earthscope

A NEW VIEW
INTO EARTH

PROJECT
PLAN

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Project Summary

Earth is a dynamic planet. Motions of the fluid core produce the dynamo that gives rise to the magnetic field. Convection in the mantle drives plate motions, resulting in the relentless cycle that creates oceans, builds mountains, shapes landforms, and concentrates the world's energy and mineral resources. While these motions are gradual and usually go unnoticed, at times the outer layers of the crust shift rapidly, with catastrophic impact on Earth's surface and the fragile web of human infrastructure and lives. In the United States, vivid examples include the 1980 eruption of Mount St. Helens and the 1994 Northridge earthquake in California. The plate-tectonic forces responsible for devastating earthquakes and volcanic eruptions in the western U.S. and Alaska operate throughout the entire North American continent. They are tied to large earthquakes that struck the New Madrid seismic zone in central U.S., and Charleston, South Carolina in the 19th century. No region of our continent is exempt from the influence of these great forces.

While earthquakes and volcanic eruptions annually cause billions of dollars in damage and tragic loss of life, they also reveal the inner workings of our planet. If we can understand the geologic processes that control these phenomena, we can reduce risks to life and property and, perhaps, one day predict them.

EarthScope is a new Earth science initiative that will dramatically advance our physical understanding of the North American continent by exploring its three-dimensional structure, and changes in that structure, through time. By integrating scientific information derived from geology, seismology, geodesy, and remote sensing, EarthScope will yield a comprehensive, time-dependent picture of the continent beyond that which any single discipline can achieve. Cutting-edge land- and space-based technologies will make it possible for the first time to resolve Earth structure and measure deformation in real-time at continental scales. These measurements will permit us to relate processes in Earth's interior to their surface expressions, including faults and volcanoes.

> Recent California [and Washington] earthquakes have demonstrated that cities and towns in tectonically active areas are built on complex systems of faults with hundreds of potential "moving parts," some of which do not even breach the surface, and any one of which might suddenly shift.
>
> Active Tectonics and Society: A Plan for Integrative Science, 1993

EarthScope includes new observational technologies in seismology, geodesy, and remote sensing, that will be linked through high-speed, high-performance computing and telecommunications networks. The new facilities build on existing strengths in these fields, as well a strong tradition of excellence in field observations and laboratory research in the broader Earth sciences. Combined with funding for integrated Earth science research and education, EarthScope provides a unique framework for basic and applied geological research across the United States and its neighboring countries. EarthScope will make new and fundamental contributions, permitting us to address the following key questions:

- What are the underlying geologic processes that build mountains, deform continents, ignite volcanic eruptions, generate earthquakes, and ultimately tear continents apart?
- How do continents interact with the whole Earth system?
- How are features at Earth's surface related to structures and deformational processes in Earth's deep interior?
- How does the long-term process of stress accumulation in Earth result in the greatly accelerated catastrophic failure associated with earthquakes and volcanic eruptions?
- What are the architecture and physical state of the lithosphere, and how do they relate to deformation?
- What are the spatial and temporal scales of deformation across the continent?
- How are earthquakes, volcanoes, and mountain building related to preexisting geologic structures and patterns of ongoing deformation?
- How can the spatial and temporal patterns of deformation, together with knowledge of their associated structures, be used to predict the behaviors of seismic, volcanic, and other geodynamic phenomena?

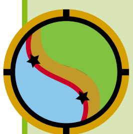
EarthScope will provide the scientific community with opportunities to engage in integrated studies of entire geosystems. The program's continent-wide scope opens the door to major advances in our understanding of continental dynamics, while at the same time allowing scientists to select natural laboratories across the country to optimize the study of particular systems. For example, exploring a continental arc system—from subducting slab through magmatic plumbing to surface volcanism—is best done in portions of Alaska and the Pacific Northwest, while natural laboratories in the central and eastern U.S. afford some of the best opportunities for examining relationships between intraplate stress and earthquake occurrence.

EarthScope resources will be accessible to the entire scientific and educational communities. Data acquired from the new observational facilities will be telemetered in near real-time to central processing facilities and made freely and openly available to the research community, government agencies, educators, and the public and private sectors. End users also will have online access to software that will aid in data integration, manipulation, and visualization. An Earth science information system of this type will build on the nation's increasing capabilities in the development and use of information technology. EarthScope will provide mechanisms to unite North American Earth scientists with diverse tools and perspectives in a decade or more of interdisciplinary studies of the continent. In doing so, EarthScope will expand the culture of shared and coordinated resources and research in Earth sciences. At the same time, it will encourage the interpretation of the results of basic research to support a society increasingly dependent on Earth resources and one susceptible to geologic hazards.

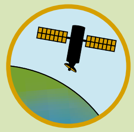
EarthScope provides an excellent opportunity to improve science literacy in the U.S. through a comprehensive education and outreach program extending across the country and continuing throughout and beyond the lifetime of the program. Earth science naturally integrates fundamental concepts in math, physics, chemistry, and biology. EarthScope will capitalize on the public's interest in earthquakes and volcanoes by demonstrating how active geologic processes shape our modern environment

EarthScope's facilities include the following four coupled components:

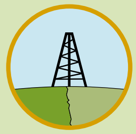
USArray (United States Seismic Array): A continental-scale, portable seismic array will map the structure of the continent and the underlying mantle at high resolution.



PBO (Plate Boundary Observatory): A fixed array of GPS receivers and strainmeters will map ongoing deformation of the western half of the continent, from Baja California to the Bering Sea, with a resolution of one millimeter or better over regional baselines.



InSAR (Interferometric Synthetic Aperture Radar): A remote-sensing technique will provide spatially continuous strain measurements over wide geographic areas with decimeter to centimeter resolution.



