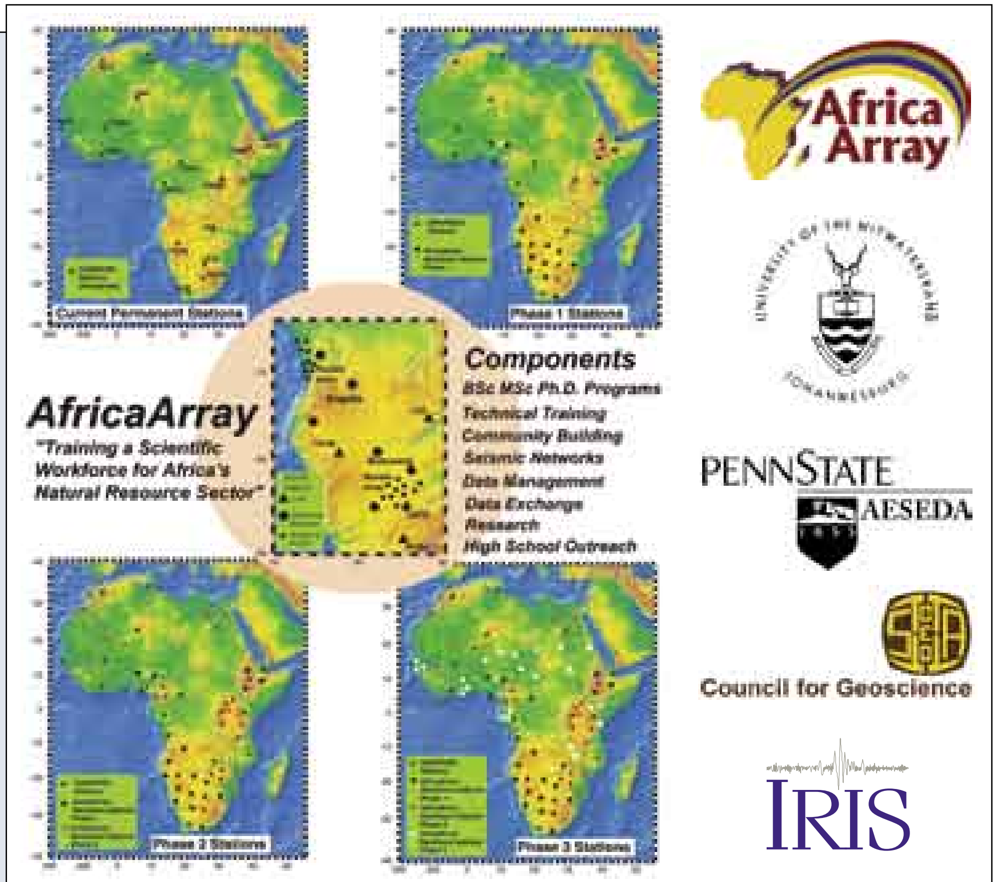
The vast territory of Antarctica presents exciting scientific opportunities tempered by formidable technological challenges. Over the past five years, IRIS has been actively involved in Antarctic initiatives, including GSN stations such as SPRESSO, and PASSCAL deployments. The community is developing ambitious research plans for new portable and long-term seismic deployments (see http://ciei.colorado.edu/array/). One concept is a regional-scale network of permanent observatory sites distributed across the continent (Antarctic Array) and densifying the current coverage. Another concept is deploying a dense array of seismic stations in the special, seismically quiet sector established near the South Pole. Numerous PASSCAL-type deployments are also envisioned. The upcoming International Polar Year program (2007) will stimulate additional Antarctic initiatives. Current activities can be sustained within existing budgets, but more ambitious undertakings are constrained by severe technical and financial challenges of operating and maintaining seismic and geodetic instrumentation in Antarctica. Although GSN and PASSCAL define some instrumentation initiatives in the current proposal, IRIS intends to coordinate with UNAVCO on development of critical infrastructure, prerequisite for more ambitious initiatives. This would involve seeking funding from NSF's Office of Polar Programs (separate from this proposal) to develop integrated power and communication systems that will enable reduced maintenance costs for seismic and geodetic deployments in Antarctica. This approach is another style of innovation on the base: IRIS facilities will lead the developmental effort (it would be very difficult for member institutions to obtain funding on their own). The long-term intent is to facilitate future scientific initiatives. (Figure courtesy of Michael Ritzwoller, University of Colorado at Boulder.)

the availability and quality of data from overseas networks; (3) promulgate data acquisition and quality-control standards and promulgate free and open data exchange in developing countries; (4) help to strengthen agencies in developing countries with responsibility for operating seismic networks; (5) amplify the impacts of NSF investment in IRIS facilities by increasing the access of U.S. investigators to new data and new collaborations; and (6) contribute to the nation's goals in using science and technology to promote international development.

Even more important, by making a dedicated effort to promote international collaborations, IRIS will have a direct impact on the developing world's needs for scientific and technical infrastructure, training, education, and institution-building. With natural hazards risk reduction now being recognized as a component of poverty reduction and economic development by international aid organizations, IRIS, through its global reach and basic collaborative premise, is uniquely positioned to help. IRIS provides one of the pathways by which individual scientists at member institutions can themselves innovate and adapt their projects to help build technical and scientific capacity.

Some investigators succeed by maintaining their own contacts with overseas partners, U.S. government agencies, and international organizations. Nevertheless, these individual contacts may not contribute progress towards the goals of the community as a whole. Alternatively, many others—especially young investigators trying to establish their own independent research programs—are able to leverage the technical and organizational credibility of IRIS to develop partnerships with domestic and foreign academic and government institutions. In effect, for these scientists, the existence of IRIS has lowered one of the barriers to developing effective collaborations. IRIS is a powerful convening tool, and signifies to many potential partners the existence of a resource base and framework for standards-driven data collection, open data management, and data exchange for scientific collaboration. Individual investigators can take advantage of this framework for large and small programs. Each of the IRIS programs has a role in supporting these partnerships,

IRIS Engagement with AfricaArray



AfricaArray (http://africaarray.psu.edu/) is an initiative to promote geophysics training and research in Africa. It involves development of educational programs and a continental-scale broadband seismic network. IRIS has partnered with AfricaArray to provide data storage and management through the DMC, and is providing an initial complement of refurbished surplus RefTek data loggers that have been retired from the PASSCAL program. The E&O program is planning to participate by supporting teacher workshops. This is an exemplary demonstration of innovation on the base, as the existence of IRIS infrastructure is helping to keep costs and logistical challenges manageable for the AfricaArray PIs, while the partnership ensures free and open access to the data acquired by the new broadband network. During the next five years, IRIS will explore providing additional surplus equipment, will work with the evolving African capacity for seismic station operation to achieve efficiencies in operations of GSN stations in Africa, and will possibly expand GSN stations into geophysical observatories with additional sensors of interest to researchers at the African institutions. (Figure courtesy of Andy Nyblade, Pennsylvania State University.)

individually or collectively, and the IRIS standing committees and central office provide pathways for IRIS members to structure and realize their own initiatives.

Achieving these goals will be enhanced by a coordinated approach managed through IRIS. In the next five years, IRIS will charge its Director of Planning with coordinating and implementing a community-based strategy for building domestic and international partnerships. This will include logistics support in coordinating and sustaining the contributions of the core programs to specific projects and, at a more senior level, developing a comprehensive program for foreign affiliates and engaging them in high-level partnering discussions. The goal is to make international relationships responsive to the circumstances in different regions and countries without overly rigid adherence to a pre-defined template. This organic structure will allow even more innovation to take root.

Some of these partnerships may be broad community-based initiatives such as EarthScope that require multiple organizing workshops and ultimately need direct, programmed IRIS involvement. Others, such as AfricaArray, merge the ideas of individual investigators with the organizational and technical capabilities of IRIS to help create entirely new projects.

"IRIS the Consortium" has an organizational role in developing these partnerships, in response to community directives and with the participation of the standing committees and the Board of Directors. This is especially true internationally. In the next five years, IRIS proposes to assist in providing pathways for developing increased participation by the U.S. scientific community in international Earth science, hazard reduction, education, and economic development programs. Major emphasis will be placed on the promulgation of standards-driven data collection and a free and open data exchange environment. The promotion of free and open data exchange will directly result in increasing the potential for individual scientific collaborations globally. In addition to providing new ways of making data from other seismic stations available to a broader, worldwide community of scientists and practitioners, these new pathways can build seismological capacity in less-developed countries in ways that promote free and open data exchange, quality control of data collection, and increased scientific collaboration and educational opportunities.

An improved international posture for IRIS will also have an impact on the existing programs. For example, the management of the GSN has made use of evolving international relationships to improve local on-the-ground support for GSN stations, decreasing marginal operational costs, and increasing the reliability and data return in many foreign countries.

Developing a coherent community approach to the globalization of geophysical networks and data acquisition will demand increased attention to IRIS's partnerships with U.S. government agencies. In the next five years, IRIS will build on the cooperative agreements in place with the USGS and the NOAA Tsunami Warning Center, and develop collaborations with international programs at NSF and the State Department, to promote an international agenda that at its core promotes international scientific collaborations. In particular, IRIS will continue developing the GSN as an *in situ* component of GEOSS. This development will be facilitated by IRIS's existing partnership with the USGS (the USGS is a leader in the U.S. Interagency Working Group on Earth Observations), and by GSN's membership in the FDSN (the FDSN is recognized by the GEOSS international secretariat as one of the few scientific communities that has already developed agreements and technical standards for successfully exchanging Earth observations in real time).

