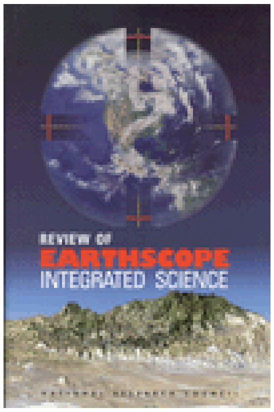

Review of EarthScope Integrated Science

Committee on the Review of EarthScope Science Objectives and Implementation Planning, Board on Earth Sciences and Resources, National Research Council

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REVIEW OF EARTHSCOPE INTEGRATED SCIENCE

Committee on the Review of EarthScope Science Objectives and Implementation Planning
Board on Earth Sciences and Resources
Division on Earth and Life Studies
National Research Council

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Preface

The Committee on the Review of EarthScope Science Objectives and Implementation Planning had the task of reviewing aspects of a very complex project plan in a very short time. Furthermore, because the members of the committee were selected to avoid any perceived conflict arising from direct scientific association with EarthScope, many members had to learn the details of EarthScope starting from a base of relatively general knowledge about the initiative. Nevertheless, the committee did collectively incorporate detailed knowledge concerning the technical aspects of the various components of the EarthScope initiative, and also had experience with large and expensive NSF projects and broad overview perspectives on earth science research. The advantages attending appointment of a committee with such a broad earth science perspective far outweighed any perceived disadvantage from the absence of EarthScope "insiders" as members, who could possibly reveal some problem areas in the details of the planning that might be missed by "outsiders."

The committee's specific task was to review the scientific objectives and implementation planning of three components of the EarthScope initiative (see Box ES1 for complete statement of task), rather than to conduct a detailed technical review of the initiative. The committee approached its evaluation with a critical and skeptical view. Members came to the committee meeting in August 2001 after having read a wealth of material on the proposed initiative, and initially were concerned that the plans had seemed to evolve in a way that may not have been optimal for advancing earth science. The committee members certainly were prepared to highlight any fundamental weaknesses that were identified. Conversely, the committee did not think it would be useful to identify minor shortcomings or implementation details that may not have been documented or presented in the material put before the committee—it was clear that the more detailed aspects of the science and implementation plans were continuing to evolve. The committee deter mined that its most constructive role would be to offer overall "high-level" comments and advice.

The report contains five chapters. Chapter 1, the introduction, sets the context for the proposed EarthScope initiative and briefly describes the basic components of the project. Chapters 2 to 4 cover the major topics the committee was asked to address: Chapter 2 discusses the components of EarthScope in relation to the science questions to be addressed; Chapter 3 discusses the two implementation and management components—EarthScope as a scientific facility and EarthScope as a scientific endeavor; and Chapter 4 discusses the broad range of appropriate partnerships that will be engaged in the EarthScope initiative. The final chapter (Chapter 5) presents summary observations and the committee's recommendations.

The committee would like to acknowledge the many members of the earth science community who, at short notice, briefed the committee or provided other input. As chair of the committee, I thank the members of the committee for their hard work in a short time and for their good-natured interactions that allowed the report to be completed expeditiously. Finally, I thank David Feary, Jennifer Estep, and Shannon Ruddy for sharing ideas and for all the logistical support.

George M.Hornberger
Chair

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

William R.Dickinson, Department of Geosciences *(emeritus),* University of Arizona, Tucson

Brian L.N.Kennett, Research School of Earth Sciences, The Australian National University, Canberra

Alan Levander, Department of Geology and Geophysics, Rice University, Houston, Texas

Bruce D.Marsh, Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland

Raymond A.Price, Department of Geological Sciences and Geological Engineering *(emeritus),* Queen's University, Kingston, Ontario, Canada

Donald L.Turcotte, Department of Geological Sciences, Cornell University, Ithaca, New York

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Marcia K.McNutt, Monterey Bay Aquarium Research Institute.

Appointed by the National Research Council, the coordinator was responsible for ensuring that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

EarthScope, a major science initiative in the solid-earth sciences, has been described as "a new earth science initiative that will dramatically advance our physical understanding of the North American continent by exploring its three-dimensional structure through time."[1] EarthScope is an entirely new venture for the earth sciences, with an immense vision and scope. EarthScope proposes to cover the United States with a dense array of instruments designed to reveal how the continent was put together, how it is moving now, and what is beneath it. It is intended to provide an unprecedented, detailed image of the surface and what lies beneath it, and will undoubtedly change our view of the earth, much as the Hubble Telescope has changed our view of the universe. Only very recently has it become realistic even to think of implementing a project such as this, not just because the imaging technology is relatively new and needed to have its capabilities proven, but because only now are the information systems (and the experience with using them) in place to handle and distribute the vast amount of data that will be produced. Because the technical elements required for it to succeed have now been developed, and most importantly because of the enormous potential that new discoveries with direct societal benefit will result from analysis of these data, the committee concludes that this is an opportune time to undertake this project.

EarthScope is composed of three components for which funding from the Major Research Equipment program of the National Science Foundation (NSF) is sought, and a fourth component primarily associated with the National Aeronautics and Space Administration (NASA). The first three are the United States Seismic Array (USArray), the Plate Boundary Observatory (PBO), and the San Andreas Fault Observatory at Depth (SAFOD). The NASA component of EarthScope is the satellite-based Interferometric Synthetic Aperture Radar (InSAR).

[1] EarthScope Working Group, 2001, EarthScope—A New View into Earth; draft EarthScope Project Plan.

Each component of EarthScope is designed to support and integrate with other components.

At the request of the National Science Foundation, the National Research Council (NRC) appointed a committee to review the science objectives and implementation planning of the three NSF components of the EarthScope initiative: USArray, SAFOD, and PBO. Although not formally asked to examine InSAR, the committee was requested to assess the overall EarthScope scientific objectives after considering the integrated nature of the entire initiative. The charge to the committee is presented in Box ES1.

BOX ES1 STATEMENT OF TASK

At the request of the National Science Foundation, an ad hoc committee under the auspices of the Board on Earth Sciences and Resources will review the science objectives and implementation planning of three components of NSF's EarthScope initiative: the United States Seismic Array (USArray); the San Andreas Fault Observatory at Depth (SAFOD); and the Plate Boundary Observatory (PBO). Although not formally reviewing the Interferometric Synthetic Aperture Radar (InSAR) element, the committee should assess the overall EarthScope scientific objectives after considering the integrated nature of the entire initiative.

In particular, the committee is asked to consider the following questions:

- Is the scientific rationale for EarthScope sound, and are the scientific questions to be addressed of significant importance?
- Is there any additional component that should be added to the EarthScope initiative to ensure that it will achieve its objective of a vastly increased understanding of the structure, dynamics, and evolution of the continental crust of North America?
- Are the implementation and management plans for the three elements of EarthScope reviewed here appropriate to achieve their objectives?
- Have the appropriate partnerships required to maximize the scientific outcomes from EarthScope been identified in the planning documents?

Following review of extensive written material and after hearing presentations by members of the EarthScope Working Group and other interested scientists, the committee was impressed with the integrated scientific objectives of the EarthScope project. Based on its review of the extensive scientific planning elements included within individual component white papers, it was clear to the committee that scientific planning is well advanced, and accordingly the committee believed that it could assess the project and make recommendations. The committee concludes that EarthScope is an extremely well articulated project that has resulted from consideration by many scientists over several years, in some cases up to a decade. During that time, the proponents have become experts, not just in the observing technology but in the data handling and retrieval systems that are necessary to manage information on this vast scale. The scientists involved could see the prospect of the EarthScope project, but waited until both the necessary expertise and reliable technology were available before proceeding.

The committee concludes that EarthScope will have a substantial impact on earth science in America and worldwide. It will provide scientists with vast amounts of data that will be used for decades. The intention of EarthScope to make all its data freely available on the Internet, in as near real-time as possible, is both admirable and open-spirited. It will encourage research and educational collaboration throughout the world, ensuring that the maximum possible benefit and insight are extracted from the data collected. The scientists involved with EarthScope recognize that the free and open use of the data ensures rigorous quality assessment. In addition, they have measured the success of existing and past global monitoring programs in part by the number of people who use the data. EarthScope has the potential of providing scientific and technological leadership to the world's seismological community. This integrated system for looking into the subsurface realm of a significant part of the North American continent could be used as a model for the other continents—Africa, Asia, Europe, Australia, South America, and Antarctica.

The committee makes a series of recommendations encompassing science questions, management, education and outreach, and partnerships.

SCIENTIFIC RATIONALE AND SCIENCE QUESTIONS

The committee concludes that the time is right to undertake a full exploration of the nature of the continental crust of the United States and its underlying mantle. Such exploration is a critical requirement for understanding the nature of the earth on which we live and how society needs to manage and adapt to its rhythms and processes.

Recommendation:

The committee strongly endorses the integrated approach to the investigation of the lithosphere and mantle underlying the United States proposed in the EarthScope initiative, including its four components: USArray, PBO, SAFOD, and InSAR. The committee concludes that the scientific rationale for EarthScope is sound, that the scientific questions to be addressed are of significant importance, and that no necessary components have been omitted. The committee recommends that that all four EarthScope components be implemented as rapidly as possible.

Answering the key questions posed for the EarthScope science initiative will require the participation of scientists from across all the disciplinary programs of the Geosciences Directorate of NSF, particularly the Division of Earth Sciences (EAR).

Recommendation:

The NSF should ensure that EarthScope's scientific potential is effectively realized and capitalized upon by continuing its support for the disciplinary and interdisciplinary programs within NSF's Division of Earth Sciences (EAR) that form the scientific foundation of the project.

In recent years, InSAR has made spectacular contributions to imaging parts of the earthquake cycle and revealing the motion of magma at depth beneath volcanoes. The committee believes that InSAR too must be perceived as an integral part of EarthScope.

Recommendation:

The committee concludes that InSAR is an integral part of the EarthScope vision that will greatly enhance the effectiveness of the project, and it should not be viewed merely as a desirable add-on to the project. The committee urges NSF and NASA to collaborate to realize this goal at the earliest opportunity, so as to make InSAR capability a reality during the lifetime of the other EarthScope components.

IMPLEMENTATION AND MANAGEMENT

The effective functioning of the EarthScope management structure, to achieve the required integration of the different components, will depend on details that are yet to be developed.[2] EarthScope will need a mechanism to ensure integration, coordination, and synthesis of the interdisciplinary studies carried out by individual investigators and small groups of investigators.

Recommendation:

The committee recommends that EarthScope look beyond the development of the facility to the operational phase of the scientific program, and develop a strategic science plan to accomplish its long-term scientific goals. Such a plan should include a scientific advisory structure encompassing all elements of EarthScope and all appropriate branches of the earth sciences to provide oversight and advice on the scientific directions of the program, and to coordinate its scientific activities. It should also incorporate a mechanism for providing advice to NSF regarding EarthScope programmatic funding priorities. The advisory structure should also include liaisons to other programs that are either complementary or will help fulfill the broader EarthScope vision of understanding the structure and evolution of the North American continent.

