GEO FACILITIES PLAN

1999-2003

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Directorate for Geosciences

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OFFICE OF THE
ASSISTANT DIRECTOR
FOR GEOSCIENCES

July 1999

Facilities and instrumentation for observation, experimentation, analysis, and computation are essential to carry out cutting edge research in all fields of the geosciences. As we enter the twenty-first century, one important priority for the Directorate for Geosciences (GEO) at the National Science Foundation (NSF) is the provision of support for both the development of new and innovative facility capabilities, and the maintenance and enhancement of existing systems. This support is important not only to the basic research enterprise but is also of great value for education and outreach activities.

This document, the ***GEO Facilities Plan*** 1999-2003, complements the ***GEO Science Plan, FY*** 1998-2002 (NSF 97-l 18) which described specific research goals that GEO will strive to attain over the next 5 years. The capabilities described in this document are intended to enable the achievement of the objectives described in the Science Plan. This is the first 'Facilities Plan' that GEO has produced and it is intended to provide guidance concerning the highest priority areas of facility maintenance and development.

Basic research in the geosciences requires a vast range of capabilities and instrumentation. GEO engages in a long range planning process that evaluates the opportunities and needs within the geosciences, and seeks to determine what facilities and instrumentation should be developed to pursue these opportunities. The planning of these facilities relies strongly on communication between GEO staff and the geoscience research community. Indeed, the basis for all the major facility components described in this document is many reports from community-based workshops and meetings, examples of which are referenced in the report.

The active involvement of the research community in GEO's long-range planning process is manifest in the active role that the Advisory Committee for Geosciences (AC/GEO) has played in the preparation and review of this document. AC/GEO consists of sixteen leading researchers and educators from the broad range of geoscience disciplines and a variety of institutional settings, including academia, government, and the private sector. AC/GEO members endorse this facilities plan and urge all those with interests in the geosciences to review this plan and contribute to the development of updated plans in the future.

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Top: Photo of the NSF-owned Electra, operated by the National Center for Atmospheric Research (NCAR).

Middle: Dots denote the globally distributed sites of the IRIS Global Seismographic Network (GSN).

Bottom: The Research Vessel *Oceanus* - a mid-sized general purpose member of the U.S. Academic Research Vessel Fleet.

1.0 Introduction

1.1 Context

The mission of the Directorate for Geosciences (GEO) of the National Science Foundation (NSF) is to advance scientific knowledge about the solid Earth, freshwater, ocean, atmosphere, and geospace components of the integrated Earth system through support of high-quality research; through sustenance and enhancement of scientific capabilities; and through improved geoscience education (GEO Science Plan, 1998).

To fulfill its mission, GEO strives to attain three goals:

- advance fundamental knowledge about the Earth system;
- enhance the infrastructure used to conduct geoscience research; and
- improve the quality of geoscience education and training.

This document describes GEO's plan to achieve the second of these three goals over the next five years, and complements the *GEO Science Plan, FY 1998-2002* (NSF 97-118).

1.2 Facilities in the Geosciences

Basic research in the geosciences uses a vast range of capabilities and instrumentation, including large observation platforms (e.g., research vessels, planes), ground-based observatories, supercomputing capabilities, real-time data systems, and laboratory experimental and analysis instruments.

Facilities in the Geosciences are systems that serve the experimental, analytical, observational, or computational needs of extended user communities.

In this context, "systems" includes not only hardware and instrumentation, but also, in some cases, necessary technical and operational support. "Extended user communities" refers to users outside of the facilities' immediate location or campus, and generally refers to regional centers at a minimum, but frequently to operations that serve national or international communities. It is the role and function of a particular system in the community that determines whether or not we call it a facility, not the mode of financial support or the management structure. Modes of support and management are highly variable across the different programs within GEO, because modes of operation of the different facilities vary substantially. Support and management approaches are tailored optimally to the characteristics and needs of each facility. In all cases, management practices require responsible maintenance programs, and encourage the continuous development of plans for system upgrades to insure capabilities are 'state-of-the-art.'

The importance of instrumentation systems and facilities maintained by individual investigators for their own use is recognized, but is not the subject of this document. Individual investigator experimental and data acquisition capabilities are essential to a healthy and innovative basic research activity, but as previously stated, this plan is concerned only with those systems that serve the needs of extended user communities.

Decisions concerning the development and continued operation of facilities are made by GEO management only after considerable consultation with the scientific community. Throughout this document, the superscripts reference key workshop and planning documents that have played important roles in GEO deliberations. While it is impossible to provide a completely exhaustive list of these references, the examples used are intended to illustrate the extent of the community-based discussion and deliberation process that precedes any significant decision by GEO management concerning the support of facilities.

1.3 Characteristics of Facilities

All facilities supported by GEO should have the following seven characteristics:

- Their characteristics and capabilities should be driven by the basic research supported by NSF programs.

- They should perform at the cutting edge of their respective research topics and demonstrate the capacity to evolve and continuously improve their services and capabilities.

- They should be managed in the most efficient and cost-effective manner possible, and where appropriate, foster and encourage competition between various centers.

- Their characteristics and capabilities should be well publicized in appropriate ways, and guidelines for gaining access to the facility must be readily and widely available. In general, access to the capabilities of the facility should be as open as is reasonable and practical to appropriate members of the U.S. academic community.

- The data produced by GEO facilities should be made openly available to the national and international scientific communities in a timely way, protecting the interests of the principal investigator, but strongly supporting the concept of free and open access to scientific data.

- They should form, where possible, partnerships with operating institutions, private foundations, states, industry, other federal agencies, and also with other nations.

- They should, when possible, play important roles in education at many different levels - opportunities should be recognized and programs established to reap the maximum benefit.

In making choices about the distribution of resources, GEO managers must maintain an appropriate balance between development of innovative capabilities and the support and maintenance of important, but routine measurement systems. Decisions concerning both the development of new facilities and whether or not to continue support of existing capabilities should be driven by the needs of the research programs. These requirements are outlined in the *GEO Science Plan FY 1998-2002* (NSF 97-118), updated every two years, reviewed by the Advisory Committee for Geosciences, and based upon broad input from community-based workshops and planning documents.

The structure of funding mechanisms is designed to ensure support is provided only to those facilities for which appropriate demand exists from NSF-supported investigators. When usage falls below critical levels so that operation is no longer cost-effective, the facility is restructured or phased-out, in consultation with the community.

1.4 Competition and Recompetition

Recommendations in the recent National Science Board (NSB) resolution (NSB-97-224) on “Competition, Recompetition, and Renewal of NSF Awards” will be followed. The NSB supports the principle that expiring awards are to be recompeted unless it is judged to be in the best interest of U.S. science and engineering not to do so. This position is based on the conviction that peer-reviewed competition and recompetition is the process most likely to assure the best use of NSF funds for supporting research and education. It is essential that NSF determine periodically whether a particular facility still represents the best use of NSF funds, however, because of the complexity of major facility awards there is no single procedure for their review.

1.5 GEO Facilities and the Government Performance and Results Act

GEO recognizes the special importance of achieving the four primary performance goals on Facilities Oversight included in NSF's Performance Plan:

- Keep construction and upgrades within annual expenditure plan, not to exceed 110 percent of estimates.
- Keep construction and upgrades within annual schedule, total time required for major components of the project not to exceed 110 percent of estimates.
- Keep total cost within 110 percent of estimates made at the initiation of construction.
- Keep operating time lost due to unscheduled downtime to less than 10 percent of the total scheduled possible operating time.