A new area to explore in the next five years will be increasing the interaction of IRIS and the IRIS community with international development organizations, such as the United Nations Development Program and international development banks such as the World Bank. In addition to providing a potential new resource base for U.S. participants, such interactions could serve to integrate geophysical data collection more systematically into sustainable development agendas. Many observers note that aid programs are successful at capitalizing technical projects, but the record on sustaining technical activity is mixed. Real-time data collection and standards-based archiving, which lead to scientific and educational collaborations in support of development objectives, offer a framework for building the country-level capacity that will sustain the technical infrastructure over the long run. The global role played by the GSN and the DMC can be translated into regional approaches, providing new opportunities for the IRIS membership and partners to leverage existing capabilities.

GSN Activities

The GSN has grown into the fiducial network for global seismographic instrumentation. Since its inception, the GSN has adhered to standards-driven policies of free and open data exchange, real-time data availability wherever possible, and comprehensive archive and network calibration. Consequently, the GSN, which at its core is a scientific network, has evolved a monitoring capability that is used by U.S. and international institutions with earthquake and volcano monitoring and tsunami-warning responsibilities. This dual use has been recognized in the designation of the GSN as a U.S. observing system contribution to GEOSS.

Improve O&M and Refurbish Equipment

More efficient operations and maintenance (O&M) will be achieved by the adoption of standardized data acquisition hardware by the IRIS/IDA and USGS/ASL network operators, as recommended by the 2003 external review. GSN operators continue to explore productive relationships with local on-site operators that encourage them to share the burdens of routine O&M. O&M is better and more efficient at sties with telemetry; the GSN is also exploring extending telemetry to the few sites that have not yet been connected. The GSN benefitted from Congressional action to enhance support for the USGS/ASL network operator following the 2004 Sumatra-Andaman earthquake; installation of the newly funded stations and telecommunications are being coordinated with other GSN activities. The GSN continues to work with other international networks through constructive relationships such as those underlying the FDSN.

The primary budget items under this task are overall GSN management and governance and support of the subaward to the University of California, San Diego for operation of the IDA component of the GSN. To meet equipment-related requirements and catch up with deferred maintenance, we plan to increase equipment spending to improve the refreshment rate to about 10%, or about a 10-year life cycle. A major

In 2003, the National Research Council completed a study funded by the National Academy of Sciences to "assess the current scientific understanding of earthquake processes." The study report, *Living on an Active Earth: Perspectives on Earthquake Science*, provides an overview of the wide range of observations, experiments, and analyses that are advancing our understanding earthquakes and our ability mitigate seismic risk. In its evaluation of current technologies for observing Earth, the report explains that the GSN is indispensable to recent and future progress.

"The Global Seismic Network ... is furnishing unprecedented data on the source processes during major earthquakes in remote areas ... The GSN data acquired over the last 15 years have facilitated many advances in the study of global Earth structure and earthquake sources ... [and] have also improved the plate-tectonic framework for understanding earthquake hazards ... Discoveries based on data now being collected by the GSN will undoubtedly continue into the indefinite future ... With each passing year, GSN [will] add new information to the evolving pattern of global seismicity by the direct observation of large, rare events and the delineation of low-level seismicity that may mark the eventual occurrence of such events."

Very Broadband Sensors for Global Seismology

From the start, IRIS has been at the forefront in deploying the most capable seismometers. Stations that cover a very broad band (1 mHz to 20 Hz) are essential to global seismology for monitoring and studying earthquakes and for studying free oscillations to better understand Earth structure. Recent reviews demonstrate that the current state-of-the-art GSN sensor, the STS-1, performs in the field better than alternatives such as the KS54000 and the CMG-3, reflecting the higher specification to which the STS-1 performs in calibration tests.

Streckeisen no longer manufactures the STS-1. IRIS is committed to fostering development of, and deploying, a successor that is at least equally capable. In the interim, IRIS has used its international partnerships to locate and procure STS-1's for as many GSN sites as possible, deploying them at the best sites and employing alternative sensors at noisier sites. IRIS's contributions towards a capable STS-1 replacement include organizing workshops with participants from government, universities, and industry. A 2004 workshop sponsored by IRIS crystallized realization that industry will not develop a substitute instrument due to supply and demand economies (a total production run of 200 units is projected). An ambitious $10M-$20M program over five to ten years will be required to develop partnerships and technology transfer among industry, academia, and government; new and innovative designs; testing standards and testing facilities; funding strategies; and an educational perspective, including new university programs to nurture the next generation of U.S. seismic system developers.

IRIS plans to continue related activities. The GSN has long-term plans to deploy a replacement sensor starting sometime after 2011, by the time its proposed budget will have made it possible to substantially complete replacement of the GSN data loggers.

component of this equipment purchase will be the gradual replacement of all data acquisition systems with the new generation standardized unit.

Encourage Next-Generation Sensors

There are currently no known replacements for the primary GSN surface sensor (Streckeisen's STS-1). A complete development program for the engineering design of a replacement to the STS-1 is most likely beyond the scope of funding available for the GSN, but funds will be programmed (1) to research and evaluate sensors and sensor emplacement techniques to find a suitable replacement and (2) to work with manufacturers to guide new sensor development. GSN may bargain, trade, or purchase STS-1's in various other networks around the world if those other groups determine they are no longer required at their current site.

Improve Telemetry

IRIS directly supports hardware and recurring costs for telemetry for parts of both the UCSD and USGS portions of the GSN. In cooperation with the USGS and international partners, this support will be used to continue and upgrade communication circuits, with the goal of 100% real-time access during the next five years.

Extraordinary GSN telemetry growth was achieved in the past five years through modest investment of NSF funds. Current GSN station telemetry coverage exceeds 80%, which was achieved through orchestration of a diverse suite of national and international, and satellite and Internet, arrangements, though the bandwidth and robustness of many links need improvement. GSN will focus its telecommunications funds toward taking advantage of newly available and higher-quality global telemetry, which is driven by commercial, national, and public interest. Following the Indian Ocean tsunami, there is strong national (via the USGS) and international interest in expanding, upgrading, and enhancing GSN telecommunications. The additional support available through post-tsunami activities is an example of the GSN's ability to leverage its backbone fiducial reputation among many different international organizations.

Enhance the Network

Just as equipment must be refreshed and upgraded to preserve the quality of the GSN, the civil works of GSN stations—vaults, boreholes, buildings—require maintenance. For a network of 138 stations diversely located in all climates and environments, problems arise that affect GSN data availability and quality. GSN plans ongoing refreshment of civil works with annual spending equal to approximately 1% of the total investment.

The GSN will improve data quality by continuing its noise studies, often by coordinating with PASSCAL experiments in the vicinity of a GSN station, and by the aforementioned program of civil works assessment. Information from noise studies will guide decisions regarding instrumentation flexibility, station upgrades or relocation, and new siting. No station will be moved precipitously, but bad performance will not be accepted.

The current collection of stations and their network operator affiliation grew out of logistic necessity and historical precedent. While recognizing that data from a site collected over a long time has greater value, the GSN plans to review the network configuration and make adjustments if necessary to enhance data-quality goals and O&M efficiency.

Make Progress in the Oceans

The oceans are vast, and no one approach will achieve a substantial improvement in seismological coverage in the near term. To make progress, the GSN plans to purchase borehole instruments to emplace in existing ocean-floor drill holes in the near future in conjunction with IODP and ORION. In addition, the GSN plans to purchase and designate for global use several sets of broadband ocean bottom seismometers to be managed under the OBSIP. Through a nascent Arctic/Antarctic Cetacean and Earthquake Science (ACES) collaboration, the GSN will seek independent funding from NSF/OPP to add OBSs to existing acoustic recording packages currently being deployed by the marine mammal community.

This is an example of leveraged support, where the GSN investment in hardware for ocean floor use will be used to stimulate collaboration with ocean science and polar programs to increase oceanic coverage.

Develop Polar Region Capabilities

Seismological coverage of the polar region of the southern hemisphere is sparse and limited to Antarctic coastal bases, plus the South Pole (U.S.) and Dome C (Italy/France). The GSN plans a new station in West Antarctica at either Siple or Byrd Camp, where there is logistical support during the austral summer.

To expand GSN coverage into the Antarctic interior will require the development of an autonomous power and telemetry capability. Recent power reductions in GSN equipment will engender a coordinated approach with PASSCAL and the UNAVCO/GPS community to develop a remote, autonomous power/telemetry capability. Funding for this capability, which will have substantial applicability beyond seismology, will be sought from NSF's OPP. GSN would provide funds for the sensors to be used for GSN deployments, coordinated with OPP logistics. Additional coverage (2-5 sites) would be sought for an area between South Pole and the coast, which can be supported by fixed-wing aircraft deployed from the Pole. Over the next five years, we anticipate phased improvements in both the power and telemetry capabilities, growing from initial summer operation with internal recording to eventual year-round operation with real-time telemetry. Initial testing could be conducted at the SPRESSO site near the South Pole. To shorten the development/test cycle, collaboration would be sought with the Arctic Program of OPP to use the existing base at Summit, Greenland and summer camp at the North Pole.

Broaden Geophysical Observatories

The vast GSN infrastructure serves as a platform for other geophysical instrumentation. The GSN plans to develop simpler, standardized power and communications interfaces to facilitate the installation of new, collocated sensors systems and to improve integration of the GSN as an *in situ* framework for GEOSS. Continuing the installation of microbarographs throughout the network will fulfill the GSN scientific quest to measure simultaneously both sides of the seismo-acoustic interface for long-period, globally propagating signals, and complements higher-frequency, infrasound array measurements made by the IMS for regional distances. The primary budget item requested is funding for additional geophysical and meteorological sensors. As the GEOSS community becomes more aware of the potential for observations at GSN sites, IRIS will work with NSF and the USGS to seek collaborative sources of funding for this effort.