SAFOD (San Andreas Fault Observatory at Depth): A borehole observatory across the San Andreas fault will measure subsurface conditions that give rise to slip on faults and deformation in the crust.

and concentrate natural resources. EarthScope has the potential to make these subjects relevant on a region-by-region basis as continental-scale results emerge, including both overarching and regional scientific issues as well as links between science and society. At the advanced level, EarthScope affords graduate students in the Earth sciences with an introduction to system-level integrative science and information technology. Through unrestricted access to real-time data and integrated scientific information, EarthScope has the potential to impact Earth science education in new ways.

An EarthScope Coordinating Committee, composed of representatives from the EarthScope facilities and Earth science community at large, will provide coordination among the component facilities, foster science integration, education, and outreach, establish and oversee data policies, coordinate annual reporting and funding requests, and provide advice to the funding agencies as requested. Implementation, operation, and maintenance of EarthScope facilities will be carried out by organizations that demonstrate the highest level of expertise through a competitive process. Each successful organization will be expected to have outstanding management and technical staffs, a solid mechanism to incorporate input from the user community, and a demonstrated commitment to operating community facilities.

EarthScope is being developed jointly by the scientific community and the National Science Foundation in partnership with other science and mission-oriented agencies including the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA).

A New View Into Earth

The Deformation of a Continent

Geological processes create the rich fabric of our continent's landscape, from the ancient, eroded Appalachian Mountains to the youthful volcanoes of the Cascades and the shattered crust of the San Andreas fault system. The development of plate tectonic theory during the last half century provided a framework for explaining, to first order, the structure of continents, the origin of mountain belts, and the distribution of earthquakes and volcanoes. Despite the elegance and utility of this paradigm, important questions concerning the deep Earth processes that deform continents remain unanswered. For example, while we know that continental crust grows progressively outward, we know little about the driving mechanism of plate tectonics, how surface features relate to structural, compositional, and thermal differences in Earth's interior, or how plate tectonic stresses are transferred to individual faults. Although we have made major progress over the past decade in understanding how faults rupture and what ground motions earthquakes generate, our understanding of what controls earthquake size, why great earthquakes occasionally strike plate interiors, and when and where the next major events are likely to occur remains remarkably incomplete. Moreover, the rules that govern plate motion do not apply, in simple fashion, to broad plate boundary zones such as western North America from the Rocky Mountains to the Pacific Ocean, where strain is distributed and inhomogeneous.

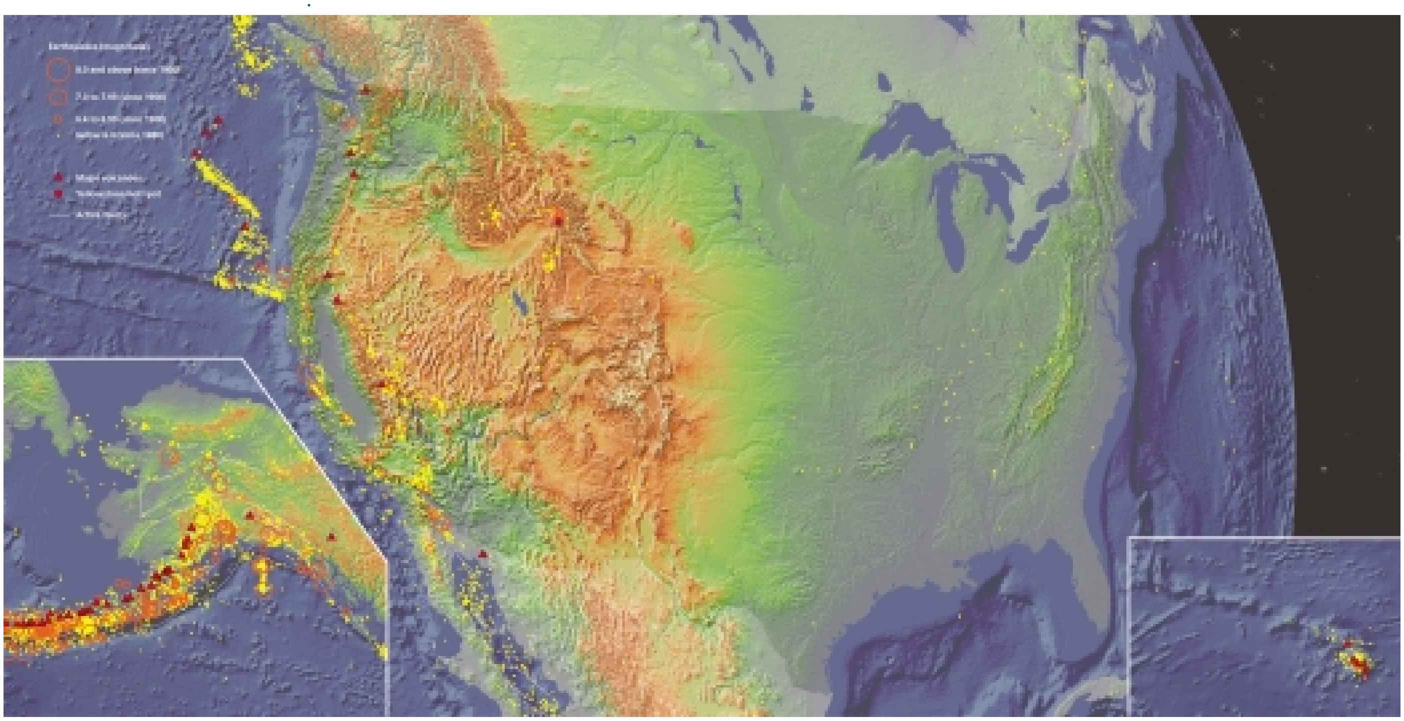


Figure 1. The face of North America reflects the variety of geological forces that have sculpted the continent. EarthScope will create a linked infrastructure for a continental-scale observatory of remote-sensing geophysical instruments to probe deep beneath the surface. These instruments will illuminate the underlying structure of the continent, permitting a better understanding of the processes that continue to build and change the North American landscape.