These performance goals will not stifle risk-taking and innovation in the development of new facilities, but will impose planning strategies designed to recognize important uncertainties in development costs and duration, and will require management approaches capable of responding effectively to these uncertainties.

2.0 An Integrated View of the Future

Several common themes will dominate the development of research capabilities over the next five years. To varying degrees, they are themes that can be recognized in today's research programs, and in the future will play an even stronger role in guiding directions and decisions.

- **The Access Revolution** One of the most powerful and productive trends in modern-day basic research in the geosciences is the increasing access investigators have to both specialized research instrumentation and data.

  Research vessels have been readily available to all NSF investigators, independent of whether they are affiliated with a major oceanographic center, and now extremely sophisticated seagoing instruments are available in an analogous fashion. State-of-the-art seismological instrumentation is now routinely provided for continental seismic experiments whereas in the past it was not as accessible. Research aircraft and specialized instruments are now broadly available to the geosciences community.

  A computer-based collaboratory system allows real-time, remote access to data from the chain of incoherent scatter radars. The Internet has revolutionized access to large data bases: U.S. investigators have near-real-time access to data recorded by the Global Seismographic Network (GSN) through the Incorporated Research Institutions for Seismology (IRIS) data center; high-resolution multibeam sonar images of the ocean floor can be accessed by any interested investigator on the Ridge Interdisciplinary Global Experiments (RIDGE) program multibeam data base; Unidata links universities to National Center for Atmospheric Research (NCAR) and other atmospheric databases. These are only a few examples of the expanding capabilities GEO funding brings to the academic community. Future emphasis will be placed on supporting those facilities that expand and improve access to the most sophisticated capabilities and data sets. Several examples of proposed initiatives are described in this document: the data assimilation activities in oceanography, the collaboratory concept, and the growing IRIS data management system.

  Investigators from the smallest of the nation's universities can compete for funds based on the quality of their ideas, not upon their ability to gain access to the required data or instrumentation. Increasingly, access to data sets in near-real-time is allowing investigators to respond to natural 'events,' and design powerful experiments around natural perturbations occurring in the Earth's complex systems. Real-time access also provides unique opportunities for communicating the excitement and mysteries of the Earth's dynamic environment to students, educators, and the general public. Many are unaware of the magnitude of the continuous changes occurring in the Earth system so providing accurate and timely information to the broadest possible audience is an important goal. Many activities supported by GEO exemplify these objectives; e.g. seafloor observatories and the relocatable atmospheric observatory.

- **Integration Across Disciplines** The boundaries between traditionally distinct disciplines are eroding to meet the intellectual challenge of understanding the Earth as an integrated system. The GEO facilities must follow this trend, and provide capabilities crossing traditional disciplinary boundaries. As the continental drilling program and the next generation of ocean drilling develop, their goals and objectives must be coordinated, and where appropriate, integrated. As new systems for ocean floor seismology are designed, they must be integrated with existing network capabilities on the continents. Atmospheric sciences facilities must extend measurement capabilities to better observe processes occurring at the boundaries between physical domains. Although individual GEO facilities are managed within atmospheric, earth, or ocean sciences, science trends demand they evolve to provide the overall geosciences community with the broadest possible spectrum of capabilities and serve communities beyond individual disciplines. For instance, several atmospheric sciences facilities at remote locations, such as the Sondrestrom Radar in Sondrestromfjord, Greenland may eventually serve as focal points for studies of Arctic seismology, glaciology, biology, and social science. Another example is the infrastructure provided by the stations of the GSN that can be used to measure other geophysical parameters at a globally distributed array of observation points.

- **Interagency Coordination** The facilities that GEO funds are justified first by their utility to NSF investigators. However, in many cases these facilities are community-wide resources that receive support from multiple agencies. It is Directorate policy to actively seek out and maintain partnerships with other agencies in order to most effectively provide the research community with the highest quality facilities. Working cooperatively with the Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration (NOAA), and National Aeronautics and Space Administration (NASA), along with industrial partnerships from Orbital Sciences Corporation and Allen Osborne Associates, the Division of Atmospheric Sciences led the effort to launch a satellite carrying a Global Positioning System (GPS) receiver that demonstrated GPS radio signals can provide accurate measurements of tropospheric and ionospheric properties. In the earth sciences, the IRIS GSN receives roughly two thirds of the support required for the operation and maintenance of its 110 stations from the United States Geological Survey (USGS). In the ocean sciences, through an interagency partnership that has been in place for over 25 years, more than 10 federal agencies cooperate to support the Academic Research Vessel Fleet. These are only a few examples of the large number of interagency agreements currently in place that allow GEO to more effectively provide facilities to its community. This policy of actively seeking out new relationships with sister agencies to cooperate in the support of key facilities will continue to be a strong component of GEO's plans for the future.

- **Data Quality** The need to maintain high standards of quality in data collection systems and databases is obvious. However, as the heart of all cutting-edge research, data quality management deserves emphasis. As the users of large complex data sets become more widely distributed than the investigators who collect and archive the data, it is increasingly important to develop practices and procedures ensuring the integrity and accuracy of the data. All GEO supported efforts will include management systems to guarantee that data characteristics and uncertainties are clearly defined.

- **Continuing Exploration** As more structured and sophisticated (and therefore costly) data collection systems become available, appropriate priority of support must be established for research that extends beyond the boundaries of current understanding. Recent discoveries in dynamic time-dependent characteristics of many important phenomena underscore the need for sustained time-series measurements of parameters, the time-variability of which is not fully understood. This can be termed 'exploring-in-time,' because often unexpected events or variations are revealed when consistent measurements are made for extended periods. The GEO facilities must provide data access to enable investigators to seize these groundbreaking exploratory opportunities.

- **Facilities and Research: Ever-Tightening Bonds** It is crucial to maintain and strengthen links between facilities and the research they support. The GEO facility capabilities must be driven by research needs. Facility selection, operation, and management procedures must allow continuous evolution of capability to match community needs. This 'matching' of facility capabilities to research needs must occur at every level - from the interaction of individual investigators with facility providers, to maintaining clear links between the goals enumerated here with those in the *GEO Science Plan, FY 1998-2002*.

3.0 Key Areas for Development of Existing Facilities

Scientific advances in environmental and geosciences research require significant investments in observational, computational, laboratory, and sample and data access systems. Many field projects supported by GEO require extensive facility support for the study of complex, interdependent processes extending over large areas. Large data streams and more comprehensive models of Earth systems require significant investments in computational systems and coordination between modeling and observational communities. Laboratory capabilities are essential. Shared access to samples and data for analysis of environmental processes requires the development of new technologies and new approaches to distributed information management. GEO is committed to the support of necessary laboratory instrumentation for use by individual investigators via conventional research project grants. This plan is restricted to consideration of those systems that serve the needs of extended user communities. Here we describe existing GEO facilities and potential plans for their maintenance and improvement over the next five years.

3.1 Environmental Observation Systems for Basic Research in the Geosciences

The geosciences have always employed a wide range of observational and experimental tools, but recent technical progress has substantially expanded the scope and accuracy of measurements that are possible today. GEO facilities support for environmental observing systems focuses on both maintaining and upgrading existing capabilities, while enabling the innovative technologies that will provide the foundation for future discoveries.

- **The Global Positioning System (GPS)**[18,28] is currently capable of determining positions anywhere on Earth with precision of better than a few millimeters. Predictably, such capabilities have spawned an explosion of applications in the geosciences, including the direct measurement of lithospheric plate motions, deformation in plate boundary zones, seismic and volcanic deformation, motion of glaciers and ice sheets, post-glacial rebound, and sea level changes.