Tap into University Innovation

Considerable talent and expertise reside in the university community, which operates state-of-the-art regional seismic networks, participates in international projects, and maintains cross-disciplinary contacts in the broader geophysical sciences. GSN plans to continue collaboration with university partners, providing support for joint siting of stations and new developments in hardware and software

PASSCAL Activities

Operate the Core Program

PASSCAL plans to continue providing NSF-funded researchers with state-of-the-art, low-power portable instrumentation and high-level technical expertise to maintain and assist in operating that instrumentation. This includes adequate maintenance and upgrades as well as replenishment of lost, damaged, and aging equipment. Sustaining state-of-the-art instrumentation entails adopting new technologies, notably in communications, power sources, and sensors as they become available, and pursuing the development of lower-cost instrumentation in general. In concert with advancing instrumentation, funding over the next five years will also be used to build and streamline simpler and more sophisticated field and data handling tools and improve methods for user training, aspects of which are discussed below.

Day-to-day operations of the core program will continue at the PASSCAL Instrument Center (PIC), supported via a subaward to New Mexico Tech in Socorro, New Mexico. The PIC, which is collocated with the USArray Array Operations Facility, houses the staff and facilities for instrument maintenance, experiment support, software development, and user training. Staff at the PIC is responsible for acquiring and maintaining the PASSCAL instruments, supporting users through training, and assisting in-field operations. Although the original PASSCAL concept was for the facility to act primarily as a instrument maintenance depot, there has been a substantial shift towards providing user services to the research community in training, software development, documentation, and field support. Additional staff will be added to the PIC over the next five years to respond to this increased demand, especially in the area of software support and data management.

Support is also provided through subawards to the University of Texas El Paso for maintenance of UTEP-owned Texan instruments, which are shared with PASSCAL, and to UCSD for support and development of communication systems, which are used in the PASSCAL Telemetered Broadband Array.

Acquire Additional Instruments

The PASSCAL instrumentation pool, coupled with technical support from the PIC, will continue to give NSF-funded seismologists the capability to pursue innovative research anywhere in the world. We anticipate that a potential outcome of USArray will be to increase the demand for similar dense deployments elsewhere in the world. Thus, we seek to maintain and slowly expand the PASSCAL pool to meet this demand.

Purchase of 100 Texans per year is proposed to replace lost and damaged units, and increase to approximately 1400 the number of systems available for (overseas) active-source experiments. This plan is based on the assumption that the USArray program will acquire 2,000 Texans and arrangements will be made with NSF to make these units available on a non-interference basis for use (at least in the U.S.) on non-EarthScope funded projects.

To support current and anticipated levels of passive source experiments, the acquisition of a total of 105 broadband sensors and recording systems (21 per year) is proposed. Approximately 6 of these sensors and data loggers per year are required to replace aging equipment and units that are lost or damaged. Acquisition of broadband sensors began in 1990, but they have not been replaced. Although those sensors remain state-of-the-art, equipment failures are on the increase and a gradual loss of sensors due to aging is coupled with ever-increasing demand for their use in experiments. The remaining 75 broadband systems (15 per year) are intended to provide limited growth in the pool of complete field systems for broadband recording, which currently number 434. Many passive broadband experiments today deploy on the order of 50 instruments for 18 to 24 months; the budgeted increase in the broadband pool would effectively enable one additional such experiment each year.

As part of our increased emphasis on integration with other areas of geophysics, we propose to acquire a data-logging gravimeter and four sets of 60-channel high-resolution multichannel recorders for shallow imaging.

PASSCAL will be actively seeking new generation broadband sensors before the end of this proposal period. Several leading-edge technologies are promising and we plan to purchase prototypes and carry out testing of new broadband sensors, seeking more portable, more rugged, lowercost sensors that enhance our ability to deploy larger arrays. We will also continue to encourage manufacturers to develop new intermediate-period sensors, and we plan to purchase and test prototypes to determine if they are compatible with PASSCAL's needs.

Poor sensor orientation remains a quality-control issue, but recent development of an accurate GPS sensor-orienting device can eliminate the most common causes of poorly oriented sensors. We plan to purchase 10-20 of these units over the next five-year period.

Advance Performance

PASSCAL plans to work with the DMS to implement a full suite of procedures to assure strict quality control of portable array data such that the broader seismic community can use the data with confidence. Some of these tests can be implemented while the PI is in the field and can still make repairs or changes.

Although datalogger improvements have been recently realized, we plan near the end of this cooperative agreement to purchase and test prototypes of new dataloggers. We plan to continue monitoring battery technologies that could reduce the need for solar panels and thus simplify station siting and operation.

Experience has demonstrated that real-time data recovery dramatically increases data return and data quality and drastically reduces operational costs. Global communications are rapidly changing. The new-generation hardware now incorporated in the PASSCAL data loggers will allow IRIS to adapt to changes in communications technology as these changes emerge in the next five years.

PASSCAL plans to acquire moderate numbers of "state-of-health" communication systems such as ARGOS and Iridium to meet critical needs for remote and foreign deployments, as well as to expand and improve capabilities during the next few years. As the technology improves and power and transmission costs make it possible to acquire low-power telemetry systems that can transmit all of the data from a remote station, we plan to integrate such new systems as rapidly as possible.

Software development in support of telemetry and field operations will be done in cooperation and coordination with the other IRIS programs. For instance, many problems that are important to PASSCAL, GSN, and DMS can be addressed through remote station control and data quality control, which require coordinated and program-specific software development.

In addition to an enlarged active-source instrument pool, increased scientific demand for 3-D and 3-component high-resolution imaging depends on large artificial sources. PASSCAL will play an active role in facilitating permitting for seismic shooting and land use, and contracting of industry crews where appropriate. To maintain the capability of explosion source investigations, PASSCAL will seek to establish a formal partnership with the USGS. Funding for these activities has been requested in the budget.

Foster Integration and Enhancements

Over the last 20 years, PASSCAL broadband experiments have evolved from a handful of moderate-scale experiments incorporating few (10-30) instruments, to a significant number of experiments each year that involve 50 or more instruments deployed over large geographic areas. Increased efficiencies, in conjunction with the development of more powerful imaging techniques, make it likely that experiment size will continue to increase. Thus, in addition to steady expansion of the instrument pool through NSF funding, PASSCAL and IRIS will seek to obtain new broadband instrumentation through additional sources of funding and via partnerships with other geophysical facilities.

A promising programmatic integration opportunity for IRIS is in the development of power and telemetry systems suitable for deep field Antarctic deployments. This is of great scientific interest and has a great logistical incentive in reducing costly and difficult deep-field support. For example, an autonomous seismic and general geophysical observatory that would only require field support a handful of times per decade would contribute to efficiencies of PASSCAL in general, not solely for Antarctic deployments. Because seismic systems typically involve relatively high data rates for the various types autonomous remote instrumentation that are of interest for Antarctica, such systems offer a platform for partnering with other types of broad geophysical sensors, such as weather, magnetic, infrasound, and geodetic GPS. This initiative is of significant interest to both PASSCAL and GSN, and IRIS plans to collaborate with UNAVCO on a separate proposal to OPP for this development.

Develop International Partnerships

PIC's primary function has been to support NSF-funded experiments, and it will continue to do so; however, opportunities exist at little cost to expand the purview of this resource to benefit seismology broadly through the world. Through numerous field programs, PASSCAL has developed a web of international scientific contacts throughout most of the scientifically interesting regions of the planet. In many cases, PASSCAL field personnel have provided technical advice and assistance to collaborators in developing countries on an ad hoc basis, as it seems appropriate to the particular experiment being supported. In a small number of carefully selected cases, this relationship could be extended on a more formal basis through long-term loans of depreciated equipment and by serving as a pool of expertise to frequent foreign collaborators who are also operators of in-country seismic equipment. Initiatives could take the form of technical training sessions at PIC for groups of regional collaborators, assistance with hardware or software development, or minor repairs of PASSCAL-compatible instrumentation.

In part because of PASSCAL's example, central repositories of seismic sensors that are similar to the PASSCAL pool now exist in Canada and many European and Asian countries. Moreover, large-scale projects modeled after U.S. initiatives, such as EuroArray, have started to develop. Therefore, we plan to seek a larger complementary international collaboration through the use and sharing of PASSCAL instruments and technical support overseas. This collaboration may include use of PASSCAL equipment overseas and use of foreign equipment in the United States. By combining instruments, technical expertise, and efforts, we ensure a larger efficiency in terms of amount of data acquisition, reduction of waiting time, and exchange of technical expertise. This collaboration complements other IRIS efforts to develop a global culture of open data access. Limited funding is requested in the PASSCAL and Consortium Activities budgets to support efforts to assist foreign programs in instrumentation deployment and training. Opportunities will be explored to leverage this through International Programs and non-NSF development-related programs.

Seek Efficiencies Through Education & Training

We anticipate that the seismic community, with IRIS coordination, will greatly expand the scope of higher-level data-processing tools, which ultimately allow much more efficient processing of large data volumes. PASSCAL can further promote the advancement of science through training sessions, both real and virtual, in the processing and analysis of seismic data. PASSCAL, in association with the E&O program, plans to enhance distance-training opportunities for the community and coordinate workshops in response to community needs. This training should also expand IRIS outreach to international PIs and collaborators to advance international projects.

The PASSCAL community has proven adept at achieving its scientific goals, but increased efficiency and performance could be attained through better communication between PIs and the PIC, as well as development of targeted education and training modules by PASSCAL. At the proposal stage, information about the costs and benefits of PIC field support could lead to lower overall costs to achieve experiment objectives, as well as more accurate initial estimates of those costs. Feedback on an instrument capability and availability, especially if it is tailored to particular instrument requests, could reduce the instrument demand, both in total quantity and in use of the specialized instrument types. At the deployment stage, training in and adoption of standardized vault construction would reduce costly field time and improve data quality. Training and support for the data archiving process also promises to simultaneously cut costs and improve data recovery rates. PASSCAL plans to add personnel to take advantage to these opportunities.