[2] A final EarthScope scientific planning statement was not available when the committee met, and the written description of the scientific program as currently envisaged lacks the detail that will be required once funding is approved.

EarthScope will result in observations that are certain to reveal new and unexpected events and targets.

Recommendation:

The committee urges EarthScope management to establish a mechanism to rapidly and effectively direct appropriate equipment and expertise towards any unexpected phenomena that may be revealed during its implementation.

EDUCATION, OUTREACH, AND COMMUNICATION

EarthScope provides an excellent opportunity to excite and involve the general public, as well as K-12 and college students, to work together with the earth science community to understand the earth on which they live.

Recommendation:

Because EarthScope provides a unique opportunity that must not be missed, the committee recommends that the education and outreach aspects of EarthScope, as currently incorporated in EarthScope planning documents, should be strongly and realistically supported. They must be an integral component of the project. Education specialists should be involved in both the development and execution of the education and outreach programs.

The earth sciences have the task not only of understanding how our planet works, but also of dealing with the societal and economic impacts of the earth's processes and their effects on human life on the earth's surface.

Recommendation:

As they continue to develop documents to inform the public about the project, the committee recommends that the EarthScope proponents forcefully communicate the role of EarthScope as an important source of the earth science information required by

society for natural hazard mitigation, resource utilization, land-use planning, and environmental protection.

APPROPRIATE PARTNERSHIPS

Understanding the dynamics of plate movements and plate boundaries requires knowledge about motions offshore, because although the continental crust extends far beyond the present shoreline, the EarthScope USArray and PBO installations do not extend into the marine realm. A complementary program, NEPTUNE, plans to make similar measurements off the coast of the Pacific Northwest, and other members of the ocean science community are planning to deploy ocean bottom seismometers (OBS) at a range of locations off the coasts of North America.

Recommendation:

The committee recommends that the EarthScope Working Group actively pursue coordination between the EarthScope and ocean geoscience programs, including NEPTUNE, to ensure that the establishment of EarthScope facilities and the deployment of GPS-acoustic, strainmeter, and OBS arrays supported by the marine geological and geophysical community are complementary.

Several large scientific programs are currently in the process of planning extensive educational efforts. An example of particular scientific significance to EarthScope is the proposed NEPTUNE program.

Recommendation:

The committee recommends that EarthScope establish liaisons and communications with other appropriate programs to build on existing progress in the development of major geoscience educational and outreach efforts.

The EarthScope Working Group has categorized the EarthScope initiative as seeking to "…dramatically advance our physical understanding of the North American continent by exploring its three-dimensional structure…" and has indicated that it will seek to collaborate with colleagues in Canada and Mexico to integrate data produced by programs in these countries with EarthScope data from the United States. The committee considers that international collaborative programs will significantly enhance the value of the information amassed by research in the United States.

Recommendation:

The committee endorses the intent of the EarthScope proponents to seek collaborations with colleagues in Canada and Mexico to extend the understanding of crustal and lithosphere dynamics beyond the political borders of the United States. The committee believes that EarthScope will provide a powerful stimulus for joint international scientific programs, in the same way as the transects compiled during the Decade of North American Geology (DNAG) and the creation of continent-wide data sets for potential fields (e.g., gravity and aeromagnetics) stimulated past collaborations.

SUMMARY COMMENTS

The committee concludes that the plan for the integrated EarthScope facilities is sound. The plan reflects the input of a very broad cross-section of the geophysical community and mature consideration and planning over a decade. The project is very well conceived. The committee is confident that through broad earth science community involvement, the detailed science plans and strategies for the use of the facilities will be similarly well conceived and articulated. The potential scientific benefits of the total program to the earth sciences are of immense importance; the potential benefits to society of "applied science" stemming from the program are equally outstanding. EarthScope represents a truly visionary program for the earth sciences. The committee enthusiastically endorses the total program and all of its components.

1

Introduction

Whether one views with awe a sheer wall of rock in Yosemite Valley, Old Faithful geyser in Yellowstone, lava flows in Hawaii, or an image of Earth taken from an orbiting satellite, a sense of wonder about the forces that shape our world is all but inescapable. From earliest times, humans have demonstrated a deep hunger for knowledge about the earth, for an understanding of their surroundings, and how the earth works and affects their lives. This desire to understand the earth finds expression in the origin myths of the world's cultures, as well as current widespread public interest in knowledge about the earth.[1]

Within the sciences, the fields known as "solid-earth sciences" have the enviable job of understanding how the earth "works." The solid-earth sciences deal with the most tangible of objects—the earth beneath our feet, the landscape around us, and the source of the resource abundance of our lives.

> "The goal of the solid-earth sciences is: to understand the past, present, and future behavior of the whole earth system. From the environments where life evolves on the surface to the interaction between the crust and its fluid envelopes (atmosphere and hydrosphere), this interest extends through the mantle and the outer core to the inner core. A major challenge is to use this understanding to maintain an environment in which the biosphere and humankind will continue to flourish.[2]"

[1] For example: Torrance, R.M., ed., 1998. Encompassing Nature: A Sourcebook. Washington, DC: Counterpoint, 1224 pp.

[2] NRC, 1993. Solid-Earth Sciences and Society. Washington, DC: National Academy Press, page 2.

The historian Will Durant is widely quoted as suggesting, "Civilization exists by geologic consent, subject to change without notice." The solid-earth sciences play an essential role in developing the scientific understanding and knowledge that enable humankind to manage its environment wisely. Information about natural hazards, such as volcanoes, tsunamis, and landslides, are obviously critical to decisions about public health, safety, and security. As population has increased, this information has become increasingly important for the mitigation of potential damage from earthquakes, volcanic eruptions, and other earth movements that are the inevitable consequences of living on an active planet.

Many of the resources that make our civilization possible are found in the subsurface realm within the earth's crust. From this realm we derive fresh water, oil and gas, coal, and minerals. Large areas of the crust contain sedimentary basins that are up to 16 kilometers deep and contain complex and dynamic fluid systems that are only poorly understood. These basins contain faults that cross rail and road systems, and lie beneath many of our major cities that were settled near river mouths—their soft sediments are subject to liquefaction in earthquakes.

> "The world is rapidly changing; revolutionary technological advances, demographic growth, competing demands for resources, and increased awareness of the interconnectedness and global scale of many natural science issues are shaping tomorrow's science needs. Managers, planners, and citizens are demanding more and better scientific information, delivered more rapidly, that will help them make decisions about the world around them.[3]"

For the past century or so, solid-earth scientists have known that the earth has a crust, averaging 5–10 km thick beneath the oceans and about 35 km thick in continental regions, composed chiefly of minerals containing oxygen and silicon ("silicate minerals") with varying amounts of aluminum, iron, potassium, sodium, calcium, magnesium, and other elements. This is underlain by a mantle about 3000 km thick, composed chiefly of silicate minerals rich in magnesium and iron; and a core of iron-nickel alloys. In the last half of the 20th century, the most exciting developments in the solid-earth sciences centered on the theory

[3] USGS Strategic Plan, 1999.

of plate tectonics. The concepts of sea floor spreading and continental drift changed our view of the earth from a static globe to a dynamic, live planet. We now recognize that the outer part of the earth (the crust and part of the upper mantle, called the lithosphere) is composed of a series of segments, or plates, that are in motion relative to each other. Plates move apart at ridges in the middle of oceans, they slide past each other along fault zones such as the San Andreas Fault of California, and they converge in regions such as the Pacific "Ring of Fire" where one plate descends beneath another. Nearly all earthquakes and volcanoes (with important exceptions such as Hawaii) occur at the boundaries between plates. Continents drift as plates move, coming apart in some places and coming together in others. As they move apart, features such as the Great Basin of the western United States or the Red Sea form, and oceans such as the Atlantic develop. Where continents come together and buckle, mountain ranges such as the Alps or the Himalaya are created. For example, the Appalachians developed some 300 million years ago as Africa approached and collided with North America. The western margin of North America has been an active plate boundary for at least 200 million years, and this activity is directly or indirectly responsible for the spectacular scenery of the region.

Since its inception, the theory of plate tectonics has dominated investigations of the earth and exploration for the mineral and petroleum deposits needed to supply our growing and increasingly technological society. In addition, plate tectonics has captured the imagination of nonscientists the world over. In recent years, technological advances have provided tools that have led to major improvements in our knowledge of the earth, increasing our understanding of the processes acting in the earth's interior and our knowledge of plate tectonics and how it works. Techniques developed in the petroleum industry now make it possible to drill a deep borehole at an angle and target a particular area of a fault system for investigation with a precision of a few meters, even at a depth of 4 kilometers. Seismometers at the surface of the earth can be placed in arrays to generate high-resolution images of the internal structure of fault zones and volcanoes. Data from the global positioning system (GPS) offer the possibility of determining movements of the earth's crust with great precision, both across fault zones and also in the vicinity of volcanoes as they become active. Satellites using sophisticated radars can map small positional changes with time, and thus document the slow movements of the earth's crust (approximately at the rate that a fingernail grows) that are the surface manifestations of the movements in the earth's interior that drive the motions of the plates. The recent development of these tools of perception have enabled earth scientists to peer into the subsurface realm with much greater precision, and to significantly increase understanding of this dynamic region of the earth.

In the 1990s, a broad-based community of solid-earth scientists began to discuss how best to utilize these new technologies in an integrated way to advance earth science ("to understand the past, present, and future behavior of the whole earth system"[4]) and to provide information of critical concern to the public ("more and better scientific information, delivered more rapidly, that will help them make decisions about the world around them"[5]). This activity ultimately engaged a broad cross-section of the geophysical community in the solid-earth sciences and resulted in the NSF's EarthScope initiative. With the coordinated and integrated EarthScope elements, the earth science community will have the ability to image earth movements in both the horizontal and vertical plane. By taking advantage of new technological capabilities, it should be possible to derive an image of the United States at a level of detail that has no equal anywhere else in the world.

> "EarthScope is a bold undertaking to apply modern observational, analytical and telecommunications technologies to investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions. EarthScope will provide a foundation for fundamental and applied research throughout the United States that will contribute to the mitigation of risks from geological hazards, the development of natural resources, and the public's understanding of the dynamic Earth.[6]"

The goals of EarthScope include: to produce the first high-resolution synoptic views of the crust and mantle beneath the United States to generate the first comprehensive maps of crustal deformation

[4] NRC, 1993. Solid-Earth Sciences and Society. Washington, DC. National Academy Press, page 2.

[5] USGS Strategic Plan, 1999.

[6] EarthScope Working Group, 2001, EarthScope—A New View into Earth; draft EarthScope Project Plan.