  The University NAVSTAR Consortium (UNAVCO) facility provides infrastructure support for efficient, economical pooling of community resources. Current UNAVCO activities include maintenance and repair of receivers and associated equipment, assistance for GPS field projects, station installations for permanent networks, antenna calibrations, and data acquisition, archiving and distribution.

  To keep pace with GPS applications in the geosciences during 1999-2003, UNAVCO proposed plans include: (1) installation of permanent stations for the International GPS Service Global Geodetic Reference Network, as well as permanent stations for focused regional studies, and (2) completion of the GPS Seamless Archive Center, with nodes at UNAVCO-Boulder, the Jet Propulsion Laboratory at the California Institute of Technology, the University of California at San Diego, and the University of Texas at Austin, providing a unified system for data management for the GPS-geodesy community.

  NSF is working with other federal agencies to ensure the GPS continues as the international navigation, positioning, and timing standard for peaceful civil, commercial, and scientific applications.

- **Research Vessels**[8] A modern and efficiently operated fleet of research vessels is essential to support field programs for a diverse set of research projects from all fields of environmental and oceanographic sciences. The 28-ship academic fleet can be broadly divided into three categories, with operating modes and capabilities responsive to differing components of research requirements:

- 6 ships with capabilities for extended global research cruises to regions distant from home port;
- 12 intermediate and large coastal ships with capabilities for multidisciplinary and single investigator studies throughout U.S. waters and adjoining regions; and
- 10 regional and local research ships with capabilities for smaller projects close to homeport and in near-shore waters.

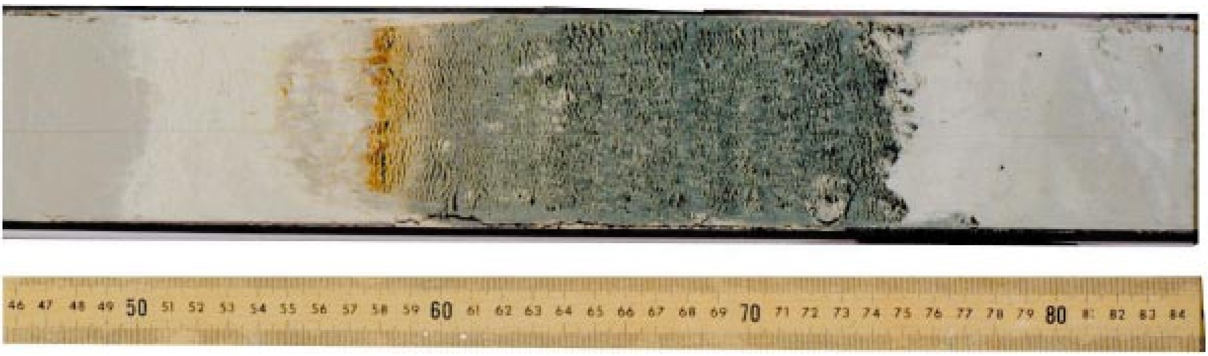
Specialized capabilities for sea-going research include the deep submergence facility, ALVIN, associated remotely operated vehicles (ROV's), and new autonomous undersea vehicles (AUV's). Upgrading existing systems, including possible major changes to ALVIN for increased depth capability, and developing new unmanned systems is needed.

NSF works closely with other federal agencies and the academic community through the University-National Oceanographic Laboratory System (UNOLS) to ensure an appropriate match of research and operating funds to meet national requirements. A comprehensive evaluation is being conducted of science support services and capabilities, ship operation, size and composition of the academic fleet, and organizational structures. The external review report, with recommendations for ensuring the most cost-effective means of providing support for research requirements, will be available in mid 1999. The need for changes in fleet capabilities will then be determined.

- **Scientific Drilling**[1, 19, 29, 30, 31], both on the continents and in the oceans, is essential in studies of the Earth. Drilling has the special characteristic of providing direct observations of active geological processes, such as the mechanics of faulting, fluid circulation in hydrothermal systems, thermal and eruptive regimes of volcanic systems, models of geologic structure and stratigraphy, and the origin of mineral and hydrocarbon deposits. The success of the Ocean Drilling Program (ODP) and the widespread use of drilling in mineral and hydrocarbon exploration demonstrate the value as a geologic tool in testing exploration models.

The ODP uses the drillship *JOIDES Resolution* as the primary facility for studies of the ocean basins and continental margins. The continuation of scientific ocean drilling (currently scheduled to end in 2003) would require a replacement of this capability. Continued drilling should support acquisition of a global array of high deposition rate cores for climate studies, development and emplacement of borehole observatories, and time series studies of seismicity, fluid flow, and crustal deformation.

The U.S. Continental Scientific Drilling Program is coordinated by the NSF, the USGS, and the Department of Energy (DOE). As part of the Program, a consortium of universities provides a mobile facility for wireline coring, wireline geophysical logging equipment, onsite core processing, large lake and continental margin sediment drilling and coring equipment, and associated drilling database and archive support. The facility adapts to the wide range of scientific and environmental constraints required by different drilling projects. In addition, the facility provides technical, engineering, and contracting infrastructure to help Earth scientists access drilling and coring support. Future targeted research includes global studies of the continental impacts of climate change, the origin of explosive volcanism, the mechanics of faulting leading to earthquakes, the evolution of hydrothermal systems and associated mineral deposits, the geological history of sea level change, and studies of major extinctions. Long-



ODP Cores. Sediment and rock cores recovered by drilling the seafloor provide access to a vast repository of geological and environmental information on Earth's history. The core shown above, collected 300 miles off the northeast Florida coast, reveals an amazingly detailed record of a meteorite impact event in the Caribbean 65 million years ago. This event is believed to have caused mass extinction, perhaps as much as 70 percent of all species, including the dinosaurs. The dark layer contains the debris from the impact. The rust colored layer represents the debris from the vaporized meteorite. The graded gray core material overlying the rust layer shows the gradual repopulating of the ocean with microorganisms. The approximately 40 cm of core material was collected at a water depth of about 2600 meters, 110 meters below the seafloor.

Other cores contain detailed records of past environmental changes, helping to better understand the critical processes and mechanisms controlling the climate system, and correlating land and marine climate records.

Results from coring the ocean crust have also been striking. For example, in the early days of scientific drilling, beginning in 1968, cores proved the hypotheses of seafloor spreading through the relationship of crustal age and magnetic reversals. This led to our present concept of plate tectonics.

The ODP provides the only capability for scientific sampling of anything but the shallowest layers of ocean sediments and crust.

term objectives include increased integration of the ODP and the International Continental Drilling Program to meet drilling needs of studies of the continental and ocean margins.

- **The Global Seismographic Network (GSN)**[20] is a network of over 108 broadband, digital seismic stations distributed globally to monitor earthquakes, underground nuclear explosions, volcanic activity, and to research deep Earth structure. GSN station operation and maintenance is managed by IRIS, collaborating with the USGS, the University of California at San Diego, other U.S. university groups, and cooperating international seismic networks partners, including GEOSCOPE (France), MEDNET (Italy), POSEIDON (Japan), and GEOFON (Germany). Seismic data acquired through the GSN is an indispensable resource for many seismological research areas: tomographic imaging of core, mantle, and lithosphere structure, rapid and accurate location of earthquakes and other seismic sources, and better understanding of the driving forces moving lithospheric plates and crustal deformation patterns leading to earthquakes.