PASSCAL will also continue to support 1 or 2 summer interns each year at the graduate and undergraduate level. Each intern contributes to a specific technical development or support of a particular program at the PIC under the supervision of the PASSCAL staff. The inception of USArray and other EarthScope activities offers an opportunity to expand education and outreach activities in coordination with the EarthScope Facility Office, such as additional summer interns and intensive siting outreach efforts. Siting outreach efforts range from working with a local high school near a particular USArray site, to coordination with classes at universities in selected regions to educate students in use of GIS and other tools, to special projects that respond to unique conditions such as those in parts of Arizona, where diverse cultures and land management present unique opportunities to enhance the diversity of populations engaged with seismology.

DMS Activities

Continue Core DMS Operations

The primary role of the DMS is to receive, provide quality assurance, archive, and distribute data from GSN, PASSCAL, EarthScope/USArray, and contributed data from other national and international organizations. This requires the ongoing operation and maintenance of the DMS as distributed but coordinated nodes in an extensive hardware and software system for storage, management, and distribution of terabytes of waveform and associated metadata. The primary node in the DMS is the IRIS Data Management Center in Seattle, where IRIS staff are responsible for operation of the key computational and mass storage systems and the development and maintenance of the software systems for data management and user services. Other nodes in the DMS partially supported through the IRIS Cooperative Agreement include GSN Data Collection Centers at UC San Diego and the Albuquerque Seismological Laboratory, a Waveform Quality Control Center at Harvard, the DMC and a software development group at the University of South Carolina.

Funding is requested in this proposal to support the established staffing and computational hardware infrastructure at the DMC and, via subawards, the operations of the associated nodes of the DMS. Information on the personnel and hardware base at the DMC is provided in the DMS program description and budget section of this document. Because of the modular nature of the hardware and software systems at the DMC, including the mass store, most of the equipment items in the budget request for operation and maintenance are relatively low-cost devices for incremental expansion as required by increased data volume, and replacement of aging or outdated hardware. More significant proposed expansions of the hardware system, for offsite backup and cluster computing, are indicated below.

Provide Enhanced User Services

The DMS has a strong record of developing and supporting various software systems that provide users with enhanced capabilities for selection, access, quality assessment, and pre-processing of waveforms in the DMC data holdings Development of these user services evolves though a productive feedback between users and the DMC staff, with overall guidance and priorities set by community representation on the DMC Standing Committee. The budget impact for these developments is primarily in personnel support at the DMC and consulting services. A staged increase of three additional software personnel is requested over the next five years to support development in user services.

Meet Requests Using Pre-Computed Attributes. Historically, the DMC has employed a model for data requests where users ask for data they need based primarily on event, station, and time parameters. If the DMC has the data, they are sent to the users who then determine the quality of the waveform data and suitability for their specific scientific application. The DMC plans to develop a framework within which users can make requests for data that have attributes related to the waveforms themselves (e.g., amplitudes, signal-to-noise ratio, spectral content). The QUACK (quality control) system currently makes routine measurements on a large fraction of the data entering the DMC in real time. We will extend DMS request mechanisms so that they can support data selection based upon these pre-computed estimates of data quality. For instance, we anticipate having signal-to-noise ratio estimates available for all the data we receive in real time. Users will be able to request data from specific station channel time window selections, but only have the data returned to them if the estimated signal-to-noise ratio exceeds a specific value. Another example would be where a user could request a time series, but only if it contains no gaps or fewer than some number of gaps in a 24-hour period. As the DMC continues to mature, the types of pre-computed measures that can be used for data request purposes should continue to grow.

Offer Computation on Demand. The DMC plans to work closely with the CIG consortium to develop a flexible framework that users can invoke to measure data attributes dynamically at the time of the request. If a user has a particular algorithm that measures signal to noise and they would prefer to use their algorithm rather than a predetermined one that QUACK uses, then they could dynamically configure that algorithm into a processing system at the DMC, make the measurement, and only return the data if they surpass certain user-defined tests. We intend to implement this within a web services framework. Thus, while much of the computation can be done on systems at the DMC, it will be possible for certain algorithms to be computed on remote systems either at the requestor's location or, potentially, on grid machines.

Provide Web Services and Expand Capabilities of SAC. The DMC plans to develop a web-services-based processing framework that will be configurable by individual researchers. This can allow algorithms to be run both at the DMC and at a users computing system, and will provide access to the cluster system at the DMC for pre-configured algorithms. We plan to provide such services quickly by wrapping the Data Handling Interfact (DHI) within a web service framework. IRIS has recently acquired a license for the widely used Seismic Analysis Code (SAC). The DMC plans to wrap individual SAC functionality within web services and make this available on compute servers at the DMC. We will encourage the development of web service contributions to this processing framework with a variety of workshops and by funding small subawards to researchers to enable web service access to the most desirable community codes.

Develop an Active Offsite Backup Archive

The DMC already has well-established mechanisms for data back up, including off-site tape storage. As the DMC matures and as requirements for closer to 100% up-time are encountered, we plan to develop an offsite system that will be capable of data ingestion, data archiving, and request processing functions. The offsite system will be unmanned and normally controlled by DMC staff, but would operate in the event of a catastrophe in Seattle. In the event of a catastrophic failure, staff might relocate to the backup location for several months while the primary system at the DMC was rebuilt. The primary expense is for hardware acquisition and costs are summarized in the budget section.

Deliver Cycles Close to Data

For large data sets, such as those found in seismology, the present bandwidth that connects data users with supercomputing centers is often inadequate to transfer multi-gigabyte data sets. For this reason, the DMC proposes to acquire a small LINUX/Beowulf Cluster for operation at the DMC, with high-speed networking to the primary RAID data storage system. This cluster will be used in routine processing and for user-requested data products and analyses. For instance, the DMC might begin calculating synthetic seismograms for all events above a certain magnitude. Additional synthetics for smaller events could be computed on demand when a particular user desires them. "As required" processing is used in several DMC processes already, and applied to as many as 5000 real-time seismic channels, so the DMC already has significant experience with managing large-scale, on-demand services. Other uses for the cluster would be to make routine computations on seismic data through user-supplied algorithms. The QUACK framework already in operation at the DMC could be used for these types of problems quite easily.

The budget request in this proposal is for a 256-node cluster and an additional staff person for development and support. This is an area where it is anticipated that significant partnerships could be developed, and partial funding from EAR could be matched with support from NSF cyberinfrastructure or other programs. Discussions within the DMS Standing Committee and with the CIG consortium have indicated strong support for development of a natural link between the data and computational resources at the DMC, with the software and algorithm strengths of CIG.

Collaborate with Other Groups

There are a large number of collaborations related to data management and processing that are possible in the next five years. The DMS is positioned very well to work with a variety of current partners as well as new scientific groups where joint developments and cooperation will be of great benefit to the broader community. The incremental budget requirements for these activities are minor and consist primarily of staff involvement, joint meetings, and support for workshops. It is anticipated that some of these collaborations could also lead to joint funding opportunities for expanded activities.

EarthScope (NSF): The DMS plans to continue being closely involved with EarthScope both in the management of USArray data as well as data from PBO and SAFOD. Significant EarthScope resources will be focused on development of an Integrated Data Access System (IDAS). The DMC is already heavily involved in these and other EarthScope developments, such as developing a web-services-based infrastructure for managing data products. The DMC staff will insure that the technology developed for EarthScope will also be applied to other products at the DMC.

Advanced National Seismic System (USGS): A key component of the evolving ANSS is the development of a data archiving and distribution system for all ANSS components, including data from broadband seismic stations, free field strong motion stations, and strong motion sensors in structures. The total data volume from a fully funded ANSS is large, up to 18 terabytes per year. The mass store at the DMC was designed to incorporate these data rates and the DMC already deals with seismic data volumes approaching this magnitude. The DMS is prepared to work with the USGS and NSF to respond to a request by the USGS to participate in the USGS ANSS Archiving and Distribution System, assuming that incremental costs required to manage ANSS data are provided by the USGS. Providing unified and coordinated access to the combined ANSS, IRIS, and international data sets would be of significant value to the scientific community. In addition, the experience of the USGS in the area of ANSS product generation can be used as a model for further product development within IRIS.

Engineering Community (NSF and USGS NSMP): The DMS already manages data from strong motion sensors installed in the FACTOR building on the UCLA campus and the Cape Girardeau Bridge in Missouri. Although these data are of great interest to the engineering community and we can manage them with little extra effort, our focus is to demonstrate a model of how these valuable data can be managed. We plan to seek funding from NSF Engineering and USGS National Strong Motion Program (NSMP) to develop the proper interfaces with the engineering community so that the waveform data in SEED format can be presented to the engineering community in a format they are used to working with. The current IRIS linkages with the ANSS and the NSMP should be beneficial in this arena.

Computational Infrastructure for Geodynamics: The DMS plans to develop cluster computing and flexible processing frameworks in close collaboration with the CIG consortium, which is a recently funded NSF initiative. CIG is interested in working with IRIS to develop the next generation of synthetic seismograms; we will be able to use their expertise and resources in this activity. CIG will be staffed with up to 10 professional software engineers. Close collaborations with the software engineering group at the DMC will benefit both groups.

UNAVCO & UNIDATA (NSF EAR and ATM): The DMS plans to continue working closely with UNAVCO and UNIDATA to develop data and metadata connections to their extended data sets and various visualization capabilities. This may include activities such as methods to manage volume data (e.g., Earth models) and the ability to automatically transform them into NetCDF files. The UNIDATA Consortium has developed the Integrated Data Viewer (IDV). It is intended for use with atmospheric sciences data, but there are clear uses for IDV in the solid Earth sciences. UNAVCO has already leveraged some of these IDV strengths. IRIS will work with UNAVCO and UNIDATA to allow streamlined data throughput from the DMC FISSURES DHI systems into the IDV arena.