(change in shape or displacement of one crustal block relative to another) in geologically active portions of the continent, and to provide the first look at the inner workings of an active fault system. The EarthScope facility has four interrelated parts: the United States Seismic Array (USArray; see Figure 1), the San Andreas Fault Observatory at Depth (SAFOD; see Figure 2), the Plate Boundary Observatory (PBO; see Figure 3), and the Interferometric Synthetic Aperture Radar (InSAR; see Figure 4). These facilities are described briefly in Boxes 1 to 4, quoted from EarthScope descriptive materials.[7]

BOX 1 USARRAY (UNITED STATES SEISMIC ARRAY)

USArray is a dense network of portable and permanent seismic stations that will allow scientists to image the details of Earth structure beneath North America. Over the course of a decade, using a rolling deployment, a transportable array of 400 broadband seismometers will cover the continent with a uniform grid of 2000 sites. As the array moves across the country, 2400 additional sensors will support high-resolution investigations of key geological features. At some sites, special instruments will record electrical and magnetic fields to provide constraints on temperatures and fluid content within the lithosphere. In coordination with the US Geological Survey's Advanced National Seismic System, observatory-quality permanent stations will be installed to extend the temporal and spatial continuity of earthquake monitoring. By studying the recorded waveforms of hundreds of local, regional and global earthquakes, and large explosions from mines and quarries, scientists will be able to identify and map subtle differences in the velocity and amplitude of seismic energy traveling through Earth. These observations will result in a vastly improved ability to resolve geological structures throughout the entire crust and upper mantle and into Earth's deepest interior.

[7] EarthScope Working Group, 2001. A New View into Earth. EarthScope descriptive brochure.

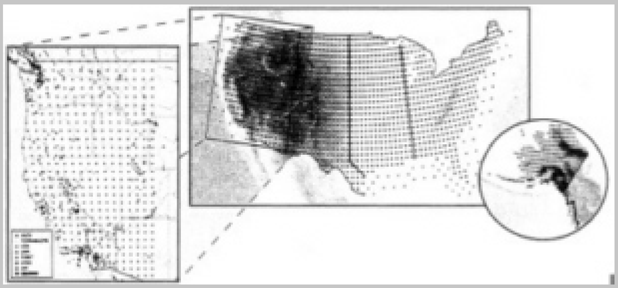

Figure 1. Planned distribution of the USArray broadband seismometer grid; the rolling deployment over a decade will reveal the deep structure beneath the United States in great detail (from EarthScope Working Group, 2001; EarthScope—A New View into Earth).

BOX 2 SAFOD (SAN ANDREAS FAULT OBSERVATORY AT DEPTH)

SAFOD is a 4-km-deep observatory drilled directly into the San Andreas fault zone near the nucleation point of the 1966 magnitude 6 Parkfield earthquake. The project will reveal the physical and chemical processes acting deep within a seismically active fault. Initially, fault-zone rocks and fluids will be retrieved for laboratory analyses, and intensive downhole geophysical measurements will be taken within and adjacent to the active fault zone. The observatory's long-term monitoring activities will include decades of detailed seismological observations of small- to moderate-sized earthquakes, and continuous measurement of pore pressure, temperature and strain during the earthquake cycle. SAFOD will provide direct information on the composition and mechanical properties of faulted rocks, the nature of stresses responsible for earthquakes, the role of fluids in controlling faulting and earthquake recurrence and the physics of earthquake initiation and growth. Drilling, sampling, downhole measurements and long-term monitoring will allow testing of a wide range of hypotheses about faulting and earthquake generation, and the pursuit of a scientific basis for earthquake hazards assessment and prediction.

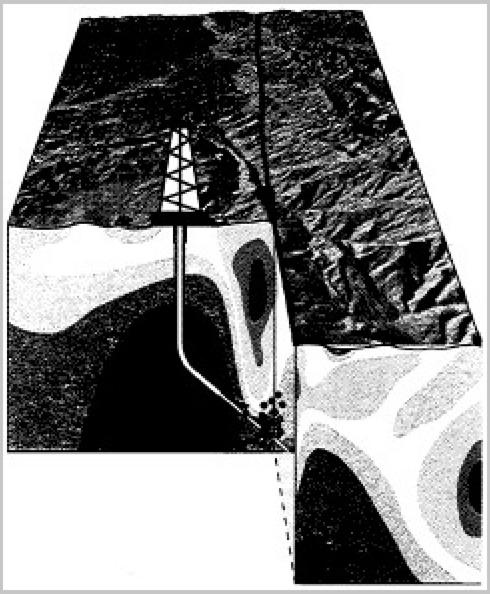

Figure 2. Schematic showing the planned SAFOD drillhole through the San Andreas fault zone near Parkfield, CA. In addition to providing rock and fluid samples, geophysical instrumentation emplaced deep in the drillhole will improve understanding of the nature of fault movement and earthquake activity by creating a long-term fault observatory (from EarthScope Working Group, 2001; EarthScope—A New View into Earth).

BOX 3 PBO PLATE BOUNDARY OBSERVATORY

PBO is a distributed observatory of high-precision geodetic instruments designed to image the ongoing deformation of western North America. The geodetic network will extend from the Pacific coast to the eastern edge of the Rocky Mountains, and from Alaska to Mexico. Two complementary instrumentation systems—global positioning system (GPS) technology at about 1000 sites, and ultra-low-noise strainmeters at 200 locations—will provide superior time resolution. A sparse GPS network at 100–200 km spacing, connecting about 20 dense clusters located at active volcanoes and the most active earthquake faults, will provide complete spatial coverage. PBO will significantly improve our ability to image and characterize the slow deformation that accompanies earthquakes and volcanic events. These data will elucidate the poorly understood processes that precede earthquakes and volcanic eruptions, and could provide a firm basis for their prediction. The broad geographic coverage will permit quantitative understanding of tantalizing connections observed between activity in different regions. Complementary geological investigations will link present-day deformation to longer-term processes that have shaped the plate-boundary region.

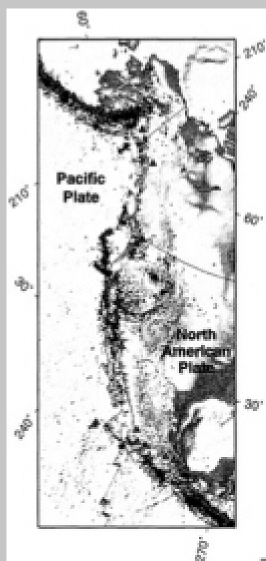

Figure 3. The plate boundary observatory will consist of a network of Global Positioning System (GPS) receivers and strainmeters that will record deformation along the western boundary of the North American Plate. The intention is to augment U.S. (California to Alaska) stations with additional networks in Canada and Mexico established in collaborative programs. The plate boundary is marked by active faults (white lines), active seismicity (black dots), and active volcanism (red triangles) (from PBO White Paper, resulting from PBO Workshop, October, 1999. Available at http://www.earthscope.org/; accessed September, 2001).

BOX 4 INSAR (INTERFEROMETRIC SYNTHETIC APERATURE RADAR)

InSAR is a dedicated, science-driven satellite mission that will provide dense spatial (30 to 100 m) and temporal (every 8 days) measurements of the North American and Pacific plates as they move past each other and deform the surrounding regions. Precise comparisons of images acquired at different times (repeat-pass interferometry) can reveal differential horizontal and vertical motions accurate to 1 mm over all terrain types. This new radar imagery, in concert with PBO's continuous GPS and strainmeter measurements, will enable mapping of surface displacements before, during and after earthquakes and volcanic eruptions, providing insights into fault mechanics and earthquake rupture. InSAR will enable mapping of earthquake strain accumulation across broad, actively deforming zones, highlighting regions of highest risk for future earthquakes. InSAR will permit imaging of the location and migration of magma through a volcanic system that may lead to an eruption, and will also provide a tool for mapping subsidence induced by petroleum production and ground water withdrawal.

Figure 4. InSAR interferogram overlaid on an oblique digital elevation model showing ground deformation associated with Peulik Volcano, to illustrate the value of InSAR for monitoring potential volcanic activity (from http://www.earthscope.org/; accessed September, 2001; image courtesy Dr. Wayne Thatcher, USGS). Peulik Volcano is a 1474 m stratovolcano on the Alaska Peninsula, located 540 km southwest of Anchorage.

At the request of the National Science Foundation, the National Research Council (NRC) appointed a committee to review the science objectives and implementation planning of the three NSF components of the EarthScope initiative: USArray, SAFOD, and PBO. Although not formally asked to examine the InSAR element, the committee was asked to assess the overall EarthScope scientific objectives after considering the integrated nature of the entire initiative. In particular, the committee was asked to consider the following questions:

- Is the scientific rationale for EarthScope sound; are the scientific questions to be addressed of significant importance; and are the proposed methods appropriate?
- Is there any additional component that should be added to the EarthScope initiative to ensure that it will achieve its objective of a vastly increased understanding of the structure, dynamics, and evolution of the continental crust of North America?
- Are the implementation and management plans for the three elements of EarthScope reviewed here appropriate to achieve their objectives?
- Have the appropriate partnerships required to maximize the scientific outcomes from EarthScope been identified in the planning documents?

The committee on the Review of EarthScope Science Objectives and Implementation Planning reviewed a great deal of written information on EarthScope, including workshop reports, proposals, and, most importantly, the July 2001 draft Project Plan. The committee had the benefit of a series of excellent briefings from members of the EarthScope Working Group (Box 5), who had recently prepared this draft Project Plan. In addition, the committee heard presentations and had discussions with other members of the solid-earth sciences community, with other interested scientists, and with NSF staff.

Although a final EarthScope scientific planning statement was not available at the time of the committee meeting, it was clear from presentations to the committee and from the extensive background scientific planning elements included within individual component white papers that scientific planning is well advanced, and accordingly the committee believed that it was able to assess the project and make recommendations.

BOX 5 HISTORY OF THE EARTHSCOPE INITIATIVE

Planning for the individual components of EarthScope had been taking place for as long as a decade prior to their integration by NSF into the EarthScope initiative in 1999. The SAFOD proposal was developed throughout the 1990s, with community workshops contributing to the proposals and expert panel evaluations that were submitted to the sponsoring agencies—the U.S. Geological Survey (USGS), the NSF, and the U.S. Department of Energy (DOE). Present plans and the project time-line are summarized in a SAFOD “fact sheet."[a]

USArray was first proposed in the mid-1990s under the auspices of IRIS (Incorporated Research Institutions for Seismology), and the experience of the IRIS community (made up of 93 member institutions and supported by NSF) in instrumentation development, data management, and instrument deployment and support is a key element of the EarthScope plan. The USArray Steering Committee has continued planning for USArray deployment, including presentation of a “white paper”[b] describing the science goals and facility implementation plans.