Anticipated improvements of the GSN to ensure continuing exciting scientific discoveries during 1999-2003 and beyond include: (1) up to 35 new station installations to complete the global (land-based) coverage, (2) operating a key Pacific Ocean GSN seafloor station, Hawaii-2 Observatory (H2O), with an ocean bottom broadband seismometer midway between Hawaii and California on a donated AT&T wire cable, (3) conversion of selected stations to 'geophysical observatories,' with addition of GPS receivers, magnetometers, gravimeters, and microbarographs to form the nucleus of a multi-purpose geophysical network, and (4) continued improvements of telecommunication capabilities for rapid data acquisition and distribution.

- **Seismic Instrumentation**[3, 20, 28, 29, 30, 31] A large pool of portable seismometers, available worldwide for field deployment, is provided by the IRIS-PASSCAL Program (Program of Array Seismic Studies of the Continental Lithosphere). The PASSCAL pool consists of over 400 seismic recording systems, with a total capacity of more than 1500 channels, and includes 200 broadband sensors, as well as intermediate period instruments. The PASSCAL instruments are serviced and supported by an instrument center located at the New Mexico Institute of Mining and Technology. Since its inception, the PASSCAL Facility has supported over 180 field experiments. The capabilities of the PASSCAL pool are complementary to the GSN, allowing for higher-resolution imaging with closer spacing of stations and special array geometries. Possible improvements and activities anticipated during 1999-2003 include: (1) significantly increasing the existing instrument pool capacity in order to reduce the current wait of 18-30 months to instrument field projects, (2) expanding the use of telemetry and extending the capabilities of broadband arrays, and (3) acquiring small, lightweight, inexpensive instruments, activated to record by radio command and intended for use in active source experiments for high-resolution crustal imaging experiments needing many instruments at close spacing.

- **Ocean-Bottom Seismic (OBS) Instrumentation Pools** are being established to meet academic community needs for short- and long-term deployments of large numbers (more than 50) of ocean-bottom seismometers and/or ocean-bottom hydrophones. The OBS instrument pools serve the broad community by providing engineering, technical, and management staff. This staff supports maintenance and technical capa-

Whole Earth Dynamics. Data from the IRIS GSN can map the variation of the velocity of seismic waves in the Earth (tomography). These variations depend on both temperature and the crystallographic orientation of the material the seismic wave is passing through (anisotropy). Until recently, the effect of temperature, which produces isotropic variations in seismic velocity, was believed to be much greater than the effect of anisotropy. For example, velocity variations in the upper mantle beneath the Pacific Ocean were thought to result from the cooling of oceanic lithosphere as it moves away from the East Pacific Rise spreading center. A new global three-dimensional tomographic model of seismic velocity shows that the uppermost mantle beneath the Pacific Ocean is considerably more complicated than this simple thermal model. The figure shows that the anisotropic variations in velocity (top panel) are at least as large as the isotropic variations (bottom panel) due to temperature. The bottom panel also correlates the isotropic variations with the age of the seafloor, as expected from a simple thermal cooling model. The anisotropic variations, however, do not appear to be correlated with the age of the seafloor. Because seismic anisotropy is an indicator of strain in Earth materials, these results can be used to put constraints on both buoyancy forces (thermal effects) and flow patterns in the upper mantle (anisotropy).

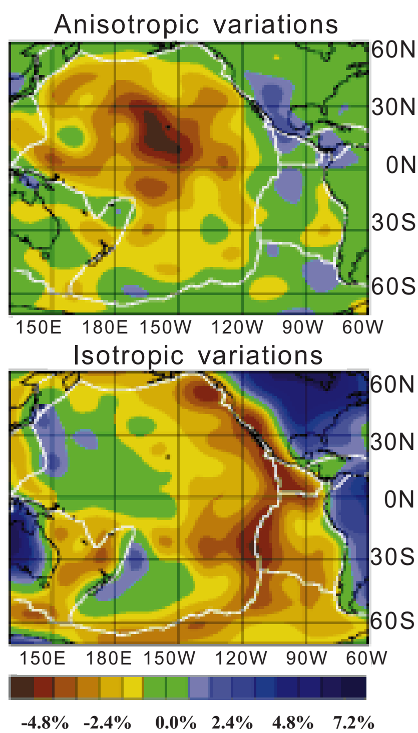


Figure: Shear wave velocity variation beneath the Pacific plate at 150 km depth. (Reproduced from Ekstrom, G. and A.M. Dziewonski, The Unique Anisotropy of the Pacific Upper Mantle. ***Nature****, 394:168-172, 1998.)*

bilities for the instrument pools, provides necessary interface between users unfamiliar with instrument details and operational limits, and provides assistance with experimental design, deployment and retrieval issues, and data reduction processes.

- **Research Aircraft and Airborne Instruments**[9] Advancements in geosciences are inextricably linked to detailed observations of the Earth system only accomplished with specialized instrumentation flown on capable aircraft. NCAR operates and maintains a Lockheed C-130 aircraft (planned to support community research for another 15-20 years) and an Electra aircraft (to be phased out around 2004). Additionally, NSF provides grantees access to a Beechcraft King Air and North American T-28, managed by cooperative agreements with the University of Wyoming and South Dakota School of Mines and Technology, respectively. The King Air should provide service many years into the future, and the T-28 will undergo review in 2000 for its continued maintenance and operation needs. The WB-57F NSF aircraft was transferred to NASA's Johnson Space Center, Houston, Texas in 1998. NASA presently makes the aircraft available to NSF-supported and other researchers on a cost reimbursement basis. Both the Electra and the C-130 have capabilities of carrying large, airborne research instruments, which include a multichannel cloud radiometer and a scanning aerosol backscatter lidar. In addition, the Electra carries the Electra Doppler Radar (ELDORA). A GPS Dropsonde system provides atmospheric measurements on both the C-130 and the Electra. Both aircraft can also support specialized instrumentation provided by individual investigators for field projects.

  Because operating and maintaining airborne capabilities are costly, GEO must continue to build alliances in coordination and cooperation with other federal and foreign organizations so that diverse airborne resources can be made available to the NSF-sponsored research community. Base support will continue to provide reliable and affordable combinations of payload, range, and capability to achieve the most important science goals. Airborne platforms that can accommodate multiple instruments (as well as multiple investigators) will be emphasized. Capabilities to support research over the troposphere and into the lower stratosphere should be maintained, as well as aircraft providing extensive global operations over the oceans and polar regions.

- **Surface and Sounding Systems**[10] Two transportable, multi-parameter, dual-polarization Doppler radars, the S-POL and CHILL, are operated by NCAR and Colorado State University (CSU), respectively. NCAR also operates several transportable and mobile surface measurement and upper air sounding systems, providing the community with accurate measurement capabilities for many atmospheric parameters. These include the Integrated Sounding System (ISS), the Integrated Surface Flux Facility (ISFF), the GPS Rawinsonde systems, and the GPS Dropsonde systems for aircraft.

  Anticipated improvements in the capabilities and communications of the S-Pol system include the application of real-time precipitation particle identification algorithms, use of bistatic receivers to produce real-time multiple-Doppler wind fields and incorporation of horizontal refractive index/humidity measurements from phase delays. Operation of the CSU Pawnee radar (formally called the HOT radar) in conjunction with CHILL, should provide a dual-Doppler radar capability, with remote, real-time access via the Internet. Upgrades in the digital signal processor, polarization bases, and product generation capabilities are also projected. In addition, improvements in the measurement, data processing, and remote operation capabilities of the ISS and ISFF should be undertaken. A GPS version of the Rawinsonde will allow worldwide operation of these instruments.