Integration of Earth Sciences Data (NSF, GEON, OBSIP): During the next five years, DMS plans to take an active role in defining XML-based systems, which underlie web services. We expect to play a role in defining systems that characterize several types of data, including seismological data, other data collected at GSN and PASSCAL stations, and data in related fields such as geodesy, infrasound, and hydroacoustics. We will ensure that the web-services approach that we are implementing at the DMC can extend to other types of data. We intend to reach out to other communities that do not have formal data management systems and work with them to explore ways in which the IRIS facilities can support their data activities. The DMS could provide tools and resources to assist the appropriate groups convert time-series data streams to SEED format. Once the data are ingested at or available elsewhere in SEED format, the DMC could make them visible across broader domains by leveraging the XML-based web services that we are developing. We expect these activities to be relatively low cost (primarily involving DMC staff time). The DMS Standing Committee will retain tight advisory control as to which areas should be pursued.

Organize International Workshops

The DMS has received a very positive response to workshops we have held for training U.S. and international groups on a variety of topics related to the use and operation of data management systems. Traditionally, we have done this by organizing training courses where international participants come to the DMC for a few days or a few weeks. During the past year we teamed with ORFEUS, a non-profit organization that promotes digital, broadband seismology in Europe, and jointly convened a workshop on Managing Data and Metadata from Seismic Networks, held in Palmanova, Italy. The response to this workshop from the 40 participants from 37 countries was very strong and indicated that there is a significant need for this type of training to assist network operations in the developing world. We propose to collaborate closely with other IRIS programs and the FDSN, as described later in this proposal under Consortium Activities, to carry out one or two international training courses and workshops per year.

E&O Activities

Over the past seven years, the IRIS Education and Outreach Program has developed a range of products and activities that balances the desire to reach multiple audiences with the need to remain focused on activities that relate to IRIS strengths. In the next five years, the E&O program will maintain some successful activities in their current form, improve activities that show the greatest opportunity for increased impact, and develop several new initiatives. To maximize the reach of our activities, we will continue to collaborate with a wide range of institutions and develop projects and materials in partnership with EarthScope. To improve and focus our activities and assess their impact, we plan to implement an external evaluation of the program midway through the next award cycle.

Example display from the Museum Lite exhibit at Sunset Crater Volcano National Monument visitor center.

The AS-1 is an affordable seismometer that is robust enough to be operated in high schools and that transparently demonstrates seismometry principles.

Maintain Core E&O Program

The E&O Program is currently implemented by the Program Manager and a staff of two based at IRIS Headquarters and half-time support for an FTE at the Data Management Center. A search is underway for an additional person at the main office to develop and maintain the E&O web site and assist in the development of web-based materials. Support for an additional staff member to work on the museum display and informal education is requested in this proposal.

Operate IRIS/USGS Museum Exhibits

We plan to continue working with major museums to develop new displays based on the exhibits at the American Museum of Natural History and the Smithsonian. We expect to develop new partnerships with two to four major museums. The existence of established partnerships with major museums and a careful evaluation of the displays, combined with the demonstrated potential of the new Museum Lite display, provide the basis for expanding the program. The Museum Lite display is a simple-to-implement and low-cost way of providing high-quality, real-time seismology and other museum-quality information to a very wide audience. The Museum Lite display is also of significant interest to IRIS members and Educational Affiliates and thus will serve Consortium membership as well as the general public. Museum Lite is particularly well-suited to EarthScope/USArray outreach, as new results and discoveries can easily be added as they become available; the display can be easily customized for a particular region and for large numbers of venues. To achieve this, E&O proposes to develop an interactive customization system and associated web resources to support up to several hundred such systems within five years.

We propose a new staff person with expertise in museum exhibits and informal education to build on the success of this program. Other budget support for the museum displays includes personnel support for the development of software and content materials and the purchase of specialized equipment. Individual museums are responsible for the development and funding of individual exhibit displays customized to their specific sites.

Support the IRIS-SSA Lectureship Program

In partnership with the Seismological Society of America, IRIS has established a national lectureship program to provide prominent research scientists with a forum to bring seismology and earthquake science to the public in partnership with established speaker series at museums, colleges, and scientific societies. Two or three speakers are selected through an annual competition, approved by the SSA and IRIS Boards, and provided with travel support and an honorarium.

Promote Seismology in K-12 Education

Improving the quality and quantity of seismology-related teaching at the K-12 level requires enhanced teacher training and new products that can be used in the classroom. A recent formal assessment of our professional development workshop activities has shown them to be an extremely effective mechanism for engaging teachers and having a measurable impact on classroom practices. E&O plans to continue the one-day teacher professional development workshops in seismology held before major national meetings of scientific and educational organizations. Educational materials, including posters, one-pagers, and classroom aids are integrated into the workshops and provided to teachers and made available on the web. We plan to begin working with partners to offer more comprehensive teacher professional development, such as our recent initiative to partner with entire school districts for long-term, systemic reform.

Budget support is requested to continue to produce workshop and classroom materials and provide support for teacher participants at workshops. The AS-1 Seismograph in Schools program will be continued, providing 25-40 schools per year with AS-1 seismographs and associated instructional aids.

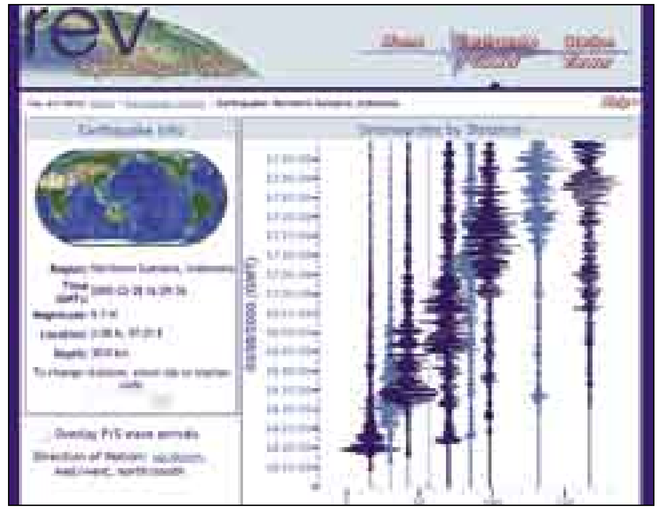
Encourage Diversity

E&O will continue to place a priority on reaching and enfranchising a diversity of audiences with all of our activities. We will establish and strengthen partnerships with programs and organizations already serving underrepresented groups, expand individual E&O activities to engage these same groups, and target underrepresented groups to include them in greater numbers in existing activities. Partnership examples include societies such as the Society for Advancement of Chicanos and Native Americans in Science (SACNAS) and the National Society of Black Physicists. We will also partner with IRIS Consortium members such as UT El Paso and UT Austin, who are either minority-serving institutions themselves or who have close ties to such institutions. We will provide more structured assistance to PIs at other IRIS institutions in outlining ways they can disseminate their research and its implications to more effectively reach locally diverse audiences. We are partnering with UNAVCO on RECESS, a program to provide a summer research environment for undergraduates from underrepresented groups based on the successful SOARS program at UCAR. We plan to work with Pennsylvania State University in AfricaArray, which has a component for the engagement of African-American students and for teacher workshops at Historically Black Colleges and Universities (HBCUs).

We plan to expand our ongoing relationship with the Yuma High School District (which is ~70% Hispanic) to translate more of our materials into Spanish, and to initiate a professional development effort with at least one other large urban school district. IRIS's location in downtown Washington, D.C. provides ongoing opportunities to work with local underrepresented groups, such as the students at Kipp Academy, a charter school dedicated to providing strong mentoring for minority students. We plan to target underrepresented groups in our existing programs as part of the internship program's recruitment efforts. Teachers who are not participating in the large national conferences where we typically hold our workshops are recruited from local urban school districts to participate in professional development efforts. Diné College, a Native American college, was one of our first Educational Affiliate members, and we plan to engage one or more HBCUs as Educational Affiliates. We will hold at least one Distinguished Lecture annually at a minority-serving institution. We also plan to increase emphasis on distribution of AS-1 seismographs to schools with a large percentage of students from underrepresented groups.

Lead the U.S. Educational Seismic Network

The U.S. Educational Seismology Network (USESN) is envisioned as a federation of universities and other groups promoting seismology education in their regions, with IRIS assisting in its leadership. E&O plans to continue facilitating USESN by providing web-based software and professional development for teachers to ensure that seismographs are used effectively in schools. E&O plans to provide overall coordination and to focus on widely applicable software, classroom exercises, simple stand-alone seismographs, and the teacher professional development needed to support these products. We are developing an improved model for the educational aspects of regional USESN programs, which we expect to include partnerships with local schools, teacher professional development, and modified classroom exercises for state standards and local curriculum. As part of its leadership role, E&O will continue to focus on providing web-based tools such as the Seismic Monitor and the new Rapid Earthquake Viewer (REV), and will continue to work with the University of South Carolina and DLESE to improve the educational capabilities of the Global Earthquake Explorer (GEE), a platform-independent seismic analysis tool that is designed for student use and accesses IRIS data via the Internet. E&O also plans to improve software and classroom modules related to the AS-1 seismograph. We plan to redesign AS–1 electronics and explore other teaching-appropriate seismograph options. If a still lower-cost seismograph can be developed, a worldwide partnership with the international GLOBE program may be seeded.



The Rapid Earthquake viewer (REV) (http://rev.seis.sc.edu/) is a web-based tool designed for general audiences that provides simple access to images of seismic data stored in the DMS. The development of REV is a cooperative project led by the University of South Carolina. REV includes contributions from the Digital Library for Earth Systems Education (DLESE) as well as IRIS E&O

We have recently embarked on an effort to establish a more formal structure for management and support of the USESN. Funds are requested to continue to support the centralized activities required to provide national coordination of the regional USESN activities and to provide an annual subaward to an IRIS institution to assist in the support of the USESN.