The Plate Boundary Observatory concept was developed over the past 4 years, again using NSF-funded workshops as the prime medium for project refinement. As a result of a workshop held in October 1999, the PBO Steering Committee produced a white paper[c] presenting a detailed scientific justification, deployment strategy, education and outreach plans, and an outline of the relationships between PBO and the other EarthScope initiatives.

Unlike the other three components of EarthScope, development of the InSAR concept from the early 1990s was largely supported as a NASA initiative, and NASA retains the lead role in its continuing development. The latest plans indicate that operations and science support costs for the InSAR component within an integrated EarthScope would require the contribution of $150 million by NASA together with $100 million by NSF.

After NSF integrated the individual components into the EarthScope initiative in 1999, an EarthScope Working Group was established to assume responsibility for organizing the community planning workshops that have refined the integrated science objectives and produced a draft Project Plan.[d] This project plan indicates that the total cost to the NSF Major Research Equipment (MRE) account for the 10-year duration of the initial three EarthScope elements—USArray, SAFOD, and PBO, will be $356 million, of which

$172 million will be for facilities, with the remainder budgeted for operations ($72 million) and science management ($112 million). The original MRE FY2001 budget request to Congress (at that time including only USArray and SAFOD) was not funded, although the notation “without prejudice” added by Congress encouraged NSF to prepare an FY2003 budget request, this time including the USArray, SAFOD, and PBO elements. Planning for the InSAR element continues, in a partnership between NSF and NASA.

[a] San Andreas Scientific Drilling Project, 2001. Testing Fundamental Theories of Earthquake Mechanics: The San Andreas Fault Observatory at Depth (SAFOD). [Online]. Available: http://pangea.stanford.edu/~zoback/FZD/; accessed September, 2001.

[b] USArray Steering Committee, 1999. USArray—A Synoptic Investigation of the Structure, Dynamics, and Evolution of the North American Continent. IRIS Consortium workshop report. [Online]. Available: http://www.earthscope.org/USArray_wtpaper.pdf; accessed September, 2001.

[c] PBO Steering Committee, 1999. The Plate Boundary Observatory— Creating a Four-Dimensional Image of the Deformation of Western North America. Available online: http://www.earthscope.org/PBOwhitepaper.pdf; accessed September, 2001.

[d] EarthScope Working Group, 2001, EarthScope—A New View into Earth; draft EarthScope Project Plan.

The committee’s answers to the questions posed in the charge indicate a consensus that the EarthScope project should proceed apace. The committee concludes that the scientific rationale for EarthScope is sound, that the scientific questions posed are of great importance, and that the methods are appropriate. The committee considers that the components that have been identified are comprehensive, and that there are no additional components to be developed. The implementation and management plans at this early stage of the project are appropriate, although it will be critical to develop a detailed plan to address issues of integration as the project proceeds. Finally, the committee considers that appropriate partnerships have been identified by the EarthScope proponents, but encourages the continued development of these partnerships with the ocean science community and with programs and colleagues in Canada and Mexico.

2

Scientific Rationale and Science Questions

OVERVIEW

The overriding question underpinning the EarthScope initiative is, "If we know in detail the anatomy of the United States lithosphere, and what lies beneath it, and how it is moving today, can we then understand how it works?" This is really equivalent to asking whether detailed knowledge of one place will provide an understanding of the general processes that operate on our planet. The answer to this broad question is almost certainly "yes"—earth scientists have always made general advances in this way—but here the approach being tried is on a much grander scale than was ever possible before. Examples of the more specific questions and processes that EarthScope seeks to address are:

- How do earthquakes result from the accumulation of strain (the change in shape from an original configuration) in the earth? If we can see how strain accumulates and know the properties of materials at depth in a fault zone, can we recognize signals that tell us that an earthquake is imminent?
- To what extent are the present motions on the surface influenced by the inherited effects of previous events over the earth's long history as preserved in the rocks within and beneath the North American continent?
- What is beneath the major geological features at the earth's surface? Do they continue at depth? If so, what is their shape? Are they a result of processes occurring deep in the mantle beneath the

continents, or are they inherited from earlier plate boundary processes?

- How is molten rock (magma) generated in the mantle? How does it migrate upward through the mantle and crust? How long does magma stay in shallow chambers in the crust prior to eruption?
- With the knowledge of how elevations over the surface of a volcano vary with time, and an understanding of the earthquake activity and density variations at depth beneath it, are there characteristic features that might provide advanced warning of volcanic eruptions?

North America is the ideal natural laboratory to address these questions. It is a large, geologically varied continent with a complex active plate boundary along its Pacific margin and with many other sparsely but significantly active regions. It has a long geologic history extending back in time over 3 billion years, and boasts a robust, active, superbly qualified earth science community and the world's most advanced electronic communication network. Because techniques are now being developed that will allow this earth science community to image the earth in unprecedented detail, the emerging challenge is to exploit the new imaging capabilities to develop as complete a picture as possible of the interior of our planet, its evolution, and its present-day deformation.

THE EARTHSCOPE INITIATIVE

EarthScope in its broadest sense is composed of two parts. The first part is the installation of equipment to gather data, and the development of the mechanisms to make those data widely available. The second part involves the exploitation of the accumulating data to address specific scientific questions of both national and regional importance that will enhance our scientific understanding of the North American continental lithosphere. The scientific goals and objectives of EarthScope are ambitious and challenging. Achieving them will require both a high degree of collaboration among diverse earth science disciplines, and the ability to interpret and synthesize a wide range of scientific evidence. That this collaborative process is already underway is clearly shown by the numerous community workshops and meetings that have been used to help develop and refine the EarthScope initiative.

The degree of collaboration to date is impressive and the committee is confident that this collaboration will continue and expand.

The primary tools of EarthScope mainly involve the fields of geophysics and remote sensing. The effectiveness of the scientific interpretation of the geophysical data, however, will depend upon the widest possible knowledge of geology, rock properties, geochronology (determination of the age of a given rock body), and the results from many other fields within earth science, including geomorphology, petrology, structural geology, tectonics, and soil science. The nature of the available geological information is quite variable throughout the United States. In most areas, modern geological maps are available. In some regions, however, the best available mapping is of only a reconnaissance nature; some maps date from before many modern geological concepts, especially the plate tectonics model, were formulated or widely adopted. The old aphorism “the eye seldom sees what the mind doesn’t anticipate” applies here. The proper interpretation of much of the data to be provided by the EarthScope facility will require detailed geological maps in many regions, and optimal siting of EarthScope instrumentation may also require improved geological maps. Much other new scientific input will be needed from the many subdisciplines of the earth sciences, and it is likely that knowledge and information from outside the conventional earth sciences, such as geotechnical engineering, may also be required. The committee suggests that one of the key challenges of the EarthScope program will be to ensure that this integration of information, knowledge, and expertise occurs in the most effective way possible.

In the remainder of this chapter, the committee presents comments concerning each of the science components of EarthScope— the United States Seismic Array, the Plate Boundary Observatory, the San Andreas Fault Observatory at Depth, the Interferometric Synthetic Aperture Radar mission— and the integrated EarthScope Education and Outreach Program.

EarthScope Components: United States Seismic Array (USArray)

USArray proposes to instrument the entire lower 48 states and Alaska with a grid of broadband seismometers with roughly 70-kilometer spacing, achieving this with a transportable array of 400 instruments (informally called “Bigfoot”; see Figure 1) that will be deployed in successive north-south bands across the continent over a 10-year period. The results from USArray should allow mapping of the structure and thickness of the crustal and mantle lithosphere in unprecedented detail, as well as the mantle beneath the lithosphere as deep as the core-mantle boundary. This knowledge is one of the most obvious deliverables of the EarthScope project, and one that will present opportunities for all earth scientists concerned with the evolution and behavior of continents: they simply will be seeing the earth in a way that has never before been possible.

The committee notes that the EarthScope and USArray proponents had given much thought to how to deploy the transportable array, and to the geometry and sequence in which it rolls across the continent. The one-year deployment time and 70-kilometer spacing will necessarily place some limitations on the scale of observations that can be made with the transportable array, especially in regions with low natural seismicity. As discussed below, the portable seismometers are designed to address some of these limitations by examining particular areas and features in greater detail. It is important to recognize, however, that there are some geologic features that could only be well characterized using a seismometer grid with closer spacing and longer deployment times. Even so, the committee is satisfied that the operational decisions built into the implementation plans were justified in cost-effective terms that did not jeopardize the scientific goals. This element of USArray is a massive logistical task, but the committee is confident that the EarthScope seismologists have sufficient experience to carry it out successfully and efficiently.

In addition to the “Bigfoot” transportable array of 400 instruments, USArray also includes 2400 portable seismometers to be deployed in flexible network geometries to examine particular areas and features in great detail. The sheer number of these instruments should reveal images with a detail and accuracy that has never been seen before. It should allow, for example, entirely new and detailed knowledge of crustal structure and thickness variations in regions of active faulting. In addition, it will help address the question of how the distribution of deformation in the lower crust compares with that at the surface. Many other important and hitherto unanswerable questions could be addressed with networks of this density. The EarthScope proponents have indicated that this flexible capability will be allocated toward projects that are chosen through the usual competitive grant-submission process at NSF This intent is admirable, fair, and sensible in principle, but it requires careful thought to ensure that the new capability is exploited to the maximum possible extent. Issues include: the realization that although the use of very large numbers of instruments simultaneously in a dense configuration is a formidable tool with great scientific problem-solving potential, such a deployment may be beyond the logistical capability of small investigator groups; and an appreciation that the rolling “Bigfoot” array, or any of the other three components of EarthScope (PBO, InSAR, SAFOD), probably will identify unexpected features or phenomena whose investigation would greatly benefit from the focused attention of the flexible US Array network. Some of these unexpected features may be urgent priorities, such as indications of imminent earthquakes or volcanic eruptions. Accordingly, the committee suggests that it will be important not to commit the whole flexible network to projects in advance in such a way that it cannot fulfill this role. The priority of the portable network goals should be flexible in both time and space.

Preparing for operational eventualities is a formidable management and planning challenge. Thus far, the attention of the EarthScope proponents has understandably been focused on instrument specification, deployment, and operation. The committee has confidence that the community concerned can effectively address these additional issues relating to management of the scientific objectives, but would urge them to start doing so now. Many of these management concerns apply equally to the flexible component of the GPS networks that form part of the PBO.

EarthScope Components: San Andreas Fault Observatory at Depth (SAFOD)

Apart from scientific ocean drilling during the Deep Sea Drilling Project and its successor, the Ocean Drilling Program, deep drilling in sedimentary rock sequences on continents and offshore has been carried out mainly in the context of hydrocarbon (oil and gas) exploration and recovery. Several deep holes have been drilled for scientific purposes in crystalline rocks in Russia, Germany, and Hawaii, and a number of deep boreholes (up to 1.8 kilometers) were drilled to intersect the Nojima Fault on Awaji Island in Japan. However, the EarthScope proposal to drill and instrument the San Andreas Fault is unique, in that it seeks to intercept an active fault zone near the depth at which earthquakes are generated to study its physical and chemical characteristics. Although many active and inactive fault zones have been mapped at the surface and imaged at depth, no active fault has heretofore been examined or sampled directly at the hypocentral depths (the actual points of origin) for small earthquakes.