A variety of continental tectonic processes, including deformation that leads to earthquakes, volcanic eruptions, mountain building, and sedimentary basins, have been observed and described for centuries, but plate-tectonic theory finally provided a context for all these events. Early plate-tectonic theory was built upon a diverse set of global observations from which plate motions could be inferred—rather than from direct measurements of oceanic and continental crustal displacements.

Within the last decade, however, limitations to directly measuring crustal motion, at all time scales, have been removed. Techniques for sensing crustal movements now have sufficient sensitivity to instantaneously measure continental deformation. Interconnected telemetered seismometer networks now allow real-time detection and analysis of rapid (seconds to minutes) movements associated with earthquakes. GPS geodesy, borehole strain, and satellite radar interferometry can precisely measure longer duration (hours to years) movements that redistribute stresses along plate boundaries and within plates. Finally, dramatic improvements in geochronology allow fine resolution within the thousand- to billion-year time scales involved in earthquake and volcanic eruptive cycles, mountain building, and continental evolution.

EarthScope offers an opportunity to measure plate motion as it happens—on a human time scale and continental spatial scale—permitting us to decipher the cause and effect of movements. Instruments capable of probing the crust in three dimensions and measuring its movements will be placed throughout the actively deforming western U.S. and slower moving eastern U.S. EarthScope will be able to track Earth's response to tectonic events and assist in finding answers to questions such as: Does volcanism and seafloor spreading in the Gulf of California set up the stresses that cause earthquakes in southern California years or decades later? Can an earthquake in the Mojave desert trigger volcanic eruptions in the Pacific Northwest? Are fault locations controlled by events that occurred millions or even billions of years ago during assembly of continental fragments? Is earthquake activity in the "stable" mid-continental region near New Madrid, Missouri related to the same forces that tried to split North America in half a billion years ago? All of these possibilities have been suggested by detective work involving the assembly of diverse clues extracted from individual, often unrelated, studies. Measuring crustal motions and how those motions are communicated across plates at the scale of North America will allow scientists to examine Earth at spatial and temporal scales commensurate with geologic processes. EarthScope may reveal whether slow stress waves from one event can propagate across the continent to load other tectonic systems, or whether secondary events are dynamically triggered and isolated to areas characterized by "soft spots" in the crust resulting from ancient geologic history.

Figure 2. Rig used to drill the 3.0-km-deep Long Valley Exploratory well near the town of Mammoth Lakes, California. A rig like this would be used to drill the SAFOD hole.

Seismic Hazard Analysis

The Intersection of Plate Tectonics and Society

Seismic hazard analysis is one, especially relevant example of interdisciplinary, integrative science that will benefit from the EarthScope initiative. It requires collaboration of scientists from a variety of Earth science subdisciplines and integration of data from all four EarthScope components, coupled with a sound understanding of regional geology. Coordinated planning, open data distribution, and a focus on a common problem are its hallmarks, as well as the foundation on which EarthScope has been conceived. Moreover, hazard models are becoming the products of natural laboratories such as the San Andreas fault system, New Madrid Seismic Zone, and Cascadia, for which EarthScope is particularly well suited with it emphasis on high-resolution, uniform, synoptic coverage of both crustal structure and rates of deformation.

As illustrated by the model ingredients, moveable seismic arrays (USArray) provide the subsurface structural representation (fault locations, fault geometries, and seismic velocities) while geodesy (PBO and InSAR), coupled with geochronology and paleoseismology, provide regional deformation patterns and fault slip rates. Fault rupture scenarios, needed for ground-motion simulations, are the products of fault-zone physics (SAFOD) and inversions of wave-fields from past earthquakes (USArray and regional seismic networks such as the Advanced National Seismic System, or ANSS). Not shown, but equally important, is the next level of integration involving the conjunction of ground motion intensity measures with performance-based earthquake engineering design.