Improve Seismology in Undergraduate Curricula

The IRIS Educational Affiliate (EA) membership category has established a community of institutions with a common interest in the promotion and enhancement of seismology education. E&O plans to develop new initiatives to enable the EA, gradually recruit additional institutions with a proven dedication to seismology education, and continue to foster a sense of community among EA members and interactions between EA members and IRIS full members. The new Sabbaticals in Seismology (SIS) initiative addresses needs of the EA community by supporting collaborative geophysical research and education efforts involving faculty at EA and IRIS member institutions. We plan to develop a multi-day workshop to help EA representatives and other participants access seismological data, identify interesting topics that can be explored with seismological data, and gain experience manipulating the data.

E&O plans to collect seismology teaching resources aimed at the undergraduate audience, including animations, slide shows, images, maps, and video clips that complement ongoing efforts such as DLESE. With a system for individuals to rapidly contribute material, we would have a critical infrastructure for the rapid provision of timely and accurate resources for use in classrooms on events in the news, similar to IRIS's Sumatra-Andaman Island Earthquake web page. We also plan to develop a flexible electronic "primer" on global seismology that can be used by non-seismologists to introduce more in-depth coverage of global seismology in undergraduate courses. IRIS community input could flesh out an outline that includes topics often ignored or poorly covered in non-seismology texts. An annual "cutting-edge" section could circumvent the long lag in textbooks adopting new research.

Expand Internship Programs

E&O plans to expand its summer internship program by leveraging newly awarded REU funding from NSF and through partnerships with PASSCAL, UNAVCO's RECESS program, and the AfricaArray initiative. We plan to bring the interns together at an orientation program before they spend 8-10 weeks with individual hosts working on seismology research projects. Each project is structured to develop successful work skills and an understanding of scientific inquiry, to gather and convey scientific information, and to use advanced geophysical technology. Interns will communicate with each other through structured interactions via video conferencing and blogs, and relatively unstructured discussion boards. Scientific results generated from the summer project are presented at a professional conference to provide the students with the opportunity to interact with the larger IRIS and Earth science community and their peers.

Provide International Leadership

E&O plans to continue providing seed equipment and sharing expertise with school seismograph programs at various stages of development, such as New Zealand, Great Britain, France, Italy, and Costa Rica. Students are very interested in sharing seismic data among schools in different countries. IRIS can take the lead in providing the mechanism for the schools to interact.

Seed New Initiatives

E&O plans three new initiatives to increase the size of the audience reached by E&O. Limited funding is requested in this proposal to seed these activities. We plan to partner with UNAVCO and GEON, using the GEON Integrated Data Viewer (IDV), and initiate a pilot project that explains seismic tomography on the scale of USArray. Second, we plan to explore development of an on-line course and associated training, "Seismology in the Earth System," which targets formal education (grades 6-12) in-service teachers. The initiative is sustainable because IRIS would only seek major funding to develop the course. The implementation of the course would be driven by the enrollment at any IRIS schools interested in offering it. Finally, we plan to work with partners such as AGI, UNAVCO, and EarthScope to expand IRIS's involvement in video products for large markets (e.g., Discovery Channel or National Geographic). Funding for the videos will be pursued in partnership with video production companies and others by leveraging core IRIS funding.

Consortium Activities

Meetings and Publications

To ensure the continued quality and relevance of our primary tasks of supporting research through data collection and distribution activities, IRIS engages the Consortium membership, the broader research community, and funding agencies through its governance structure, meetings, and publications.

After a two-year hiatus, we will reinstate the IRIS Newsletter with a Fall 2005 issue; we intend to publish three issues per year, in addition to the IRIS Annual Report. In the past, the Newsletter proved to be a powerful means of presenting the activities and results of the Consortium and its facilities to the national and international research community, funding agencies, and the public. The Newsletter will be published in both hardcopy and electronic form on the web.

The Annual IRIS Workshop has proved to be an enormously popular and effective way to bring members and a broad sector of the research community together for review of programs and activities, plan new initiatives, and stimulate interactions among PIs, member institutions, and federal agencies. The Workshop structure includes poster sessions, theme science sessions, small working groups, and planning activities. Attendance at the workshop has continually increased, reaching over 300 participants at the Joint IRIS/UNAVCO workshop in 2005. To avoid conflict with the EarthScope Annual Meeting, NSF has directed us to hold the Annual IRIS Workshop every second year; this is reflected in the budget. To maintain momentum and retain contact with the membership, limited support is requested for smaller special theme meetings in alternate years.

The budget for publications and meetings includes staff support for publications and web materials, printing costs, and participant support costs for meeting and workshops.

International Activities

In this proposal we have demonstrated that the activities and influence of IRIS, both as a consortium and through its facility programs, have a strong international component. Each of the facility programs proposes activities that will continue and expand our ability to interact with international organizations at the scientific level and encourage the long-standing IRIS goals open data exchange, collaboration, and standardization. GSN, working with GEOSS and FDSN, will strengthen the coordinated operation of global seismic stations and encourage the expansion into other geophysical observations. The DMS will continue to build on the concept of networked data centers and encourage the sharing of data through the FDSN and through direct contacts with national and regional networks throughout the world. PASSCAL will continue to support individual PIs in foreign experiments and encourage the development of an organization similar to FDSN to stimulate interactions and exchange in portable seismology.

Recent experience of IRIS staff members and of representatives from our member institutions indicates that the international community recognizes the capability of Earth scientists to contribute simultaneously to capacity-building and natural-hazard mitigation. But success in these areas requires long-term projects that deeply engage the people and institutions of developing countries to an extent that is beyond the scope of a typical seismic experiment. To help IRIS institutions contribute effectively in this area, we propose to establish a central coordination function for international activities within the IRIS Headquarters Office, with the objective of fostering the development of new activities to expand international efforts in seismological education, research, and monitoring. Headquarters staff devoted to this function will assist with activities being carried out by the core facility programs, work at the Consortium level with our member institutions, and engage with the international development organizations to explore opportunities for new funding.

Over the next five years we intend this enhanced commitment to international activities to help us bring the strengths, experience, and expertise of IRIS and its member institutions to assist in capacity-building, especially as it relates to improving seismic monitoring and research in the developing world. Following the model being established by AfricaArray, and previous IRIS experience in Central Asia, this will be done through involvement in workshops and training courses, donation of retired instruments, assistance establishing data centers, and encouragement of educational and research contact with IRIS member institutions. We envision an expansion of the IRIS foreign affiliates program, both in the number and geographic distribution of affiliates and in the commitment of foreign affiliates to principles espoused by IRIS, most importantly free and open access. We anticipate progress in this regard partly because IRIS has a well-established record of making its own data freely available, and a growing record of facilitating use of open data by researchers and other users all over the world.

Budget Plan

The plan presented in this proposal covers the five-year period July 1, 2006 to June 30, 2011. This section presents an overview of the funding request to support the activities included in this proposal, a discussion of the primary budget elements, and a brief review of funding under the current five-year Cooperative Agreement. Detailed budget information is provided separately to NSF for purposes of proposal review. More detail on the history of IRIS funding can be found in the section later in this proposal on "Consortium and Management Structure".

Budget Request by Core Program

Table 1 and Figure 1 show how the total budget request of $89,459,077 for the five-year period 2006-2011 is partitioned by time and by core program. As shown in the pie chart in Figure 2, approximately 80 percent of the budget is for support of the three largest programs, GSN, DMS and PASSCAL, with nearly equal amounts requested for each of these programs. The relative size of the core programs has evolved over the history of IRIS. Prior to the mid-1990's, when the GSN and PASSCAL facilities for instrumentation and data generation were being established, these programs constituted a larger part of the total budget. As the role of the DMS in distribution of data has expanded, the percentage of the budget applied to data management has increased. Education and Outreach accounts for approximately 5 percent of the budget and Consortium and Community Activities for 3 percent. The aggregate rate for indirect expenses and management fees is less than 10 percent of the total budget.

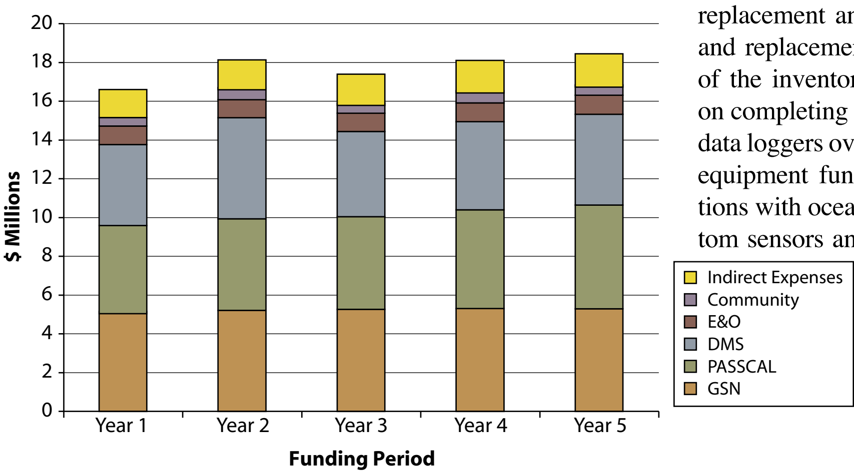


Figure 1. Budget profile, 2006-2011 by IRIS core program

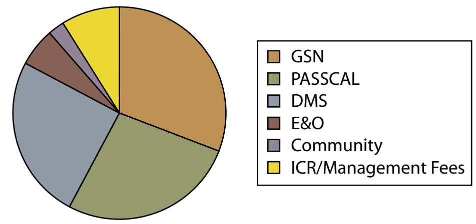


Figure 2. Budget profile, 2005-2011 by percentage for each IRIS core program.

Program Budgets by Expense Category

Figure 3 and Table 2 show the five-year funding request by different budget categories for each of the core programs. In addition to highlighting the main cost elements, this presentation also indicates the different organizational styles of the core programs.