The chosen drill site is close to the hypocenter of the 1966 magnitude 6 Parkfield earthquake (Figure 2), in a region where the San Andreas Fault moves through a combination of slip associated with small-to-moderate magnitude earthquakes and aseismic creep. This segment of the San Andreas Fault is one of the most well documented and instrumented sites along its entire length, and thus is an area where information obtained from drilling can be leveraged to the greatest extent. The proposed facility will allow scientists to build on existing knowledge to address many fundamental questions about the physical and chemical processes acting within the San Andreas Fault and, by extension, to the faulting process in general. Drilling, sampling, and continuous measurements directly within the fault zone will test controversial scientific hypotheses about earthquakes by providing direct information on the composition and mechanical properties of active fault zone rocks, the nature of stresses ("normalized" force or force intensity) responsible for earthquakes, the role of fluids (particularly pressurized water) in controlling faulting and earthquake recurrence, and the physics of rupture-initiation and propagation that cause a given earthquake. In addition to recovery of fault zone rock and fluids for laboratory analyses, intensive down-hole geophysical measurements and long-term monitoring are planned within and adjacent to the active fault zone as an integral component of the EarthScope observatory. Monitoring experiments will include near-field, wide-dynamic-range seismological observations of earthquake nucleation and rupture and continuous monitoring of variations in pore pressure (pressure of fluid within the rocks), temperature, and crustal deformation (strain, fracturing and fault slip) during the earthquake cycle. By directly evaluating the roles of fluid pressure, intrinsic rock friction, chemical reactions, in situ stress (force intensity), and other parameters during generation of an earthquake, project scientists hope to simulate earthquakes in the laboratory and in computer models using representative fault zone properties and physical conditions.

The committee is very favorably impressed with the scientific objectives of the SAFOD facility. As a component of EarthScope with both sampling (during the drilling phase) and monitoring (during the observatory phase) elements, SAFOD is the tangible, three-dimensional exploration facility that relates to the USArray, the PBO, and InSAR. The USArray and SAFOD projects have fundamental goals in common. Both aim to provide information on the structure and rheology (firmness or viscosity) of the earth in three dimensions over a range of spatial scales. Both will investigate the processes and conditions that control deformation of the earth. SAFOD will provide critical in situ data on physical and rheological properties of earth materials at depth. USArray provides the tool for extrapolating the in situ data to a broader region and larger spatial scales. PBO and InSAR also will link directly with SAFOD in that determination of the rate and distribution of deformation in the crust surrounding the drill site are critical to the goals of SAFOD. Measurements made with GPS and InSAR are exactly the kind needed to determine the overall pattern and temporal variation of deformation. The committee notes that the Parkfield site for SAFOD is well known and characterized, and recognizes that there is a realistic chance of recording activity at this site in the near future because the fault both creeps and moves in relatively frequent, moderate-sized earthquakes (rather than in big earthquakes every few hundred years, as is the case at other sites). The committee accepts that attempting to sample and instrument faults at multiple locations, although an admirable long-term goal, is unrealistic because of cost at this time.

EarthScope Components: Plate Boundary Observatory (PBO)

The North American Pacific Plate Boundary Observatory (PBO) involves deployment and integration of a network of global positioning system (GPS) stations (at approximately 1000 sites), together with strainmeters, to monitor the motions in real time of the actively deforming region of the western North American continent (Figure 3). The GPS instruments use signals from the GPS satellite network to record the position of the individual locations with great accuracy. The strainmeters measure local strains and provide the sensitivity required to detect short-lived transients; as such, they will provide the shorter time-scale readings (days to weeks) to complement longer time-scale GPS and

InSAR data (weeks to months to years). The rationale for location of these instruments in the western United States is that this region is at the confluence of two great plates, the North American and Pacific plates, and a smaller plate, the Juan de Fuca plate, which itself is a remnant of the formerly extensive Farallon plate, much of which has disappeared beneath North America in the past 100 million years. It is a region that is actively undergoing deformation (change in shape and configuration) by faulting, uplift or sinking, and folding. In addition, this region experiences most of the earthquakes in the United States, all of its active volcanism, and many of its major related earth movements, such as landslides and mudflows (lahars), which can travel many miles down river valleys, through centers of population and industry. Many of the west coast cities lie along or at the mouths of such river valleys.

The PBO data, in conjunction with data from the other EarthScope components, should allow the construction of a detailed description of earth movements within western North America. This should in turn facilitate the development of realistic dynamic models to help explain why these movements occur, and stimulate related scientific research that should lead to a reduction in risks associated with earthquakes, volcanic eruptions, and associated land movements such as landslides.

Correlation of PBO observations with data from other EarthScope components will be invaluable. In particular, the combination of PBO and InSAR measurements shows great potential for understanding the location of future possible fault movements and impending volcanic activity at known or incipient centers. Areas of activity pinpointed by the PBO will serve as appropriate sites for possible deployment of the flexible components of the USArray. In addition, the San Andreas Fault Observatory will provide an important third dimensional view to PBO observations.

EarthScope Components: Interferometric Synthetic Aperature Radar (InSAR)

Interferometric Synthetic Aperture Radar (InSAR) provides a means of measuring and monitoring the motion of the earth's surface in great detail over wide areas, and should be regarded as an essential component of EarthScope. InSAR works by comparing radar images of a given area acquired at different times. Any motion of the earth's surface occurring in the interval between recording of the two images produces changes in the radar signal from the first image to the second, which can be transformed into a map showing ground displacement. This technique allows observation of millimeter-level displacements at a resolution of 25 meters over broad swaths. Because it is a satellite-based instrument, these measurements may be made with global coverage at regular intervals.

Since its first demonstration to map the surface displacements associated with the 1992 Landers earthquake, InSAR has produced some spectacular images of deformation associated with earthquakes and volcanoes, and has been used to investigate a wide range of phenomena: the slow accumulation of crustal strain across fault zones, the motions that occur immediately following an earthquake and that allow the mechanical properties of the crust and uppermost mantle to be investigated, the inflation or deflation of volcanoes due to movement of magma at depth (e.g., Figure 4), subsidence in urban areas due to the extraction of oil or water, and the movement of Antarctic ice streams.

Despite the undoubted success of InSAR observations carried out with the European Space Agency's (ESA) European Remote-Sensing Satellite (ERS) missions, these observations were subject to many constraints and limitations. The C-band (5.6-centimeter wavelength) of the ERS radars meant that radar coherence in vegetated areas decreased rapidly with time, preventing interferograms from being formed over the long time intervals needed to isolate small ground displacements. The ERS satellites carried multiple instruments with a wide range of objectives, and as a consequence the long, regular time series of SAR images needed to observe crustal strain accumulation were acquired only in limited areas. The cost of purchasing SAR images limited the range of problems open to individual investigators. Future missions with InSAR capabilities by overseas agencies (ASAR on ESA's Envisat mission, PALSAR on NASDA's ALOS mission, RADARSAT II) will be subject to many of the same limitations.

To realize its full potential, a satellite dedicated to InSAR is essential, enabling acquisition of synthetic aperture radar (SAR) images with good radar coherence over long time intervals. Use of the L-band (24-centimeter wavelength) radar will allow observations of all terrains, regardless of vegetation cover—a considerable improvement on the present C-band radars, and a real, dramatic improvement in InSAR's capability and applicability. These measurements will help provide a synoptic view of the accumulation of crustal strain across the whole of North America, strain that may eventually be released in earthquakes. Because such a satellite mission would regularly observe North America's seismic and volcanic belts in their entirety, it should provide an early indication of new events, e.g., magma motion at depth beneath a volcano, or aseismic slip on a fault. Measurements such as these, made with complete coverage at high resolution, cannot be obtained in any other way, and hence InSAR must be regarded as an integral component of EarthScope.

In addition to contributing fundamentally to EarthScope objectives, the committee notes that InSAR, as a satellite-based instrument, could make similar measurements worldwide. Although the other components of EarthScope would not be available elsewhere, InSAR, by capturing events in other parts of the world that are similar to those in North America that can be investigated by the full suite of EarthScope facilities, would provide a starting point for applying knowledge gained by EarthScope to other parts of the world's seismic and volcanic belts, and could stimulate similar activities in other countries.

EDUCATION AND OUTREACH

EarthScope provides a unique opportunity for education and outreach (E&O) efforts that not only will capitalize on the public's natural curiosity about the planet on which they live, but also will engage them in scientific exploration through direct involvement in data collection and research. The instrument deployments and experiments that will bring earth science to local communities across the nation are the key elements that will provide opportunities for development of educational materials that are particularly relevant on a regional basis.

The committee strongly endorses the EarthScope Working Group's intention to include an extensive E&O effort in their project plan. EarthScope expects to provide opportunities for participation at two levels: development of a core of materials and resources appropriate for national-scale outreach to a broad audience, and provision of more focused educational efforts for specific audiences and regions. Both of these are important to build on the national scale of the EarthScope initiative, and the committee urges that sufficient personnel and funds be assigned to conduct these activities.

At present, the overall E&O plan is all-encompassing and includes a wide range of target audiences (K-12 and college students, earth science professionals, policy makers, the general public), and products (real-time data, analytical tools, curricular materials, and other publications). Further planning will have to focus on a subset of these audiences and products, depending upon available resources. Despite the great interest in knowledge about the earth, earth science has been generally neglected at the K-12 level for the past century. For the intellectual journey from data to information to knowledge to wisdom to occur, well-trained geoscientists are required. If students are given the opportunity to feel the excitement of discovering new information about our dynamic planet, there is an increased likelihood of training scientists who will be able to use these powerful tools of perception. The committee emphasizes that development of an effective educational outreach program for EarthScope is both highly desirable and challenging.

EarthScope is well poised to undertake a wide variety of outreach activities because several of its partners and collaborators (e.g. NASA, USGS, the Southern California Earthquake Center [SCEC]) have considerable experience in the development of successful outreach products, ranging from effective web sites to museum exhibits. In addition, education and outreach activities will benefit from the intention to make all EarthScope data freely and rapidly available—a policy the committee endorses wholeheartedly. EarthScope and its tools and techniques could furnish powerful data sets for future geoscientists. The committee encourages the involvement of all the EarthScope partners and collaborators in the E&O effort.