- **Incoherent Scatter Radar Chain**[11] The global chain of incoherent scatter radars, with facilities in Peru, Puerto Rico, Massachusetts, and Greenland, provides remote measurements of the upper atmosphere and ionosphere. By measuring densities, temperatures, velocities, and other derived properties of atmospheric constituents, these upper atmospheric facilities provide an enduring contribution to many strategic areas of research, including the Global Change and Space Weather Programs. A variety of smaller optical and radiowave devices extend observations to other altitudes and different ionospheric and atmospheric species.

  As radar technology improves, better altitude coverage and higher time resolution will be attained. Atmospheric scientists, combining data from collocated instruments and those at other chain locations, will address an ever-growing number of important research topics. The facilities will use emerging collaborative tools and networking technology to provide easier access to data and greater participation in experimental campaigns by atmospheric scientists and students. In addition to continuing support of scientific research during the next five years, radar operators should exploit new technology in a carefully coordinated strategy to gradually replace aging equipment with more robust and reliable components.

3.2 Computational Systems for Analysis and Modeling in the Geosciences

Large observational data sets produced by modern geoscience instrumentation require modern computing equipment for acquisition, archiving, distribution, and analysis. The need for long-term stewardship of large data sets is especially strong in the geosciences, where decades of observations are often the key to understanding fundamental processes occurring at decadal rates. Complementary to observational and experimental methods in the geosciences, researchers are also taking advantage of rapid advances in computing to create reliable and sophisticated models of natural systems. In the geosciences, there is a strong need for a new generation of powerful computational machines, capable of handling complex models of physical, chemical, and biological processes, at resolutions that are impossible to attain with present technology. GEO is actively investigating options whereby the community can be provided with a profound increase in computing power.

- **Computational Infrastructure**[26] Significant advances in Earth system science have been made over the last decade, driven in part by access to high performance computational capabilities, terabyte size data systems, high bandwidth networks, and four dimensional visualization. These capabilities are referred to as 'computational infrastructure.' Many aspects of Earth system research, particularly those that are computationally intensive, are poised to achieve substantial progress, but researchers must have available to them a state-of-the-art computational infrastructure if these advances are to be realized.

  One strategy to accelerate the development of computational resources available to the NSF-supported community includes coordination of efforts with other agencies to create new paradigms in the use of high performance computational environments, linked closely to a national effort in the development of information technologies. The implementation of this strategy recognizes the need to provide for all levels of computational resources to sustain progress in geosciences. The pyramid of computational resources described by Branscomb[26] remains a valid strategy for geosciences to adopt over the next decade. GEO recognizes the need for an effective balance among high performance desktop workstations versus mid-range or mini-supercomputer versus networks of workstations versus remote, shared supercomputers of high performance.

At the apex of the pyramid is a collaboratory concept, that would involve both centralized and distributed resources interconnected by extremely high bandwidth networks. The centralized node would execute complex predictive and simulation models and house data archives to provide rapid access to petabyte-sized data sets. Connected to this centralized facility would be powerful nodes that would have significant computational, data storage, and visualization capabilities.

To realize this ambitious vision, four elements of the GEO community's computational infrastructure environment would require enhancement—software; scaleable information infrastructure; high-end computing; and the information technology workforce. These long-term efforts are explicitly described in the President's Information Technology Advisory Committee (PITAC) Interim Report to the President, August 1998. The research agenda articulated in the PITAC report, though beyond the scope of geosciences, is consistent with GEO's long-term goals.

- **Climate Simulation Laboratory (CSL)**[12] A high-priority computing system is the CSL, a multi-agency facility located at NCAR that supports research related to the U.S. Global Change Research Program (US/GCRP). The CSL provides high performance computing, data storage, and data analysis systems to support large, long-running simulations of Earth's climate system.

  Possible future plans include a joint NSF-DOE initiative for substantial increases in computational resources for scientific simulation in several areas of computational research, including climate modeling. These additional resources would enable climate model simulations with improved physical and biogeochemical representations of important climate system processes at much finer spatial resolution.

3.3 Laboratory Systems for Measurements and Experiments in the Geosciences

The need for modern laboratory instrumentation and the infrastructure necessary to make it accessible to geoscientists engaged in basic research is clear. In many areas of the geosciences, it is technological advances that have actually determined the research agenda. GEO is committed to the support of necessary laboratory instrumentation for use by individual investigators via conventional research project grants. However, this plan is restricted to consideration of those systems that serve the needs of extended user communities, important examples of which are described below.

- **Accelerator Mass Spectrometers (AMS)**[21, 24, 28] GEO supports AMS facilities located at the University of Arizona, Purdue University, and the Woods Hole Oceanographic Institution. The AMS technique is unique in its ability to measure isotope species with sensitivities of one part in 10^{14} or better, making it the only analytical tool available for radiocarbon dating of old (relative to the ^{14}C decay period) or very small samples. Recent advances in AMS techniques have also resulted in the development of additional tracer and age-dating applications in the geosciences for other cosmogenic nuclides such as ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{129}I. The three AMS facilities provide the geosciences community with a balanced menu of analytical capabilities covering the entire range of research applications, including climate change and environmental studies, radiocarbon dating, exposure age dating, and radioactive tracing and dating of groundwater. Potential plans for 1999-2003 include acquisition of a new accelerator for the University of Arizona and development of new isotope analysis capabilities at Woods Hole Oceanographic Institution and Purdue University.

- **Ion Microprobes**[22, 28, 32] The ion microprobe is the instrument of choice for precise isotopic and trace element analysis combined with excellent spatial resolution. In order to provide access to this instrumentation (a two to three million dollar investment per machine) for the geosciences community, GEO supports large radius ion microprobe facilities at University of California, Los Angeles and Woods Hole Oceanographic Institution. During 1999-2003, GEO expects to add one additional multi-user ion microprobe facility to accommodate increased demand by the academic research community; for example, scientists supported by NSF's Life in Extreme Environments (LExEn) Initiative, and NASA's Astrobiology Program. High precision isotopic analyses at micro-scale to nano-scale resolution are critical for 'chemical fingerprinting' of ancient and/or recent biological activity.

- **Synchrotron Radiation Facilities**[23, 24, 28, 32] Synchrotron storage rings use magnets to bend, wiggle or undulate relativistic electrons or positrons to produce photon beams of unprecedented brilliance and energy range. When combined with modern diffraction and other spectroscopic techniques, the result is an explosion of new tools for the science of materials. Geoscientists who study Earth and planetary materials under extreme pressures and temperatures reproducing *in situ* planetary interiors, or environmental geochemists studying surface reactions between soil particles and pollutants, have access to these tools through GEO's support of synchrotron beamline facilities at the Advanced Photon Source (APS) at Argonne National Laboratory, Chicago, Illinois and the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, Upton, New York. These beamline facilities provide excellent examples of NSF-DOE partnerships. In each case, DOE operates the overall storage ring facility, while GEO supports the construction, instrumentation and operation of the user-access beamlines. Geoscience applications of synchrotron radiation have already produced important advances in our knowledge of the properties of the mantle and core (seismic velocity, seismic anisotropy, density, rheology, and melting relations). Possible future plans for 1999-2003 include advanced instrumentation for x-ray microdiffractometry of samples held at simultaneously high temperatures and pressures in diamond anvil cells and multi-anvil presses. A blossoming interest in beamtime is expected in environmental geochemistry research. For instance, atomic-scale probing of mineral surfaces and biology tissues with high-brilliance x-rays can provide site-specific data on the speciation of toxic metals and radionuclides in contaminated sediments and organics, and the oxidation state of minerals.