Seismic Hazard Model Ingredients

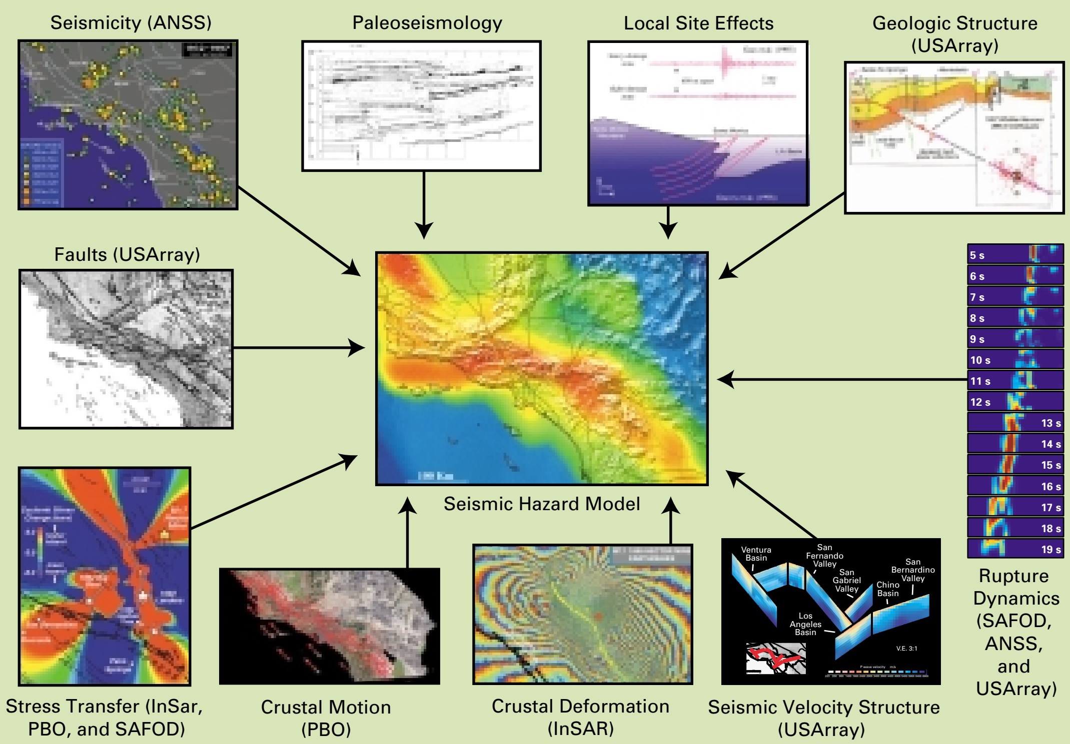


Figure acknowledgments clockwise from top left. Seismicity: Marquis, J., http://www.scecdc.scec.org/histanim.html. **Paleoseismology:** Sieh, K. E., *Jour. Geophys. Res.,* 83, B8, 3907-3939, 1978. **Local Site Effects:** Figure assembled by E.H. Field from the work of Gao, S., H. Liu, P. M. Davis and L. Knopoff, *Bull. Seis. Soc. Amer.,* 86, 1B, S209-S230, 1996 and from Graves, R. W.; A. Pitarka, P.G. Somerville, *Bull. Seis. Soc. Amer.*, 88, 1224 – 1242, 1998. **Geologic Structure:** Shaw, J. H. and P.M. Shearer, *Science*, 283, 5407, 1516-1518, 1999. **Rupture Dynamics:** Wald, D. J. and T. H. Heaton, *Bull. Seis. Soc. Amer.*, 84, 3, 668-691, 1994. **Seismic Velocity Structure:** Magistrale, H., S. Day, R. Clayton and R.W. Graves, *Bull. Seis. Soc. Amer*, 90, 6B, S65-S762000. **Crustal Deformation:** Sandwell, D. T., L. Sichoix, D. Agnew, Y. Bock, J. Minster, *Geophys. Res. Lett.*, 27, 19, 3101-3104, 2000. **Crustal Motion:** Background Image: Robert Crippen (Jet Propulsion Laboratory); SCIGN map: Crustal Deformation Working Group, Southern California Earthquake Center (Ken Hudnut, Chair). **Stress Transfer:** Image created by Ross Stein, USGS. **Faults:** Image created by Robert Crippen (Jet Propulsion Laboratory), modified by Mark Benthien, SCEC. **Seismic Hazard Model:** Image created by Ken Hudnut, USGS, based on data from D. D. Jackson et al., *Bull. Seis. Soc. Amer.,* 85, 379-439, 1995.

The opportunity to observe and measure Earth structure and deformation in unprecedented scale and detail arises now as the result of a number of critical factors:

- Development of high-precision instruments capable of being placed in remote locations for extended periods of time;
- Availability of radio and satellite telemetry that allows remote instruments to communicate directly and constantly with operational support bases;
- An expanded capability for deep drilling into active fault zones and the ability to instrument these holes to extract key information on the physical conditions within earthquake nucleation zones;
- Widespread computer networks that bring real-time data to the desktop and are capable of connecting scientists and educators across the country into a united research and educational enterprise;
- Analytical improvements in geochronology that provide both higher precision and application to a wider age range of events;
- Expanding data archival systems capable of storing and manipulating huge data streams arriving from large instrument arrays;
- A mature national infrastructure of Earth science organizations and consortia that have developed considerable experience in managing facilities similar to those in EarthScope.

EarthScope has its roots in the concept of dynamic geosystems, such as fault systems, magmatic systems, orogenic systems, and convective systems. It is no longer sufficient to simply observe these systems and their consequences; rather we must understand the underlying processes in order to predict their behaviors. To understand solid Earth geosystems, we must assimilate and integrate observations from a variety of disciplines in both ancient and modern geologic environments, and we must make detailed studies of Earth's surface as well as the regions below. This is particularly challenging because Earth's interior is inaccessible and characterized by extreme conditions. Although laborious and expensive, drilling is still the best method for direct sampling of materials in the outer few kilometers of Earth's crust. To probe deeper, we must rely on remote sensing methods including seismic, gravity, and electromagnetic techniques. For example, earthquakes and controlled (artificial) seismic sources generate elastic waves that encode an immense amount of information about the earth through which they propagate. This illumination can be captured on arrays of sensors and digitally processed into three-dimensional images of Earth's internal structure and time-lapse pictures of active tectonic processes. The more expansive the arrays, the greater the resolution and the deeper we can look.

Integrating geology, geochronology, and geophysics within EarthScope will provide us with an approach to investigate the structure of the North American continent in four dimensions. Understanding a particular geodynamic process and predicting its behavior requires knowledge of Earth materials, rates and magnitudes of motion, and the structures on which the motion is taking place. Satellite-based interferometric synthetic aperture radar can map decimeter- to centimeter-level deformation due to strain buildup and release along faults, magma inflation of volcanoes, and ground subsidence over areas tens to hundreds of kilometers wide. Moreover, these images of the strain field complement even more precise ground-based arrays of continuously operating GPS receivers with millimeter precision over baselines of thousands of kilometers. For example, GPS

> EarthScope will contribute substantially to understanding the structure, evolution, and active deformation of the continents and the attendant earthquake and volcanic hazards.
>
> Basic Research Opportunities in Earth Science, NRC, 2001

arrays can be used to map long-term strain rates across plate boundaries, such as in western U.S., and short-term deformations associated with earthquakes and volcanoes. Strainmeters, the most sensitive of the geodetic techniques, can be used to detect any pre-event transients associated with these potentially catastrophic phenomena. Finally, geologic and paleoseismic investigations extend the time dependence of dynamic geosystems back in time, providing a baseline with which to compare modern kinematic data.