SUMMARY COMMENTS

The committee reviewed a large number of documents that showed the evolution of the EarthScope initiative, and noted that the EarthScope concept and the plans for the facility have evolved fairly rapidly over the past year. As a result, the written description of the scientific program as currently envisaged is terse and lacks the detail that will be required once funding has been approved. However, presentations to the committee indicated that the EarthScope Working Group has carefully considered the many things that will need to be addressed as the initiative moves forward. The overall assessment of the committee echoes that presented earlier this year by the Committee on Basic Research Opportunities in Earth Sciences[1]—the scientific vision and goals of EarthScope are well articulated and have been developed with a high degree of community involvement. The committee strongly endorses all four scientific components of the EarthScope initiative and the education and outreach plans.

[1] NRC, 2001. Basic Research Opportunities in the Earth Sciences. Washington, DC: National Academy Press.

3

Implementation and Management

EarthScope is a complex endeavor that will require a coherent management scheme that emphasizes integration across its many aspects. The EarthScope Working Group pointed out that EarthScope will require management and coordination at several intersecting levels:

- As a facilities program—the various components of EarthScope will need to build on the strengths of the individual communities that they represent, but be undertaken in a manner that closely coordinates decision making and implementation during all phases of development —project planning, instrument definition, site selection, data collection, data management, and project review.
- As a scientific endeavor—the breadth of EarthScope's disciplinary and geographic reach will influence many aspects of earth science research in the United States for the next decade and beyond. There must be close coordination among the facilities, their management, the user community, and funding agencies.[1]

The challenge to have an effective, integrated management structure applies both to the implementation and operations of the facilities program, and to the scientific and educational endeavors that are based on the data and information acquired. In planning the management, coordination, and advisory studies of both aspects of EarthScope, incentives and strategies to ensure and encourage inte

[1] EarthScope Working Group, 2001, EarthScope—A New View into Earth; draft EarthScope Project Plan.

gration must be incorporated at the earliest stages and continually reinforced. In supporting EarthScope science, those making decisions on funding will have to recognize a wide spectrum of contributions from disciplines and activities both inside and outside the confines of the institutional earth science budgeting process. Innovation and creativity in both management and funding should match the innovation and creativity of the program goals. The overall management scheme for EarthScope will require a number of elements. These include effective mechanisms for integrating component parts of the program, for soliciting advice on science directions, for making effective decisions enabling rapid response to selected opportunities, and for accomplishing educational and outreach activities.

The current proposal of the EarthScope Working Group for a management structure has several components (Figure 5). Interagency coordination is to be accomplished by the Interagency Coordinating Group. An EarthScope Coordinating Committee is proposed to perform the "day-to-day" oversight and planning, and a Community Science Council will provide high-level advice to the agencies and coordination for the overall program. This design for the management structure is little more than a "cartoon" in the documentation available to the committee and begs questions about how it will work. Will the EarthScope Coordinating Committee have a high-level role in resource allocation and setting science priorities, or will this be undertaken only by interaction between the Interagency Coordinating Group and the individual EarthScope facility management teams (Figure 5)? The effective functioning of the EarthScope management structure, to achieve the required integration, will depend on details still to be developed. From presentations made to the committee, it is clear that members of the science community and the NSF staff have devoted a good deal of thought to the issue. It is critically important that this activity continue to ensure the evolution of a structure that will achieve the ambitious program goals.

Although it is clear that the community is aware of the challenges of managing an earth science program of this unprecedented scope, individual components of the EarthScope enterprise will also require innovative management. For example, new ways to integrate large and complex data streams to elucidate dynamic earth phenomena will be needed. One example of an innovative approach for integrating data streams involves establishing a "Community Modeling Environ ment" (Figure 6), an idea that stems from a workshop[2] convened by IRIS (Incorporated Research Institutions in Seismology). The committee encourages continued exploration of innovative structures to stimulate and provide for integration. In a similar vein, the committee encourages exploration of ways to optimize the education and outreach efforts of EarthScope.

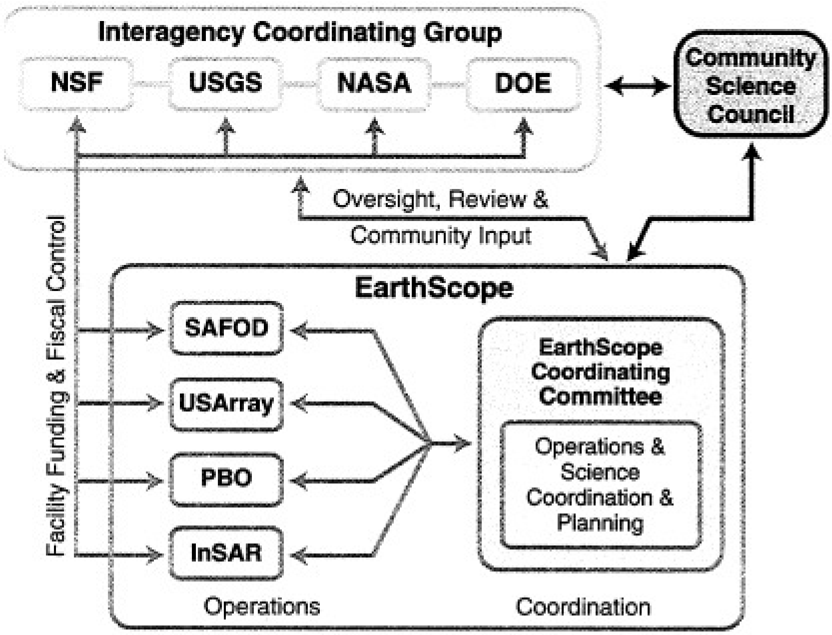

Figure 5. Proposed structure for oversight and management of EarthScope facilities (from EarthScope Working Group, 2001; EarthScope— A New View into Earth).

In conclusion, the committee stresses that management and coordination must be highly effective at several levels, and furthermore, that careful attention must be paid to the selection of an overall structure and its component parts as EarthScope moves toward implementation. In particular, the scientific advisory structure must encompass all elements

[2] 13th Annual IRIS Workshop, Jackson Lake Lodge, Moran, Wyoming, June 6–9, 2001.

of EarthScope to provide oversight and advice on the scientific directions of the program. The committee believes that the advisory structure also should include liaisons to other programs that can complement or extend EarthScope (discussed in next chapter).

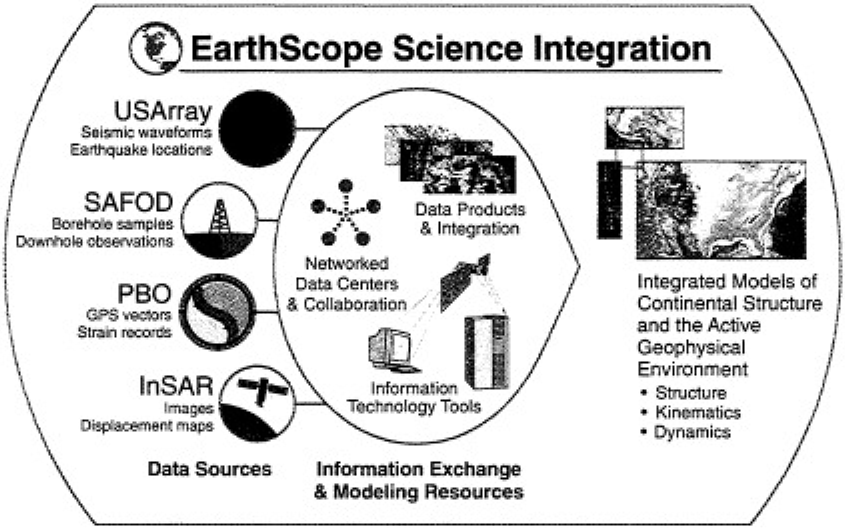

Figure 6. Schematic showing coordinated and integrated data management structure for all EarthScope elements (from EarthScope Working Group, 2001; EarthScope—A New View into Earth).

4

Appropriate Partnerships

The EarthScope Working Group has identified a wide range of appropriate partnerships to assist in reaching its goals. The committee concludes that the partnerships described as critical to the EarthScope initiative are entirely adequate; the committee did not identify any major omissions in the possible collaborations envisaged. However, the committee does have a number of comments that may be useful to the program planners as EarthScope planning evolves.

Most of the earthquakes within the United States occur in the western part of the country, including the Rio Grande Valley of New Mexico and Texas; the Yellowstone region of Wyoming and neighboring Montana and Idaho; the Basin and Range Province in Utah, Nevada, Idaho, and Arizona; and in the states along the Pacific Coast—Alaska, Washington, Oregon, and California. Plate boundary activity is not limited to the United States alone, however, but extends into contiguous parts of Canada and Mexico and the offshore areas adjacent to all three countries. Accordingly, a full understanding of the nature of the plate boundary activity will necessarily involve correlation and integration of EarthScope data with similar measurements in these other regions. The EarthScope Working Group is aware of this requirement, and there are plans to coordinate their efforts with workers in those two countries. The committee endorses this intent.

In addition, although the USArray and PBO installations as currently planned do not extend into the marine realm, the proposed NEPTUNE program to deploy ocean bottom seismometers (OBS) and other instruments (including GPS-acoustic instrumentation and strainmeters) throughout the Juan de Fuca Plate[1], off the coast of Wash

[1] See: http://www.neptune.washington.edu/, accessed October, 2001.

ington and Oregon, provides an excellent opportunity to view the results of USArray and the PBO in the context of an entire plate. Consequently, the committee suggests that close coordination of the PBO and USArray with the NEPTUNE program is highly desirable. The ocean science community is also involved in OBS deployments in other locations off the coasts of the United States. As these represent a logical and necessary extension of the "Bigfoot" deployment plan of USArray, it is important that coordination between these programs and scientific communities should be effected.

In addition, major earthquakes and deformation have occurred in other parts of the United States, particularly in the mid-continent regions (e.g., New Madrid area, southern Illinois; Kentucky; Missouri— earthquakes in 1811 and 1812) and along the Atlantic seaboard (e.g., earthquakes in 1755 off Cape Ann, Massachusetts; 1886 in Charleston, South Carolina). Although the PBO does not extend into these regions, the proponents are aware that other agencies are in the process of making GPS installations in these regions and they plan to coordinate their efforts with these other activities. The committee endorses this intent. Also, the deployment of seismographs and GPS across the country will depend on interactions with state geologists and other more regionally-oriented groups such as oil companies. The identification of at least some of the special targets for the USArray flexible deployment program will depend on such partnerships.

Landslides are the most damaging geological hazard in the United States, affecting every state of the nation and its island territories.[2] There is a complete continuum from small slumps to large landslides to extensive fault structures. Many of the rocks or other earth materials involved in landslides are similar to those involved in faulting, and the physical principles involved in many landslides, especially the largest ones, are identical to those involved in faulting. The committee encourages the EarthScope investigators to develop interactions and collaborations with the geomorphology community involved in the study of these significant and damaging phenomena.