- **Institute for Rock Magnetism (IRM)**[24] The study of magnetism in rocks contributes significantly to geoscience research on plate tectonics, mantle dynamics, origin and evolution of the Earth's magnetic field, and, more recently, environmental geology, where variations in rock magnetism are providing a useful proxy for environmental changes. Expensive, state-of-the-art instruments for special studies are available to the geosciences research community at the IRM, located at the University of Minnesota. The IRM provides free and guided access to instruments, such as susceptibility anisotropy bridges, lowand high-temperature AC susceptometers, alternating gradient force magnetometers, magneto-optic Kerr effect microscope system, magnetic force microscopes, and Mossbauer spectroscopy systems. The IRM is recognized internationally as *the* leading resource for instrumental, technical, and educational support in rock magnetism. Continued support of the IRM facility in 1999-2003, is anticipated, including investment in IRM's equipment pool and staff consistent with the research community needs.

3.4 Sample and Data Access Systems

Open and easy access to sample collections and large digital data sets is essential to almost all research programs in the geosciences. GEO aims to support the creation and maintenance of data management systems and sample archive facilities to insure valuable data needed by high-priority research projects are readily and widely available to the academic community. Innovations in the use of the Internet for interactive search and display of very large data sets is revolutionizing these capabilities and promises to provide investigators with unprecedented access to environmental observations.

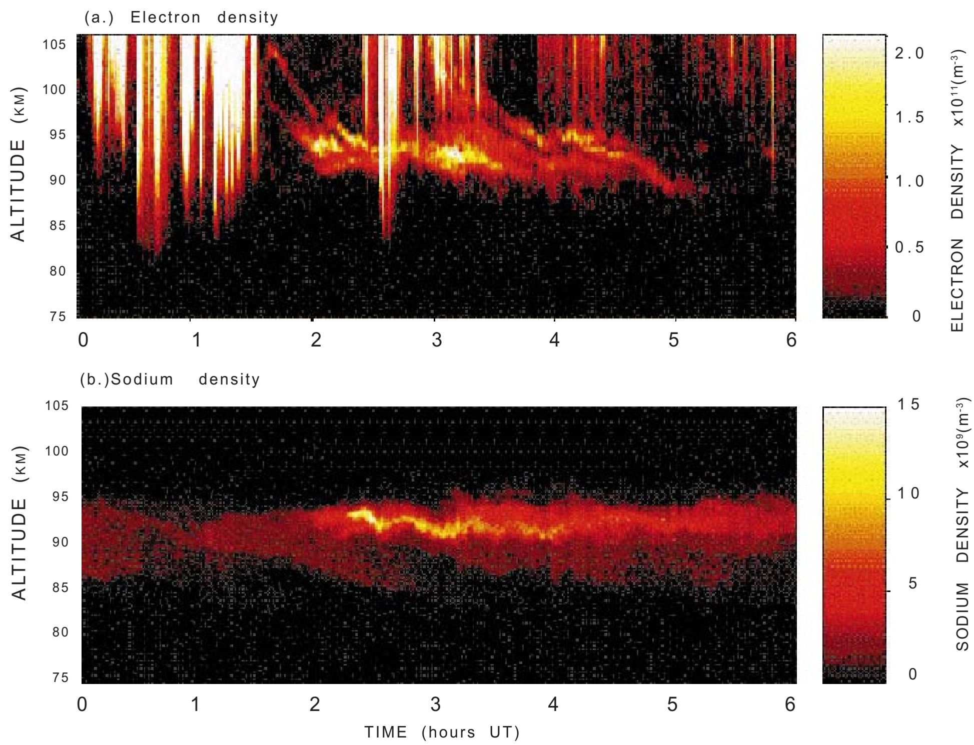
- **The IRIS Data Management System (DMS)**[20, 28, 29, 30, 31] has become the resource of choice for seismologists collecting seismic data for studies of the Earth's interior and earthquake sources. The IRIS Data Management Center (DMC) acts as the central archive and distribution point for all GSN and portable instrument pool (PASSCAL) data for the seismological community. The DMC is also the official data center for selected seismic data collected by the Federation of Digital Seismic Networks. In addition to its data collection and archival functions, the center also develops software tools for the research community, including the promotion of new 'object-oriented' software development techniques.

  GEO plans to continue to support the DMS facility to meet the demand for its products. DMS efforts during the past five years have concentrated on data gathered through the GSN. New activities during the period 1999-2003 are expected in the development of enhanced DMS services for seismic data retrieval and analysis. In addition, data from magnetotelluric investigations of the electrical conductivity structure of the Earth's interior would be archived within the IRIS DMS, and therefore easily accessed via the Internet.

- **Upper Atmosphere Research Collaboratory (UARC)**[13] Over the past six years, UARC has built the capability to design, deploy, and evaluate internet-based collaborative technology to facilitate collaborative space/upper atmosphere science. Within the UARC project, the team has supported an international community of space scientists by combining the concepts and methods from both computer science and behavioral science with the deep involvement of 'domain' experts in space sciences. UARC initially focused on collaborative interactions surrounding real-time data acquisition from the incoherent scatter radar facility in Greenland, but later expanded to include a suite of ground-based and satellite data feeds spanning the globe and the output of large-scale computational models of the upper atmosphere system.

  With sponsorship from the NSF's Knowledge and Distributed Intelligence (KDI) Program, UARC will be continued with a broadened approach, reflected in its new name: Space Physics and Aeronomy Research Collaboratory (SPARC). SPARC will combine experimental data streams and their interpretation, theoretical models, real-time campaign support, capture and replay of collaborative sessions, post-hoc analysis workshops, access to archival data and digital libraries, and extensive educational/outreach modules. These activities will significantly extend the power of technology-mediated distributed knowledge networking systems. SPARC aims to produce a next-generation collaboratory that would support a full range of scientific activities worthy of being called a knowledge network.

- **Sample Collections**[4] Chemical, biological, and geological samples from specific research studies often retain value following the initial study. The insight from the initial study coupled with sample characterization, in fact, often enhances the value. Organized sample collections, or archives, with documented records accessible to additional investigators, are required to enable second-generation studies, including evaluation of long-term environmental changes. Geoscience collections include geological samples from the ODP, other field studies, and photographic ar-



Upper Atmosphere Research. Research efforts in atmospheric sciences increasingly depend on the clustering of instrumentation to provide improved spatial coverage, better temporal and spatial resolution, and expanded measurement capabilities. An illustration of this trend is the combined lidar and incoherent scatter radar experiments being conducted at the Sondrestrom Facility in Greenland. The radar measurements of electron densities associated with thin ion layers along with simultaneous and coincident lidar measurements of the neutral sodium layer, offer new insights into the physical processes responsible for ion and neutral layering at high latitudes. The upper panel shows the sequence of incoherent scatter radar measurements in the altitude range from 80 to 110 km, with an altitude resolution of 600 meters. Thin ion layers appear to form at altitudes around 105 km and slowly descend to form a thicker aggregate layer around 93 km. The darker vertical streaks are electron density enhancements produced by aurora. The lower panel shows the presence of a thin sporadic sodium layer coincident with the ion layer and persisting for at least four hours.

Clustering instrumentation at facilities, establishing strategically located chains of stations, and improving instrument capabilities all support studies of long-term environmental changes associated with global change and the prediction of atmospheric effects from weather and space weather. The data from these instruments provide information essential for the validation of models that simulate interaction between the various components of the Earth system.

chives from deep submersible science studies. Support for existing and possible new collections (e.g., lake drilling cores, continental drilling cores) is required with a focus on preserving collection integrity while expanding opportunities for additional research. This includes more extensive promotion and dissemination of information about the collections through internet and web-based communications.