Much of what has been learned about Earth over the past half century has come from either mid-1900s technology or more recent technologies implemented only in specific regions, resulting in subcritical observations. EarthScope will provide a quantum leap in our observational capabilities. Newly available technologies range from space-based platforms and global networks of surface observatories to extremely sensitive instruments that can measure Earth materials and processes in both the laboratory and the field. Furthermore, the digital revolution has significantly improved Earth science observations through the development of many new remote-sensing and direct-sampling technologies. Data-gathering efforts have been greatly facilitated by communication systems that can transmit high-resolution data with many variables from remote locations to advanced data centers and scientists' desk tops in real or near-real time.

The next major advances in our understanding of how the dynamic Earth works, and how humankind can best deal with both the beneficial resources and the dramatic hazards Earth provides, must come by expansion of our observational network to the scale of plate-tectonics. EarthScope will provide this step for the continental United States. A national program on the scale of EarthScope, integrating geologic, geodetic, seismological, and remote-sensing data from continent-wide observation systems, will catalyze solid Earth science research in the United States and provide a new view of the North American continent and its active tectonic environment. Moreover, the scientific and organizational structure underlying this interdisciplinary effort can serve as a national model for Earth science studies in continental dynamics. Perhaps the most exciting aspect of the EarthScope initiative is the prospect of unanticipated discovery and unveiling of results and insights that we cannot yet imagine.

Scientific Themes and Motivation

North America's landforms are the result of hundreds of millions of years of active surface and deep-Earth processes. Many of these landforms reflect tectonic motion that is building and deforming the continent today. Some are subtle, such as those associated with the mid-continent rift and New Madrid seismic zone. Others, such as the Cascade stratovolcanoes and San Andreas fault system, stand out in stark contrast to their surroundings. There is a need to understand the wide range of deformational processes that result in these landforms, many of which represent threats to life and property.

Although we have developed a relatively detailed understanding of the continent's tectonic framework through high-resolution topographic and geological mapping, our knowledge of the underlying structures and processes that control the location, behavior and evolution of fault and magmatic systems, mountain belts, and crustal rifting is sparse and incomplete. We lack a comprehensive understanding of how a continent interacts with the underlying mantle, how inherited structures and compositional variations in the continental lithosphere modulate modern tectonic processes, how plate margins develop and deform, how plate tectonic motions are transferred into sudden slip on individual faults, and how near-surface magmatism couples to tectonics below. Moreover, we have only sparse data on actual deformation rates across the United States, including those rates leading up to and following major earthquakes and volcanic eruptions. Active tectonics processes operate within complex systems. To address any given part of a system, we must understand the system as a whole and the processes that span a broad range of spatial and temporal scales.

EarthScope will apply new technologies, including high-resolution sensors for seismology and geodesy, satellite imaging systems, electronic miniaturization, wide-band and high-speed communications, high-performance computers, networking, and data handling to: (1) produce the first high-resolution synoptic views of the continental lithosphere and mantle beneath North America, (2) generate the first comprehensive maps of crustal deformation across the continent, and (3) provide the first look at the inner workings of a portion deep within an active geosystem—the San Andreas fault. And most importantly, EarthScope will integrate measurements contributed by a diverse set of Earth Science disciplines and observational tools, providing a framework for broad studies across the Earth sciences. This framework will produce the next major advances in our field. The time is right, and the scientific motivation there, for an initiative of this magnitude.

The following five sections highlight the key scientific themes and important questions to be addressed by the EarthScope initiative.

Continental Structure and Evolution

Earth is unique among the terrestrial planets in having compositionally distinct continental and oceanic crust. While plate tectonics provides a cogent explanation for origin of the oceanic crust, the mechanisms that form continents remain elusive. Models for continent formation include plate-tectonic mechanisms, such as collision of island arcs, and non-plate-tectonic mechanisms such large-volume magmatism associated with mantle-plume eruption. The formation of continents, the mechanical response of continents to the forces of mantle convection and plate tectonics, and possibly the long-term survival of continents at Earth's surface are intimately linked to crustal properties, and to the combination of crust and its melt-depleted mantle root.

North America has a rich plate tectonic and geodynamic history spanning more than three billion years. The central stable craton of North America records the existence of Precambrian orogenic belts, worn down to their roots by erosion over the millennia, which can be interpreted in terms of plate rifting and convergence. In contrast, along North America's western margin, continental evolution driven by plate interactions is occurring through similar, but currently active tectonic processes. These geologic environments, and those representing the time in between, provide the targets for EarthScope's focus on the structure, deformation, and evolution of the North American continent. EarthScope will provide the first ever continuous, coherent, high-resolution images of the lithosphere at the continental scale.

Scientific Issues

- How are continents assembled?
- What is the connection between crust/mantle structure and the geographic location and character of tectonic processes and features?
- How are the various modes of continental formation and deformation reflected in the structure, composition, and physical properties of the crust and underlying mantle?
- What are the feedback loops between crustal deformation (including uplift/subsidence and erosion) and deep-seated geodynamic processes?
- What are the relationships between crustal provinces and intraplate stresses?
- How can knowledge gained from ancient orogenic systems be used to understand the behavior of active tectonic systems?
- What are the relevant time scales for continental evolution? How do geologic and geodetic deformation rates compare?