GSN. The subaward to UC San Diego for personnel (11 FTEs) and operation of the IDA component of the GSN is the primary external subaward for IRIS support of GSN operations. The major component of the equipment budget for GSN is for replacement and upgrade of GSN stations. Funding for new and replacement equipment is requested at the level of 10% of the inventory base per year and emphasis will be placed on completing the upgrade all GSN stations with standardized data loggers over the next five years. The GSN budget includes equipment funds to cost-share in expanded GSN collaborations with ocean and polar programs. This includes ocean bottom sensors and recorders (4 borehole packages and 8 ocean bottom seismometers) and specialized low-temperature sensors and recorders for use at 2-3 new sites in Antarctica. Telemetry costs and site enhancements are also significant components of the GSN operational budget. Following the Sumatra earthquake, special supplemental funds to the USGS included

	Yr1	Yr2	Yr3	Yr4	Yr5	Total	% of Budget
GSN	5,145,307	5,198,014	5,256,272	5,296,129	5,283,630	26,179,352	29.26%
PASSCAL	4,553,869	4,733,300	4,776,655	5,087,109	5,349,098	24,500,031	27.39%
DMS	4,166,464	5,212,756	4,399,673	4,552,845	4,690,197	23,021,935	25.73%
E&O	964,193	929,679	945,630	962,058	978,980	4,780,541	5.34%
Community	426,152	621,026	509,257	631,705	524,376	2,712,515	3.03%
ICR/management fees	1,503,337	1,591,096	1,666,235	1,729,638	1,774,398	8,264,703	9.24%
Total	***16,759,321***	***18,285,871***	***17,553,722***	***18,259,484***	***18,600,679***	***89,459,077***	***100.00%***

Table 1. Budget profile, 2006-2011 by IRIS core program

support for enhanced telemetry to GSN stations and over the next five years, the GSN goal is to establish and maintain full real time telemetry of data from all stations.

The operation of the Global Seismographic Network and associated activities of the Data Management System are carried out in partnership with the USGS. A Memorandum of Understanding between the NSF and USGS establishes the general framework for interagency collaboration in research in the Earth Science and an Annex on the Global Seismographic Network between NSF, USGS and IRIS describes the arrangements for support and operation of the GSN. Under this agreement, NSF, through IRIS, provides equipment for new and upgraded stations and pays for installation of new stations. The USGS provides the support for operation and maintenance of stations once they are established as part of the GSN. Full funding for the GSN thus includes the additional USGS support of approximately $3.5M per year for their component of the GSN. Most of the USGS funding is for personnel and operational support. Under the USGS-NSF-IRIS MOU, costs for new equipment and upgrades at all GSN stations are provided through IRIS/NSF.

PASSCAL. The core of the PASSCAL operations is the subaward to New Mexico Tech for operation of the PASSCAL Instrument Center (PIC), primarily for staff support. Staffing at the PIC will grow from 13 to 17 FTEs over the next five years, with emphasis placed on enhanced user services, document preparation, and support for software and data management. Support for field experiments includes training, materials and supplies and assistance with shooting and permitting. Smaller subawards include support of the shared Texan instrument facility at UTEP (1.5 FTE) and developmental support of the telemetered broadband array at UC San Diego (1.5 FTE). All permanent equipment for PASSCAL and most field supplies are charged directly to IRIS, rather than through the New Mexico Tech subaward. The primary equipment requests in the PASSCAL budget are for replacement of damaged and lost instruments and modest expansion of both the broadband and active source instrument pools. Funding for a total of 500 single channel Texan instruments and 105 broadband systems is requested. To stimulate instrumentation development, new generation sensors and recording systems will be acquired and tested as they become available.

DMS. In contrast to GSN and PASSCAL, the Data Management Center is staffed by IRIS personnel and thus the largest component of the DMS budget is for IRIS staff salaries and benefits. The staff at the DMC supported under this proposal will grow from 13 to 18 over the next five years. Equipment included in the DMS budget includes on-going upgrade and replacement of the base of server, disk and computer hardware at the DMC. In addition, costs are included for a proposed active backup system (~$1M) and a 256-node cluster computer (~$1M in year 2). Participant support costs cover workshops and courses provided by the DMS for both domestic researchers and international partners in data collection. Subawards are used to provide support to other DMS nodes including the DMC host at University of Washington, IDA Data Collection Center at UCSD and the Waveform Quality Control Center at Harvard. Licenses for the commercial database and mass store control software are included under Other Di-

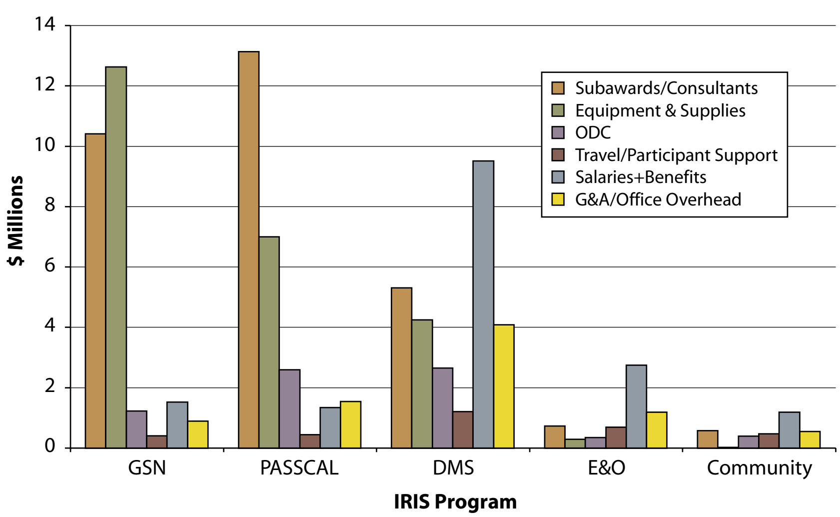


Figure 3. Budget profile 2006-2011 for each of the core IRIS programs, showing total amounts in each of the primary NSF budget categories.

	GSN	PASSCAL	DMS	E&O	Community	Total
Subawards/Consultants	10,404,156	13,135,014	5,302,375	725,000	575,000	30,141,545
Equipment	11,195,000	3,230,000	3,865,834	25,000	20,000	18,335,834
Materials & Supplies	1,432,500	3,767,500	501,000	260,000	75,000	6,036,000
Other Direct Costs	1,225,000	2,590,000	2,642,620	345,000	387,500	7,190,120
Travel/Participant Support	400,000	435,000	1,205,000	685,000	472,500	3,197,500
Salaries & Benefits	1,522,696	1,342,517	9,505,106	2,740,541	1,182,515	16,293,375
G&A/Office Overhead	888,283	1,540,203	3,938,825	1,102,639	544,752	8,014,703
Management Fees						250,000
Total	***27,067,635***	***26,040,234***	***26,960,760***	***5,883,180***	***3,257,268***	***89,459,077***

Table 2. Budget profile 2006-2011 for each of the core IRIS programs, showing amounts in each of the primary NSF budget categories.

rect Costs (ODC) in the DMS budget. The DMS carries a higher Office Overhead component than the other programs to cover support the DMC office in Seattle.

E&O. The primary budget element for E&O is salary support for the Program Manager and staff. In addition to the Program manager, current staffing includes an education specialist, outreach specialist and partial support for a software engineer. Proposed new hires include an E&O Webmaster and museum specialist. Funds are requested to continue public outreach through the successful museum programs and Distinguished Lecture series. Partial funding is requested to partner with the American Geological Institute and American Institute of Physics on video and television productions. Students and teachers are impacted through professional development workshops, internships and the provision of classroom materials including posters, educational seismometers, one-pagers and teaching supplements. A subaward for the US Educational Seismograph Network will coordinate school activities in observational seismology.

Consortium and Community Activities. In addition to the core facility programs, IRIS carries out activities through the Headquarters Office to engage and inform the members of the Consortium and coordinate with other national and international programs. The Publications Coordinator is responsible for production of the Newsletter, Annual Report and special reports and for partial support of the IRIS website. Participant support costs offset expenses for members to attend IRIS workshops. The budget requests funding for a new initiative to coordinate IRIS international activities. Over the next two years, and International Coordinator and Assistant will be hired to work with the Director of Planning, Program Managers and Foreign Affiliate Members to coordinate and provide continuity for existing efforts (e.g. training workshops, data exchange, participation in FDSN and support of regional efforts such as AfricaArray and KNET) and develop a focused and sustainable program to build upon IRIS's significant international activities.

Common to each of the programs are travel support for program staff and Standing Committees, and the program's share of IRIS administrative expenses through Indirect Cost Recovery (ICR). The IRIS ICR structure has two components:

General and Administrative covers IRIS-wide administrative and business office expenses, including senior management staff. All programs are assessed G&A at a rate of 17% on modified direct costs (total costs less equipment and most subaward and participant support costs).

Office Overhead covers the rent, telephone, office equipment and administrative support salaries at the IRIS Headquarters office in Washington DC and the DMC office in Seattle Washington. An Office Overhead rate of 22% for DC and 20% for Seattle is assessed on salaries of all staff working at these locations.

Comparison with the Current IRIS-NSF Cooperative Agreement

Funding under the current Cooperative Agreement with NSF (CAGR 0004370) is summarized in Table 3. The IRIS proposal submitted to NSF in 2000 requested a total of $76.1M over five years ("As Proposed" in Table 3). Following review by NSF and approval by the National Science Board, the funding schedule included in the Cooperative Agreement anticipated a total of $68.0M ("Funding Schedule in Table 3) for the tasks as shown in box on page 47, "contingent on the availability of funds and the scientific progress of the project...". Because of funding constraints, especially since 2003, NSF was unable to reach the anticipated funding, and the actual funding from the I&F program over the five-year period totaled $63.7M ("Actual Core" in Table 3).