- **Unidata**[14] Unidata offers software and services that enable atmospheric scientists to acquire and use an extensive array of data products, often in real time. Unidata members constitute a nationwide collection of electronically-linked researchers having common academic interests in atmospheric and related sciences and sharing similar needs for data and software. Unidata permits users to benefit not only from the best contemporary software methods for accessing and displaying environmental data, but also from increased platform independence and greater use of distributed computing.

  Future efforts should provide improved ease-of-use and greater compatibility with more data types and higher data volumes. In addition to adapting decoders and applications to analyze and display data, Unidata plans to expand the Internet Data Distribution system to incorporate new sources, handle higher data rates, adjust automatically to variations in user demands, adapt dynamically to Internet performance variations, and exploit networking advances such as multicast protocols. New capabilities would include animated, three-dimensional visualization tools and a Java-based information framework, setting the stage for eventually utilizing aggregate data holdings of all Unidata sites as a common community resource.

4.0 Potential New Capabilities

GEO is constantly evaluating opportunities to develop new facilities, either in response to the changing needs of researchers, or to replace aging or obsolescent capabilities. Changing demands from the research community are driven by scientific breakthroughs or technological advances, and the need to provide investigators with state-of-the-art capabilities requires that outdated systems be replaced in a timely way. Many of these new facilities could be supported by multiple agencies. They would be engaged in highly interdisciplinary research activities and would provide new opportunities for public outreach and education. The following projects (listed in no priority order), would help provide the community with leading-edge capabilities for geosciences research. When identifying the resources required to develop new facilities, GEO will establish an appropriate balance between the support required for stable operation, maintenance, and upgrading of existing facilities.

- **A Relocatable Atmospheric Observatory (RAO)**,[15] designed as a transportable system, would provide new capabilities for studying the properties of Earth's upper atmosphere and ionosphere. This collection of instruments, centered on a state-of-the-art phased array incoherent scatter radar with electronic steerability, would give this observatory unique capabilities in addressing problems in solar wind-magnetosphere-ionosphere coupling and its effects on the global atmosphere. For example, locating the observatory near the north magnetic pole would allow observations critical to our understanding of the way Earth's atmosphere is magnetically and electrically coupled to the solar wind. Other possibilities include sites such as Hawaii and New Mexico near large existing lidar facilities, and Poker Flat, Alaska, near the NASA rocket launching facility. The Relocatable Atmospheric Observatory would contribute to several strategic areas of research, including the National Space Weather Program (NSWP) and the USGCRP. The new observations would complement others made by state-of-the-art facilities around the world, as well as those made by an international array of satellite-borne instrumentation.

- **Coastal Research Vessel**[5] Ensuring the availability of appropriate sea-going facilities and support services is crucial to investigators supported by NSF research programs. The research vessels that support studies of coastal oceanographic systems are aging, and several may need replacement in the near future if research demands for interdisciplinary studies are to be met. A next-generation coastal research vessel would maintain needed research support capabilities.

- **High Performance Research Aircraft**[16] The High-Performance Instrumented Airborne Platform for Environmental Research (HIAPER) would be a modern mid-sized jet aircraft with capabilities to reach 50,000 feet altitude and over 7,000 miles in range. The aircraft would be outfitted with new sensors, data systems, and scientist workstations to accommodate scientific investigations important to national and global priorities in climate, hazardous weather, and Earth system science supporting human needs. HIAPER is a much needed replacement for the aging, limited-capability Lockheed Electra turbo-prop aircraft, operated by the NCAR.

- **EarthScope**[25] EarthScope would be a distributed, multi-purpose geophysical instrument array that has the potential for making major advances in our knowledge and understanding of the structure and dynamics of the North American continent. The EarthScope concept consists of three projects that would be considered and implemented separately, but which taken together could contribute to

an integrated research effort in this area of study. The projects are: (1) U.S. Array/San Andreas Fault Observatory at Depth, (2) Plate Boundary Observatory, and (3) Interofero-metric Synthetic Aperture Radar (InSAR).
The U.S. Array would be a dense array of high-capability seismometers that would be deployed in a stepwise fashion throughout the U.S. to greatly improve our resolution of the subsurface rheology. The San Andreas Fault Observatory at Depth would study fault parameters and the rupture processes of earthquakes. The physics of these processes is one of the most challenging problems in science today.

The Plate Boundary Observatory (PBO) would involve the construction of an array of permanent borehole installations of multiple instruments, including GPS receivers, strainmeters, tiltmeters, and seismometers that would be distributed across the western half of the U.S.

The Interferometric Synthetic Aperture Radar (InSAR) would involve a partnership with NASA and other agencies to orbit a synthetic aperture radar on a satellite. InSAR has produced spectacular images of crustal distortion of earthquakes, volcanoes, and land subsidence with high precision and spatial resolution.

- **Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)**[17] Over the next decade, NSF intends to collaborate with other U.S. agencies and Taiwan to support COSMIC. The Global Positioning System applied to Meteorology (GPS/MET), along with its progeny COSMIC, are elegant solutions to the problem of obtaining global, high resolution observations of the three dimensional structure of atmospheric temperature and water vapor throughout the troposphere and lower stratosphere, and the electron densities of the charged upper atmosphere. The spatial and temporal gradients of these important variables strongly influence weather, climate, and upper atmospheric electrical phenomena, all of which have profound effects on human societies. The data from COSMIC would provide a valuable new resource for atmospheric science studies.

- **Sustained Time-Series Observations in the Oceans**[6] Evolving research themes in the geosciences focus on interactive processes that occur over a vast range of temporal and spatial scales, and exhibit numerous dynamic linkages between system components; e.g., the coupling of biological, geological, chemical, and physical systems in the oceans. New advances in understanding cannot be made by simply characterizing the ocean systems over limited regions or for short periods. Investigation of the Earth as a dynamic system requires new observational capabilities. Examples of systems to potentially be designed and implemented over the next five years are: long-term seafloor observatories for time-series observations in the deep ocean environment, with emphasis upon the expansion of the GSN into the oceans (the Ocean Seismic Network [OSN]); maintenance and expansion of long-term surface and water column observatories, such as the existing stations off Hawaii (Hawaii Ocean Time-series [HOT]) and Bermuda (Bermuda Atlantic Time-series Study [BATS]); new sensor technologies and data recovery capabilities; and the development and application of controlled autonomous profiling floats to provide a near-real-time synoptic view of upper ocean dynamics on a basin scale. Providing open access to these new capabilities for the widest possible segment of the ocean sciences' community would be accomplished (in some cases) by instrument centers.

- **National Facility for Hydrological Sciences** Traditionally, hydrologic data sets have been collected independently and sporadically by a wide range of public agencies. These data are not sufficient to advance our understanding of mass balances as water moves at multiple space-time scales within watersheds. Our environment and economy are increasingly exposed by our ignorance of nonlinear coupling among water, biota, and energy which involves multiple feedback, thresholds, and natural fluctuations that can change hydrologic regimes suddenly and dramatically. New observing capabilities (radar, satellite imagery, isotopic tracers) and mathematical tools (fractals, dynamic systems) need to be organized within a sustained, integrated observational system. A National Facility for the Hydrologic Sciences would, for the first time, coordinate the full range of emerging technologies and modern computational capabilities to bear on basic, and applied, research problems in the hydrologic sciences, and would incorporate facilities for community access to modern instrumentation and data archiving and distribution.