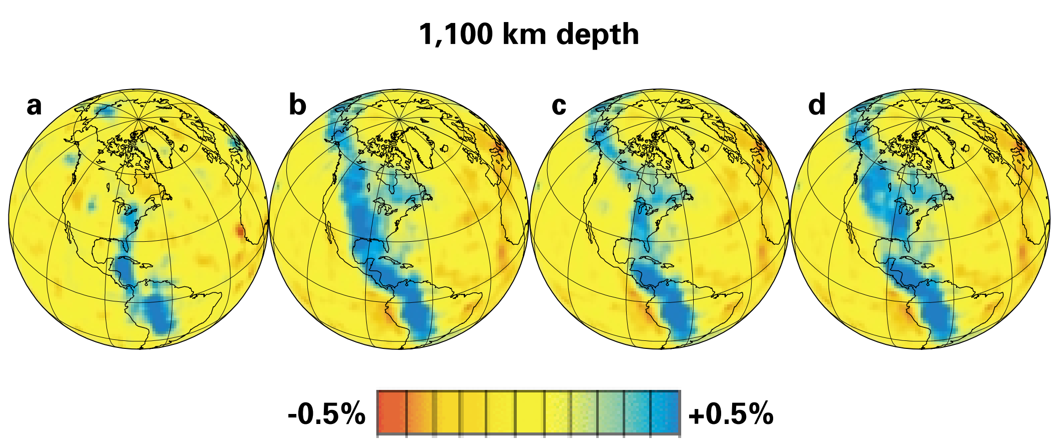


Figure 3. Seismic (a) and geodynamic (b-d) models of heterogeneity in structure at a depth of 1100 km in the mantle. The major feature beneath eastern North America is interpreted as a piece of old ocean—the Farallon plate—that was subducted to the east beneath the continent during an earlier phase of plate tectonic movements. Images derived from EarthScope data will make it possible to determine more precisely the location and composition of this structure and help constrain the geodynamic models. Modified from Bunge and Grand, 2000, *Nature*, 405, 337-340.

The Pacific/North America Plate Boundary System

We stand at a critical juncture in the evolution of the Pacific/North America plate boundary system. This zone is being transformed from an Andean-type convergent margin that has existed since the Triassic and produced the North American Cordillera with large subduction-zone earthquakes and pervasive magmatism, to the predominantly strike-slip boundary that we observe today. This unfinished transition has produced several fascinating plate-boundary structures in addition to standard subduction of the Pacific Plate beneath Alaska. These include subduction of small young remnants of the Farallon Plate beneath Cascadia and southern Mexico, extension in the Basin and Range, deformation of the western North American Cordillera, and, of course, initiation of the San Andreas fault system.

This major transform plate boundary system that began 12-14 million years ago has both grown and migrated inland, generating distributed shear across California and the Great Basin. The evolution continues to the present. Although a map of the Basin and Range suggests spatially uniform extension, geodesy reveals a recent focusing of deformation near its western and eastern edges. This, in turn, suggests dramatic differences in material properties within the crust and mantle across the Basin and Range that are probably thermally induced.

Deformation within the Pacific/North America plate boundary zone occurs over a wide range of spatial and temporal scales. On the largest scale, shortening that produced the North American Cordillera is giving way to shear and extension that is now pulling this region away from the stable continent. This provides us with an actively deforming natural laboratory that should greatly increase our understanding of plate-boundary processes. Because these processes have dominated North American geology over the last several billion years, the North American continent is an excellent place to unravel the general evolution of our continent.

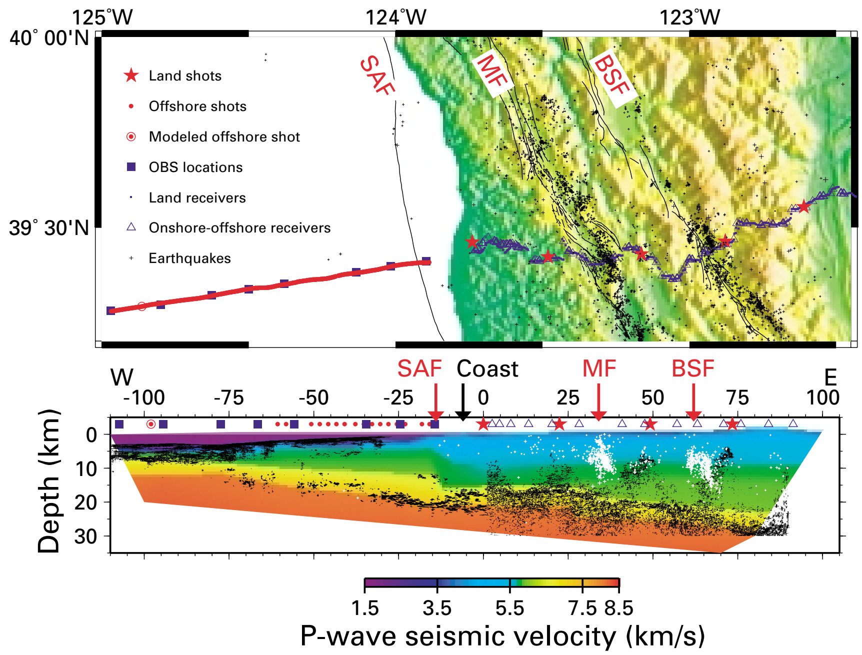
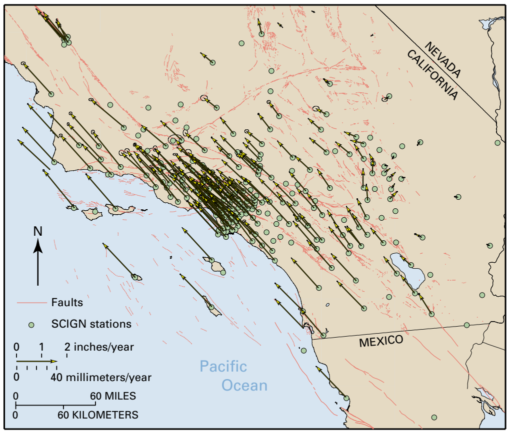


Figure 4. Seismic velocity-reflectivity cross section across the San Andreas Fault transform system in northern California. The lower crust and Moho are offset across the San Andreas and Macaama faults. At this latitude (~39.5ºN) the transform system is ~2 m.y. old. From Henstock, T.J., et al., *Science*, 278, 650-653, 1997, and Henstock T.J., and Levander, A., *Geophysical Journal International*, 140, 233-247, 2000.