During this funding period, IRIS received additional funding that was transferred through the EAR Cooperative Agreement from other NSF programs (Ocean Science, for H2O support; and Polar Programs, for special Antarctic equipment and communications) and via interagency trans-

Current Cooperative Agreement

	As Proposed	*Funding Schedule*	*Actual Core*	*Actual Total**	*06-11 Proposed*
01/02	14,570,000	12,600,000	12,600,000	14,862,934	16,759,321
02/03	14,922,070	13,100,000	12,960,664	16,184,833	18,285,871
03/04	15,239,455	13,600,000	13,158,604	16,357,792	17,553,722
04/05	15,590,823	14,100,000	12,800,000	15,812,289	18,259,484
05/06	15,969,493	14,600,000	12,160,000	12,302,931	18,600,679
Five Year Total	***76,291,841***	***68,000,000***	***63,679,268***	***75,520,779***	***89,459,077***

* Actual total includes DOE, NASA, OCE(H2O), OPP, etc., and is projected for 05/06.

Table 3. Funding under the current 2001-2006 Cooperative Agreement between IRIS and NSF. "As Proposed" are the amounts requested in the original proposal from IRIS to NSF. "Funding Schedule" shows the anticipated funding schedule included in the Cooperative Agreement. "Actual Core" shows the funding provided from the core EAR/I&F program. "Actual Total" shows the amounts passed through the Cooperative Agreement including supplemental funding from other NSF programs and interagency transfers.

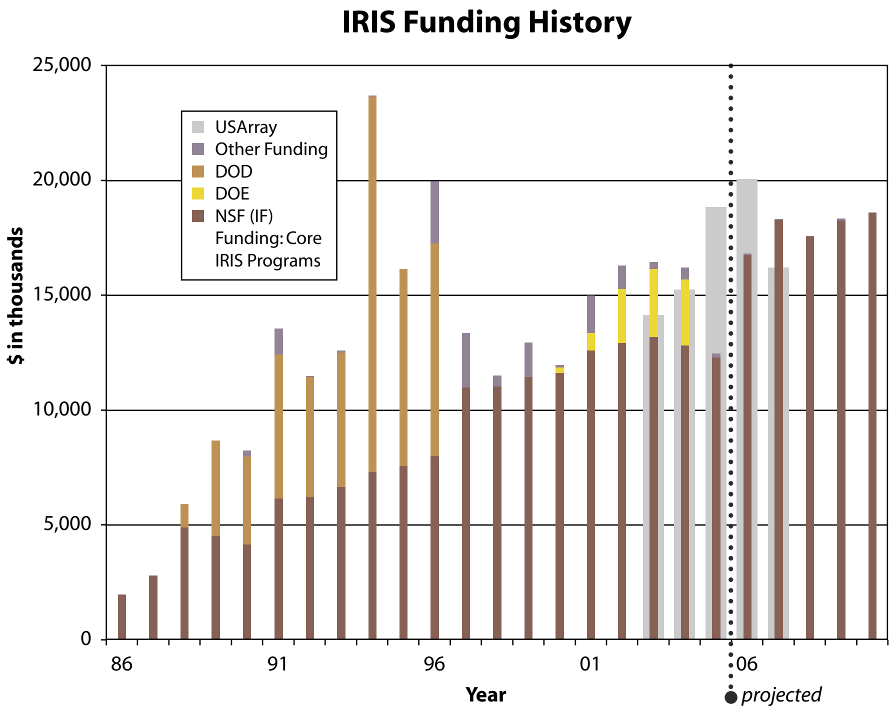


Figure 4. IRIS funding history and budget levels requested in this proposal. See later section on "Consortium and Management Structure" for more detail.

fer from other federal agencies. The most significant interagency transfer was $9.1M from DOE for replacement of the PASSCAL instruments. The total funding passed through CAGR 0004370 is shown as "Actual Total" in Table 3. The only significant funding received by IRIS to support core programs operations outside the Cooperative Agreement has been funding of $320,000 to support upgrades of communication systems at GSN stations provided by the International Monitoring System of the Comprehensive Test Ban Treaty Organization in Vienna. The core and actual funding under the current Cooperative Agreement are compared with past funding, current USArray support and the budget requested in this proposal in Figure 4.

From: NSF-IRIS Cooperative Agreement EAR-0004370 • Exploring the Earth at High Resolution: The IRIS 2001 – 2006 Program Plan

C. STATEMENT OF WORK AND AWARDEE RESPONSIBILITIES

The Incorporated Research Institutions for Seismology shall be responsible for the project in accordance with its proposal EAR-0004370 as modified by the August 1, 2001 cover letter with revised Year 1 budgets. The Awardee shall be responsible for establishing, operating, maintaining, and managing the IRIS core programs, which consist of the Global Seismographic Network (GSN), a pool of portable seismic recording instruments (Program for Array Seismic Studies of the Continental Lithosphere or PASSCAL), the Data Management System (DMS), and Education and Outreach E&O). In particular, IRIS shall:

1. Acquire instrumentation for the GSN and install it at GSN station sites in accordance with the NSF-approved Annual Program Plan and Budget.
2. Assume responsibility for the operation and maintenance of all GSN stations designated as IRIS GSN stations in accordance with the approved Annual Program Plan and Budget and work with the U.S. Geological Survey (USGS) to ensure the continued high-quality operation and maintenance of IRIS/USGS GSN stations.
3. Carry out and report to NSF by July 1, 2003, an in-depth study of the operation, personnel and instrument costs, and support of the Global Seismographic Network, in collaboration with NSF, USGS, representatives of the Federation of Digital Seismic Networks (FDSN), and GSN network operators.
4. Acquire PASSCAL instrumentation in accordance with the approved Annual Program Plan and Budget.
5. Maintain the PASSCAL instrument pool at the PASSCAL Instrument Center so that it is available to support high-quality seismic research by the U.S. academic research community in accordance with the approved Annual Program Plan and Budget.
6. Continue to operate the DMS in accordance with the approved Annual Program Plan and Budget.
7. Provide rapid access to all seismic data collected by IRIS programs and help coordinate access to seismic and other Earth science data collected with support from other national and international organizations.
8. Coordinate the siting and instrumentation of the IRIS GSN stations with the international FDSN and its member nations, as well as the USGS and other U.S. agencies so that the common goal of global coverage is achieved as rapidly and efficiently as possible.
9. Coordinate feasibility studies regarding methods of instrumenting and installing ocean-bottom GSN stations with national and international groups so that GSN coverage of the oceans is achieved as rapidly and efficiently as possible.
10. Educate pre-college and college students and the public about seismology, the Earth sciences, and IRIS through museum and school exhibits and other educational programs in accordance with the approved Annual Program Plan and Budget of the Education and Outreach Program.
11. Monitor the scientific, technical, and fiscal performance of all subawards made under the terms of this Agreement, ensuring that all NSF requirements are observed.
12. Execute the scientific, technical, and fiscal responsibilities of IRIS projects supported by Federal agencies other than NSF and approved as part of this Agreement, ensuring that all NSF requirements are observed.
13. Keep NSF informed of all activities carried out under this Agreement and other IRIS activities funded by Federal Agencies other than NSF.
14. Engage in appropriate programs to inform the Earth science community about the potential uses of the IRIS facility and to keep the community informed about its accomplishments.

Statement of Work, IRIS 2001-2006 Cooperative Agreement

Proposal Summary

These are exciting days for the solid Earth sciences; major advances are being made in our understanding of many fundamental processes in the Earth system, the ambitious EarthScope project is well-underway, and the first comprehensive global data set for a truly huge earthquake has been recorded and analyzed. IRIS facilities, mature after 20 years of development, are contributing on many fronts to the exciting advances, and the preceding proposed activities section has identified numerous innovative, heavily leveraged, and promising directions for the next five years, while sustaining the basic facility functions that continue to yield such a bounty of scientific returns.

This IRIS proposal seeks to sustain the momentum of facility and Consortium activities, to deepen and enrich the scope of international, educational, and instrumental efforts, and to enhance user services and data access to support research by users of the facilities. The introduction to the proposal posed overarching thematic questions that have guided our proposal development. Through multi-faceted data collection, data distribution, and Consortium activities, IRIS is catalyzing and supporting integrative research in the Earth sciences, extending across disciplinary boundaries, NSF program structures, and different federal research organizations. Strategies for achieving efficient, sustainable facilities for data collection are articulated by all of the IRIS core program efforts. Efforts to enhance user services are found throughout the proposed activities, in data collection in the field and in innovative IT efforts that will facilitate analysis of huge data sets from multiple data centers, supported by new data quality control and assessment tools. Attention is paid to the long-term development of next-generation instrumentation, including the challenge of encouraging development of very broadband seismometers. Specific and directed efforts to promote diversity and to partner with programs that offer strategic opportunities for real impact on diversity have been presented. The international aspect of IRIS facilities has never been stronger. A specific management plan is proposed to capitalize on international relationships and partnerships in a more sustained manner with improved follow-through. These efforts will promote international development of related geophysical capabilities and achieve efficiencies in the long-term operation of IRIS facilities. With recent restructuring of its internal governance, IRIS continues to embrace its role-model stature for Earth sciences consortia. IRIS will sustain this effort in the years ahead, continuing to advocate for community involvement in prioritization of resources, open-access policies for national and international scientific data sets, and multi-agency cooperation.

While we have tremendous enthusiasm for the full span of activities described in this proposal, we are well aware of the budgetary constraints under which NSF is currently operating. It is IRIS's strong desire and intent to work with NSF to achieve this full program, diversifying our funding base wherever possible and developing new efficiencies and partnerships to control costs. IRIS is not content to rest on its laurels, nor is it complacent about the need to continually justify the investment of community resources by providing exciting, high-impact facilities for seismology and the Earth sciences. Through steadfast engagement with the research community and our diverse partners, we will strive to innovate, evolve, and diversify as needed to best serve the research community. The broadly based community input to this proposal reflects this philosophy, which has been a hallmark of IRIS success in the past.

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