- **Ocean Data Assimilation and Modeling**[7]
  The critical environmental processes that control most Earth systems can best be understood if considered from a multidisciplinary perspective as dynamic, nonlinear systems. An important component of future global ocean sciences is the creation of an infrastructure and environment in which data assimilation, integration, modeling, and interpretation of large diverse data sets can take place. Computational capabilities must be adequate for global data sets from satellite research missions, e.g., radiometry, scatterometry, and altimetry available today; plus new types of measurements, e.g., ocean color, geode, or surface property characteristics. These synoptic data sets must be combined with interior ocean data being collected by major process studies, e.g., global change programs, in coherent ways such as via model data assimilation.

To address these needs, new infrastructure and partnerships would be required spanning the ocean community. A concept has been developed to address these needs (and evolve in a phased manner), involving a central 'hub' facility supporting a number of 'scientific nodes.' The hub facility would provide computational and data assimilation capabilities, high-level analyses, technical assistance, code and analysis software, benchmark solutions, documentation, and other services. Nodes are envisioned as small or large teams (5-15 scientists) collaborating on model/data synthesis projects requiring regional- to global-scale computational capability. The rationale is that such groups are needed to advance our capability in the simulation and understanding of the physical, chemical, biological, and biogeochemical behavior of the ocean, estimations of the state of the ocean, and the identification of essential new ocean observing capabilities. This effort would be planned as a multiagency activity.

5.0 Facilities and Education[27]

The GEO-sponsored facilities while having primarily a research-driven mission, also have ambitious education and outreach programs in place and in development. These programs typically reflect the missions of the facilities, yet are designed for broad impact at multiple educational levels: graduate and postdoctoral, undergraduate, pre-college, and public outreach.

The programs provide a continuum of learning vital to fostering geoscientific excellence, and promote public support for the geosciences enterprise. GEO can increase its support of education through traditional programmatic vehicles and expansion of GEO's Awards to Facilitate Geoscience Education Program, NSF 97-174 (continued through FY99 as Geoscience Education, NSF 99-44). Examples of the facilities programs for which expanded support is being considered are:

- UCAR supports a large number of educational programs aimed at the full range of education levels, including public outreach. The Program for the Advancement of Geoscience Education (PAGE, located at: http://www.page.ucar.edu, accessed January 22, 1999) supports the shared development and dissemination via the facility network of multidisciplinary curricula integrated with modern communications technologies.

- IRIS has established an education and outreach program aimed at using the excitement of seismology and related geosciences as a stimulant to improving science education at all levels. Of particular note is the Princeton Earth Physics Project, placing scientifically useful seismometers in pre-college classrooms, linking separate sites to the IRIS data center simultaneously, and developing supporting curricula. In cooperation with the USGS Albuquerque Seismological Laboratory and the New Mexico Museum of Natural History and Science, IRIS has developed a museum display on earthquakes featuring real-time display of seismograms from around the world. The exhibit is currently on national tour as part of the Franklin Institute's 'Powers of Nature' exhibit.

- The ODP has established a broad range of educational activities at all levels. The ODP sponsors a fellowship program, as well as the participation of students aboard the *JOIDES Resolution*. Distinguished lectures are organized each year by the ODP. The ODP also supports various efforts involved in developing public outreach and educational materials.

GEO has supported programs having significant impacts on education in the geosciences. Some examples include:

- outreach programs that emphasize hands-on learning and participation of students,
- teacher training programs aimed at involving students in research,
- partnerships with public schools,
- undergraduate research fellowship programs, and
- activities in cooperation with aquariums and museums.

GEO places profound importance on students, at all levels. Gaining direct experience with applications of state-of-the-art instrumentation in the laboratory and in the field is important and GEO should support mechanisms that provide this experience through facilities. One such approach is a program of incremental funding, allowing students to access selected facilities, while, in turn, providing the facilities with enhancement of technician support and full utilization.

Finally, as part of NSF's intention to create a national digital library as a distributed capability, GEO has begun a cooperative program with the Division of Undergraduate Education focused on an Earth systems science curriculum component. GEO will continue developing this collaboration, and pursue similar activities with other Divisions of the Directorate for Education and Human Resources (EHR).

6.0 The Challenges Ahead

The boundaries between the traditionally distinct disciplines of atmospheric, earth, and ocean sciences are being eroded as the understanding of the Earth as a dynamic, integrated system improves. This important intellectual driver must impact the way that GEO facilities are managed. Access to investigators of all disciplines must be open and straightforward, and opportunities for sharing of capabilities and sites between the Divisions of GEO must be recognized.

The coordination of facility requirements with other Directorates within NSF should be reviewed on a regular basis to determine whether opportunities for new partnerships would enhance available capabilities. The technological and instrumental challenges of recording long time series of environmental and biological variables, and the development of improved capabilities for the manipulation of biological materials in the natural environment would be most efficiently tackled by cross-directorate programs for development and support of new and innovative facilities.

Efforts to build new interagency partnerships must continue - many of the new computational or observational facilities would require investments that are beyond the resources of a single agency. Only through cooperative efforts can these goals be realized. To an increasing degree, many required capabilities are beyond the resources of the U.S. as a nation and the essential value of international cooperation must continue to be acknowledged.

The next five years will see substantial change in the way geosciences data are collected and processed. Disciplinary barriers will be further eroded, data access will continue to revolutionize the way investigators work together, and increasingly researchers will study dynamic Earth processes remotely in near real-time. GEO must be prepared to manage a rapid evolution in the observational and computational capabilities that will be required to achieve the next series of exciting advances in the understanding of our planet's natural system.

Appendix A

Representative Examples of Community-Based Facility Planning Activities

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Appendix B

Glossary of Acronyms

Acronym	*Full name or term*
AMS	Accelerator Mass Spectrometers
APS	Advanced Photon Source
AUV’s	autonomous undersea vehicles
BATS	Bermuda Atlantic Time-series Study
C4	Center for Clouds, Chemistry, and Climate
CAPS	Center for the Analysis and Prediction of Storms
CHiPR	Center for High-Pressure Research
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CSL	Climate Simulation Laboratory
CSU	Colorado State University
DMC	IRIS Data Management Center
DMS	IRIS Data Management System
DOE	Department of Energy
EHR	Directorate for Education and Human Resources
ElDoRa	Electra Doppler Radar
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FY	Fiscal Year
GEO	Directorate for Geosciences
GPS	Global Positioning System
GPS/MET	Global Positioning System applied to Meteorology
GSN	Global Seismographic Network
H2O	Hawaii-2 Observatory
HIAPER	High-Performance Instrumented Airborne Platform for Environmental Research
HOT	Hawaii Ocean Time-series
IRIS	Incorporated Research Institutions for Seismology
PASSCAL	Program of Array Seismic Studies of the Continental Lithosphere
IRM	Institute for Rock Magnetism
ISFF	Integrated Surface Flux Facility
ISS	Integrated Sounding System
KDI	Knowledge and Distributed Intelligence
LExEn	Life in Extreme Environments
MRE	Major Research Equipment
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSB	National Science Board
NSF	National Science Foundation

NSLS	National Synchrotron Light Source
NSWP	National Space Weather Program
OBS	Ocean-bottom seismic
ODP	Ocean Drilling Program
OSN	Ocean Seismic Network
PAGE	Program for the Advancement of Geoscience Education
PITAC	President's Information Technology Advisory Committee
REU	Research Experiences for Undergraduates
RIDGE	Ridge Interdisciplinary Global Experiments
ROV's	remotely operated vehicles
SCEC	Southern California Earthquake Center
SPARC	Space Physics and Aeronomy Research Collaboratory
STC's	Science and Technology Centers
UARC	Upper Atmosphere Research Collaboratory
UNAVCO	University NAVSTAR Consortium
UNOLS	University-National Oceanographic Laboratory System
US/GCRP	U. S. Global Change Research Program
USGS	United States Geological Survey

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