Successful accomplishment of the EarthScope education and outreach objectives will also require the nurturing of partnerships between scientists and educators. The success of EarthScope's educat

[2] Brabb, E.E., 1989. Landslides: Extent and Economic Significance in the United States. Pp. 25–50 *in* Brabb, E.E., and B.L.Harrod, eds., Landslides— Extent and Economic Significance. Rotterdam, Balkema.

ional efforts (as with any science program) will depend on the effective translation of the science into materials that meet national and state standards and can be used within the context of a classroom or other teaching environment. Educators will also need the training and resources to take advantage of local EarthScope instrument installations, as well as assistance to implement EarthScope-related educational activities. This is an ambitious undertaking, and will require the involvement of national professional organizations of educators, as well as state and local school districts, in the initial planning of EarthScope's scientific and educational efforts.

Several other large scientific programs are currently in the process of planning extensive educational efforts (e.g., the NEPTUNE program[3]). The committee recommends that EarthScope establish liaisons and communications with other appropriate programs to build on existing progress in the development of major E&O efforts.

[3] See: http://www.neptune.washington.edu/, accessed October, 2001.

5

Summary Observations and Recommendations

SCIENTIFIC RATIONALE AND SCIENCE QUESTIONS

Observation:

The earth sciences have rapidly moved toward the study of "geosystems"—complex systems involving many scientific disciplines, well expressed in natural laboratories where the processes can be studied in detail. The EarthScope initiative is a response from the scientific community to the need to explore the North American continent beneath the United States as a solid-earth dynamic geosystem and to provide the foundation for increased understanding of its structure and the processes that shape it. The technology for such a program and the capacity to manage the large amount of data accumulated by it are proven and in place. This is therefore the right time to undertake a full exploration of the nature of the North American continental crust and its underlying mantle, as a critical requirement for understanding the nature of the earth on which we live and how society needs to manage and adapt to its rhythms and processes.

Recommendation:

The committee strongly endorses the integrated approach to the investigation of the lithosphere and mantle underlying the United States proposed in the EarthScope initiative, including its four components: USArray, PBO, SAFOD, and InSAR. The committee concludes that the scientific rational for EarthScope is sound, that

the scientific questions to be addressed are of significant importance, and that no necessary components have been omitted. The committee recommends that all four components be implemented as rapidly as possible.

Observation:

Answering the key questions posed for the EarthScope science initiative will require the participation of scientists from across all the disciplinary programs of NSF's Geosciences Directorate. Fully exploiting the opportunities afforded by the new data collected in EarthScope not only will depend upon the analysis of geophysical data, but will require new geological mapping, new geochemical and geochronological studies, and new activities in a host of other disciplines. The basic science needs associated with the Earthscope facilities have been outlined effectively by the EarthScope Working Group in the draft EarthScope Project Plan, July 2001. However, for its success, it is critical that the NSF make a long-term commitment to fund this science, and to be prepared to augment these funds as the program evolves. The disciplinary programs in NSF's Division of Earth Sciences (EAR) that support such science currently can fund only a fraction (10– 40 percent, depending on the program) of the proposals received, and many deserving projects cannot be funded. The science challenges presented by EarthScope provide an exciting opportunity for earth scientists that will require both collaborative large-scale projects and individual investigator projects. It is likely that these will stress the existing budgets available to EAR.

Recommendation:

The NSF should ensure that EarthScope's scientific potential is effectively realized and capitalized upon by continuing its support for the disciplinary and interdisciplinary programs within NSF's Division of Earth Sciences (EAR) that form the scientific foundation of the project.

Observation:

In recent years, InSAR has made spectacular contributions to imaging parts of the earthquake cycle and revealing the motion of magma at depth beneath volcanoes, and the committee believes that InSAR must be perceived as an integral part of EarthScope. With its unique ability to measure the continuity of strain signals over large areas, InSAR represents a very dramatic enhancement of EarthScope's ability to monitor the behavior of the solid earth. It greatly improves any interpretation of signals that might first be detected by seismology or GPS, and will significantly improve the chances of detecting premonitory signals from volcanoes and earthquake faults. Of all the components of EarthScope, it is the most likely to first detect natural phenomena that require closer attention from the other components of the project. It does not replace seismology or GPS, as each component brings its own unique capabilities, but all four together are far more powerful than any one component on its own; a clear example of where the ability of the whole greatly exceeds that of its individual parts. This capability greatly increases the probability that unexpected events (e.g., premonitory motion of a volcano, motion on an unknown blind [hidden] fault) will be detected.

Recommendation:

The committee concludes that InSAR is an integral part of the EarthScope vision that will greatly enhance the effectiveness of the project, and it should not be viewed merely as a desirable add-on to the project. The committee urges NSF and NASA to collaborate to realize this goal at the earliest opportunity, so as to make InSAR capability a reality during the lifetime of the other EarthScope components.

IMPLEMENTATION AND MANAGEMENT

Observations:

The overall scientific vision of EarthScope is a four-dimensional view of the North American continent beneath the United States, to be achieved by integrating a variety of data from four observational techniques. This vision recognizes that for addressing a wide range of problems in lithosphere dynamics and evolution, these datasets are more powerful when integrated than when considered separately.

Planning for EarthScope is understandably focused at present on the major effort needed to install equipment and bring observational data on line. In parallel with this effort, it is important that planning for the science program and its management be developed. EarthScope will need a mechanism to ensure integration, coordination, and synthesis of interdisciplinary studies carried out by individual investigators. Since scientific research proposals using EarthScope-derived data will be subject to the normal NSF peer review process, there will need to be a mechanism for EarthScope management to provide advice to NSF on programmatic funding priorities.

Recommendation:

The committee recommends that EarthScope look beyond the development of the facility to the operational phase of the scientific program, and develop a strategic science plan to accomplish its long-term scientific goals. Such a plan should include a scientific advisory structure encompassing all elements of EarthScope and all appropriate branches of the earth sciences to provide oversight and advice on the scientific directions of the program, and to coordinate its scientific activities. It should also incorporate a mechanism for providing advice to NSF regarding EarthScope programmatic funding priorities. The advisory structure should also include liaisons to other programs that are either complementary or will help fulfill the broader EarthScope vision of understanding the structure and evolution of the North American continent.

EarthScope will result in observations that are certain to reveal new and unexpected events and targets. Some of these unforeseen features will require rapid response, such as signals that may be related to increased earthquake or volcanic activity. This prospect will pose a different integration and management challenge: how to coordinate and direct the flexible components of EarthScope to address new targets that emerge during the course of the program. A mechanism needs to be in place to meet this challenge.

Recommendation:

The committee urges EarthScope management to establish a mechanism that would rapidly and effectively direct appropriate equipment and expertise toward any unexpected phenomena that may be revealed during its implementation.

EDUCATION, OUTREACH, AND COMMUNICATION

Observation:

EarthScope provides a unique opportunity to excite and involve the general public, students, and the earth science community in understanding the earth on which they live. The committee believes that there is a growing need for such knowledge that the EarthScope project is well positioned to satisfy.

Another key feature of EarthScope that makes education and outreach so significant is that it will involve physical, visible, and tangible installations that will be sited within or close to local communities across the nation. By making the vast datasets and new concepts generated by EarthScope available to the general public, there is a greater likelihood that there will be support from the voters who will ultimately fund the costs of applying the geoscience to societal problems and opportunities. The EarthScope proponents and working groups have recognized this, and are to be commended for their plans and ideas.

At the same time, the committee recognizes that education and outreach on the scale envisioned will be difficult, and that some focusing will be required. Achievement of this goal will require the involvement of all the scientists within the program, plus professionals in the fields of education, public relations, and communications. EarthScope should build upon the considerable expertise that NASA and NSF have in the broader field of mass communications.

Recommendation:

Because EarthScope provides a unique opportunity that must not be missed, the committee recommends that the education and outreach aspects of EarthScope, as currently incorporated in EarthScope

planning documents, should be strongly and realistically supported. They must be an integral component of the project. Education specialists should be involved in both the development and execution of the education and outreach programs.

Observation:

Astronomy projects, such as the Hubble telescope, are fundamental to our understanding of how our universe works but have little direct significance in terms of immediate economic impact. The earth sciences, on the other hand, have the benefit of dealing not only with the beauty of understanding how our planet works, but also with the societal and economic impact of its processes and their effects on human life on the earth's surface. EarthScope will address both aspects of this dichotomy. The sense of awe in understanding the behavior of our continent, with its associated earthquakes and volcanism, will be balanced by an awareness of how it influences our daily lives. The excitement of this knowledge, and the cautions associated with it, bear directly on public health, safety, and security. The increasing urbanization of North America—with its attendant demand for more high-speed highways, dams, bridges, and tracks for new high-speed inter-city trains—requires a knowledge of the crust and its stability essential for our economic well-being and quality of life.

Recommendation:

As they continue to develop documents to inform the public about the project, the committee recommends that the EarthScope proponents forcefully communicate the role of EarthScope as an important source of the earth science information required by society for natural hazard mitigation, resource utilization, land-use planning and environmental protection.

APPROPRIATE PARTNERSHIPS

Observation:

Understanding the dynamics of plate movements and plate boundaries requires knowledge about motions offshore, because although the continental crust extends far beyond the present shoreline, the EarthScope installations do not extend into the marine realm. Extension of the seismic array beyond the terrestrial portion of North America will rely on deployment of arrays of ocean bottom seismometers (OBS). Similarly, extension of the PBO facility offshore will rely on data from oceanic GPS-acoustic and strainmeter instruments. A complementary program, NEPTUNE, plans to make a range of measurements offshore from the Pacific Northwest, based on OBS, GPS-acoustic, and strainmeter deployments. In addition, other members of the ocean science community are planning to deploy OBS instruments at a range of locations off the coasts of North America.

Recommendation:

The committee recommends that the EarthScope Working Group actively pursue coordination between the EarthScope and ocean geoscience programs, including NEPTUNE, to ensure that the establishment of EarthScope facilities and the deployment of GPS-acoustic, strainmeter, and OBS arrays supported by the marine geological and geophysical community are complementary.

Observation:

Several large scientific programs are currently in the process of planning extensive educational and outreach efforts. An example of particular scientific significance to EarthScope is the proposed NEPTUNE program that will instrument the Juan de Fuca Plate off the coast of Washington and Oregon.

Recommendation:

The committee recommends that EarthScope establish liaisons and communications with other appropriate programs to build on existing progress in the development of major geoscience educational and outreach efforts.

Observation:

Just as the crust underlying the United States extends beyond the modern shoreline, many geological features extend across the political borders of the United States into Canada and Mexico. The EarthScope Working Group has categorized the EarthScope initiative as seeking to "…dramatically advance our physical understanding of the North American continent by exploring its three-dimensional structure…[1]" and has indicated that it will seek to collaborate with colleagues in Canada and Mexico to integrate data produced by programs in these countries with EarthScope data from the United States. The committee considers that international collaborative programs of this type will significantly enhance the value of the information amassed by research in the United States.