Scientific Issues

- What is the distribution of crustal deformation throughout the Pacific/North America plate boundary between the Rocky Mountains and Pacific coast, and across southern Alaska?
- How does the pattern of deformation correlate with plate kinematic models, regional tectonics, and seismicity?
- How is the pattern of crustal deformation in the plate boundary zone related to the structure, composition, and physical properties of the lithosphere and mantle below?
- What is the relationship between regional seismicity and conditions/processes in the crust and upper mantle?
- Are there processes in the upper mantle

Figure 5. Crustal motion map for southern California derived from 250 permanent SCIGN stations (green dots). Stations are concentrated in the Los Angeles region because of its large seismic hazard; little was known about deformation in the region before SCIGN. Arrows show the slow movement of some stations relative to the N.A. plate. From USGS Fact Sheet D69-01, August 2001.

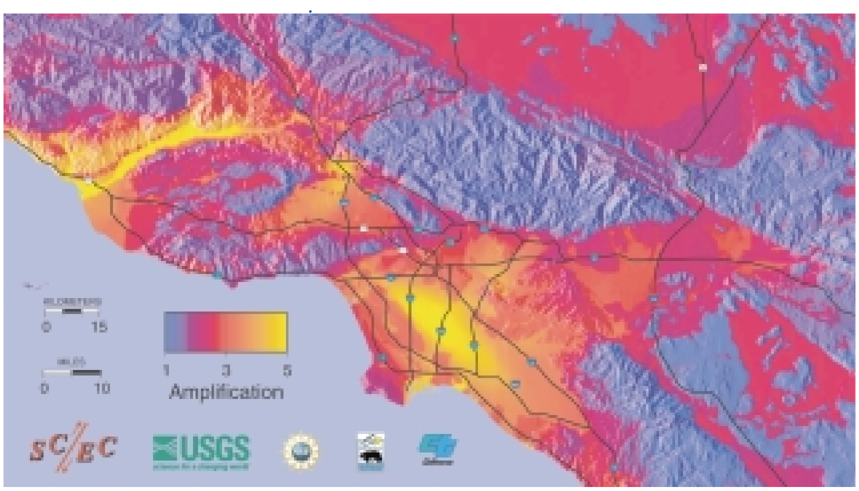


beneath the plate boundary zone that can be correlated with patterns of deformation and tectonic styles at the surface, such as Cascadia or the Basin and Range?

- What can the current crustal deformation pattern tell us about the evolution of the plate boundary?
- What is the relationship between tectonism and volcanism throughout western North America?

Fault Systems and Seismic Hazards

Figure 6. A seismic shaking amplification map for the greater Los Angeles region based on the effects of near-surface geology and depth to basement. The blue areas represent basement exposed in the surrounding mountains. Combining information about site effects with where and how often earthquakes of various magnitudes are likely to occur should provide improved assessments of seismic hazard. Image created by E. H. Field based on SCEC Phase 3 study, *Bull Seismol. Soc. Amer.*, 90, 6B, 2000.



Faults and earthquakes are common to many parts of North America, affecting tens of millions of people. Stresses that generate earthquakes exist throughout the continent, deforming Earth's outer layers most conspicuously at or along zones of crustal weakness. Because the boundaries between plates are weak links in the global plate tectonic mosaic, earthquakes and other forms of deformation occur most commonly adjacent to these zones, such as the Pacific/North America plate boundary along the western margin of North America and southern Alaska. However, zones of weakness prone to earthquakes are known to exist in others parts of the continent as well, such as along the Mississippi River in central U.S., along sections of the coastal region of southeastern U.S., and in parts of New England and the North Atlantic seaboard, and these may not be the only such zones. North America's historical record is excruciatingly short. Thus, earthquakes must be regarded as a national problem.

Although predicting the precise time, place, and magnitude of an impending earthquake must remain a long-term goal, there are important aspects of earthquakes that can be forecast, including the probable locations of future major events, and characteristics of the ground motions likely to be generated throughout the greater epicentral region. An integration of all EarthScope component facilities will be needed to quantify the kinematics and dynamics of the plate-boundary system, develop a better physics-based understanding of the behavior of faults and fault systems, and put the knowledge to practical use for hazard mitigation. Specifically, we must enhance the identification of seismogenic structures and zones of deformation that contribute to regional seismic hazard, measure their rates of deformation, explore the inner workings of an active fault including how fault rupture starts and stops, and search for evidence of strain transients or precursors that may presage potentially damaging events.

Scientific Issues

- What is the deep structure of faults and fault zones? Are faults truncated at mid-crustal detachments or do they continue through the crust and Moho?
- What material properties govern deformation in the lower crust and mantle?
- How do complex systems of faults accommodate overall plate motions, and to what extent does distributed deformation play a role within the seismogenic layer of the crust?
- What fault-zone properties govern earthquake nucleation and slip on faults?
- What factors control the space-time pattern of earthquake occurrence?
- What are the subsurface conditions and seismic wave propagation effects that control the pattern and characteristics of ground shaking during an earthquake?
- What is the relationship between the regional stress field and seismicity?
- What are the relationships among intraplate stresses, geologic structures, and regional seismicity?
- Do detectable earthquake strain precursors exist?
- How does the long-term process of stress accumulation in Earth result in the greatly accelerated catastrophic failure associated with earthquakes and volcanic eruptions? What are the physical laws governing such failures?
- To what extent are earthquakes predictable? Can the maximum magnitude on a given fault or fault system be predicted?