Recommendation:

The committee endorses the intent of the EarthScope proponents to seek collaboration with colleagues in Canada and Mexico to extend the understanding of crustal and lithosphere dynamics beyond the political borders of the United States. The committee believes that EarthScope will provide a powerful stimulus for joint international scientific programs, in the same way as the transects compiled during the Decade of North American Geology (DNAG) and the creation of continent-wide data sets for potential fields (e.g., gravity and aeromagnetics) stimulated past collaborations.

[1] EarthScope Working Group, 2001, EarthScope—A New View into Earth; draft EarthScope Project Plan.

SUMMARY

The committee concludes that the plan for the integrated EarthScope facilities is sound. The plan reflects the input of a broad cross-section of the geophysical community and mature consideration and planning over a decade. The project is very well conceived. The committee is confident that through broad involvement of the appropriate earth science community, the detailed science plans and strategies for the use of the facilities will be similarly well conceived and articulated. The potential scientific benefits of the total program to the earth sciences are of immense importance; the potential benefits to society of "applied science" stemming from the program are equally outstanding. EarthScope represents a truly visionary program for the earth sciences. The committee enthusiastically endorses the total program and all of its components.

Appendixes

Appendix A

Meeting Participants and Presentations

COMMITTEE MEMBERS

George M.Hornberger, *Chair,* University of Virginia, Charlottesville
Arthur R.Green, Exxon Exploration Company, Houston, Texas
Susan E.Humphris, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
James A.Jackson, Cambridge University, United Kingdom
Eldridge M.Moores, University of California, Davis
Barry E.Parsons, University of Oxford, United Kingdom
Robin P.Riddihough, Natural Resources Canada, Ottawa, Ontario
Karl K.Turekian, Yale University, New Haven, Connecticut

PRESENTERS AND PARTICIPANTS

Rick Carlson, Carnegie Institution of Washington, D.C.
Adam Dziewonski, Harvard University, Cambridge, Massachusetts
Bill Ellsworth, U.S. Geological Survey, Menlo Park, California
John Filson, U.S. Geological Survey, Reston, Virginia
Michael Hamburger, Indiana University, Bloomington
Phillip Harman, Lewis-Burke Associates, Washington, D.C.
Tom Henyey, University of Southern California, Los Angeles
Stephen Hickman, U.S. Geological Survey, Menlo Park, California
Leonard Johnson, National Science Foundation, Washington, D.C.
John LaBrecque, NASA, Washington, D.C.
Margaret Leinen, National Science Foundation, Washington, D.C.
Anne Meltzer, Lehigh University, Bethlehem, Pennsylvania
J.Bernard Minster, University of California, San Diego
Paul Segall, Stanford University, California
Paul Silver, Carnegie Institution of Washington, D.C.
David Simpson, IRIS Consortium, Washington, D.C.
Wayne Thatcher, U.S. Geological Survey, Menlo Park, California
Greg van der Vink, IRIS Consortium, Washington, D.C.

Terry Wallace, University of Arizona, Tucson
Jim Whitcomb, National Science Foundation, Washington, D.C.
Herman Zimmerman, National Science Foundation, Washington, D.C.
Mark Zoback, Stanford University, California

NATIONAL RESEARCH COUNCIL STAFF

Anthony R.de Souza, *Staff Director*
David A.Feary, *Study Director*
Shannon L.Ruddy, *Project Assistant*

PRESENTATION TITLES AND PRESENTERS

Overview—Introduction
Herman Zimmerman
National Science Foundation
Overall EarthScope Science Integration—active tectonics/earthquake hazards
Tom Henyey
USC (SCEC Director)
Overall EarthScope Science Integration—structure and evolution of the continent
Rick Carlson
Carnegie Institution of Washington
Plate Boundary Observatory Presentation
Paul Silver
Carnegie Institution of Washington (PBO-WG Chair)
InSAR Presentation
Bernard Minster
UCSD-Scripps
Contribution of EarthScope to USGS mission and activities (incl. ANSS)
John Filson
USGS, Reston
USArray Presentation
Anne Meltzer, Adam Dziewonski
Lehigh University (USArray-WG Chair), Harvard University

SAFOD Presentation
Mark Zoback, Stephen Hickman, Bill Ellsworth
Stanford University, USGS, Menlo Park
Funding plans for EarthScope and its role within NSF-GEO
Margaret Leinen
National Science Foundation
Potential applications of InSAR/GPS to important earth science problems
Wayne Thatcher
USGS, Menlo Park
EarthScope Education and Outreach
Mike Hamburger
Indiana University
EarthScope IT and Facilities management
David Simpson
IRIS Consortium
NASA perspective—InSAR planning
John LaBrecque
NASA HQ
Closing Comments
Herman Zimmerman, Jim Whitcomb
National Science Foundation

Appendix B

Committee Biographies

George M.Hornberger, NAE, is Ernest H.Ern Professor of Environmental Sciences at the University of Virginia, where he has taught since 1970. He has also been a visiting scholar at the Australian National University, Lancaster University, Stanford University, the United States Geological Survey (USGS), and the University of Colorado. His research is aimed at understanding how hydrological processes affect the transport of dissolved and suspended constituents through catchments and aquifers. Dr. Hornberger is a fellow of the American Geophysical Union (AGU), a member of the Geological Society of America, and has served on numerous NRC boards and committees including chair of the Commission on Geosciences, Environment, and Resources. Dr. Hornberger won the Robert E.Horton Award (Hydrology Section) from the AGU in 1993. In 1995, he received the John Wesley Powell Award from the USGS, and was elected to membership in the National Academy of Engineering in 1996. In 1999, the AGU presented the Excellence in Geophysical Education Award to him. Dr. Hornberger received his B.S. and M.S. degrees from Drexel University in 1965 and 1967, respectively. In 1970, he received a Ph.D. in hydrology from Stanford University.

Arthur R.Green is Chief Scientist for ExxonMobil Exploration Company. His research focuses on the evolution of the Arctic and its hydrocarbon potential, integrated basin analysis methods, and regional tectonic analysis. He has served on several NRC committees, most recently including: the Committee to Review the USGS Coastal and Marine Geology Program, the Committee on Arctic Solid-Earth Geosciences, the Advisory Committee to the U.S. Geological Survey, and the U.S. Geodynamics Committee.

Susan E.Humphris is a Senior Scientist in the Department of Geology and Geophysics and Director of the Earth-Ocean Exploration Institute at Woods Hole Oceanographic Institution. Her research interests include the volcanic and tectonic controls on the distribution and characteristics of hydrothermal activity at mid-ocean ridges, and the geochemistry of rock-water interactions, and the role of the associated hydrothermal fluxes in global geochemical mass balances. She is a member of the American Geophysical Union, and recently served on the NRC Committee to Review the USGS Coastal and Marine Geology Program.

James A.Jackson is a Reader in the Department of Earth Sciences, University of Cambridge. His research interests include active continental deformation on all scales, from individual faults to orogenic belts, in particular: (1) the relation between presently active deformation and the geological development and structural history of older orogenic belts, (2) the detailed relations between seismic faulting at depth and active geomorphology at the surface, and (3) descriptions and models of large scale continental kinematics and dynamics. He has received various awards and scholarships including the Bigsby Medal in 1997 from the Geological Society of London, and has more than 95 publications in refereed international journals. Dr. Jackson received a B.A. in Geology from Cambridge in 1976, and an M.A. and Ph.D. also from Cambridge in 1980.

Eldridge M.Moores is Professor of Geology at the University of California, Davis, and author of several major books on geology. He holds a B.S. from the California Institute of Technology (1959) and a Ph.D. from Princeton University (1963). His research focuses on tectonics and structural geology of mountain belts from Greece to the Sierra Nevada. Dr. Moores was President of the Geological Society of America in 1996. His other honors include the 1988 Geological Society of America Distinguished Service Award, the 1994 Geological Association of Canada Medal, and an honorary D. Sc. in 1997 from the College of Wooster.

Barry E.Parsons is Reader in Geodesy, Department of Earth Sciences, University of Oxford. He has been involved in research on mantle and crustal dynamics for more than 25 years. For the past 15 years, his work has involved geophysical applications of geodetic techniques: the construction of high-resolution marine gravity fields from satellite altimetry and ship gravity and their application in studying ocean-floor tectonics; the measurement and interpretation of crustal deformation using GPS and SAR interferometry; and the construction of high-resolution digital elevation models and geomorphological applications in studying active faulting. He has substantial experience in the planning, observation, and analysis of regional GPS surveys. Dr. Parsons received a B.A. in natural sciences from Cambridge in 1969 and a Ph.D. from Cambridge in 1973.

Robin P.Riddihough is an *emeritus* scientist at Natural Resources Canada, in Ottawa, Ontario. He was a senior manager in the Earth Sciences Sector and Geological Survey of Canada for 15 years, including 6 years as chief scientist of the Geological Survey. His research interests include regional and marine geophysics, magnetic and gravity surveys, plate tectonics and kinematics. He received a B.S. in geology from Kings College London in 1959, a DIC in applied geophysics and M.S. in geophysics from Imperial College, London in 1960 and 1961, and a Ph.D in geophysics from the University of London in 1967.

Karl K.Turekian, NAS, is Silliman Professor of Geology and Geophysics at Yale University, and Director of the Yale Institute for Biospheric Studies and the Director of the Center for the Study of Global Change. He received his undergraduate education in chemistry at Wheaton College (Illinois) and his Ph.D in geochemistry from Columbia University. His research areas include marine geochemistry, atmospheric geochemistry of cosmogenic, radon daughter and man-made radionuclides, surficial and groundwater geochemistry of radionuclides, planetary degassing, geochronology based on uranium decay chain and radiocarbon of the Pleistocene, osmium isotope geochemistry, and climate change.

NRC STAFF

David A.Feary is a Senior Program Officer with the NRC's Board on Earth Sciences and Resources, responsible for managing the earth science activities of the Board. He received B.Sc and M.Sc. (Hons) degrees from the University of Auckland and his Ph.D from the Australian National University. His research activities have focused on the geological and geophysical evolution of continental margins, using high resolution seismic reflection data and Ocean Drilling Program coring to understand the factors controlling carbonate deposition and reef development within different climatic regimes.

Appendix C

Acronyms

ANSS	Advanced National Seismic System
ASAR	Advanced Synthetic Aperture Radar
DNAG	Decade of North American Geology
DOE	United States Department of Energy
EAR	NSF Division of Earth Sciences
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
GPS	Global Positioning System
InSAR	Interferometric Synthetic Aperture Radar
IRIS	Incorporated Research Institutions in Seismology
JPL	Jet Propulsion Laboratory
MRE	Major Research Equipment
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NSF	National Science Foundation
NRC	National Research Council
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PBO	Plate Boundary Observatory
OBS	Ocean Bottom Seismometer
SAR	Synthetic Aperture Radar
SCEC	Southern California Earthquake Center
USGS	U.S. Geological Survey