Magmatic Systems and Volcanic Hazards

Volcanic arcs are found above subduction zones, and represent one of the most common forms of global volcanism. Arc volcanoes are often explosive, and eruptions pose significant hazards to local populations and air traffic. Eruptions threaten over 10 million people in the Pacific Northwest and Alaska, can potentially knock jet aircraft out of the sky by choking their engines with ash, and can disrupt global commerce by suddenly blanketing key regions with thick layers of debris. In contrast to earthquakes, which commonly strike without warning, volcanoes typically show telltale signs of unrest. Nonetheless, our ability to forecast the timing, magnitude, and impact of eruptions is frustratingly imprecise.

Volcanism builds new continental crust either *in situ*, or through the development of island arcs on oceanic crust that may later be accreted onto a continent. The output of these systems offers a window into the lower crust and upper mantle, through melt chemistry and xenoliths (included fragments of lower crustal and mantle rocks). Globally, active volcanic arcs are typically found above the ~100 km depth contour of the downgoing slab. However, active volcanoes are absent from sections of some arcs, and the chemistry and productivity of volcanic systems vary tremendously from arc to arc and along any single arc. EarthScope will provide abundant geo-

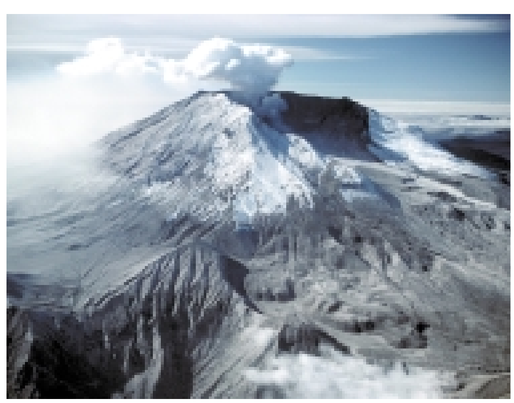


Figure 7. Mt. St. Helens after May 1980 eruption.

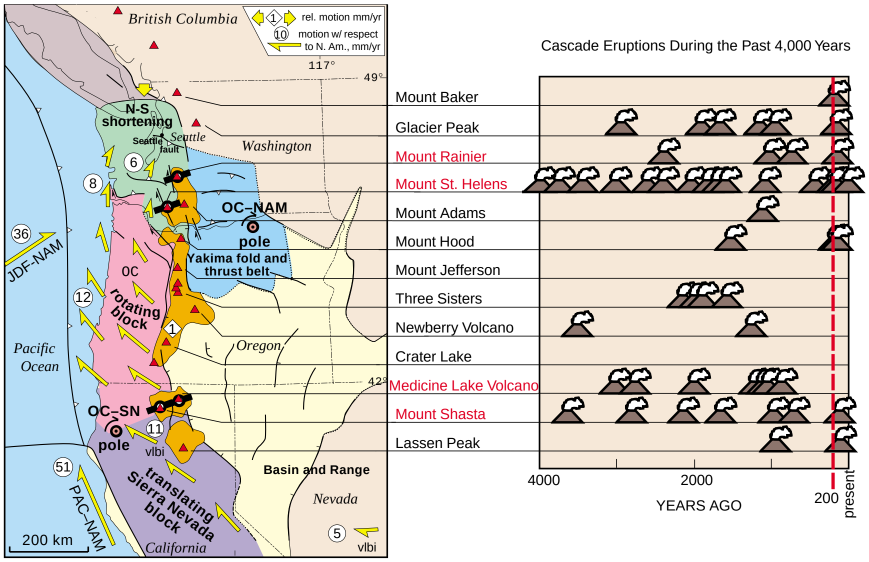


Figure 8. Cascadia tectonic setting and history of Cascade volcano eruptions. Yellow arrows show motion relative to North American Plate (NAM). Proposed target volcanoes have red names and cluster deployments are marked with black bowties. Figure from Lisowski, M., D. Dzurisin, E. Roeloeffs, Plate Boundary Observatory Workshop, October 2000.

physical data from multiple disciplines that will complement the rich data set from geochemical studies; together, these data may allow us to answer fundamental questions about magmatic systems.

EarthScope's geodetic data can be used to quantify the rate of magma accumulation in the upper crust beneath several active volcanoes in the Aleutian and Cascade arcs. Using these data we will be able to determine how rapidly magma accumulates, and whether the accumulation rate is steady (over a time scale of a few years) or episodic, representing either a continuous trickle of new magma or discrete blobs. EarthScope geodetic data may also permit detection of the rise of large magma bodies through the upper mantle and lower crust.

EarthScope's broadband seismic data can be used to construct three-dimensional tomographic images of the downgoing slab, asthenospheric wedge, and crust of the overriding plate. Changes in velocity and attenuation are sensitive indicators of temperature and the presence of melt. Broadband seismic data will also provide sensitive records of the vibrations induced by the flow of magma and the breaking of rock as magma moves through it.

Scientific Issues:

- What controls magma genesis in the asthenospheric wedge between the slab and the overriding crust? What are the time scales for magma genesis and rise from the asthenosphere to the base of the crust, and then into the upper crust, and what controls these time scales?
- Are variations in productivity controlled by variations in the rate of magma genesis, or by conditions that affect magma rise? What are the links between magma rise and eventual eruption, and how long do magmas reside in the upper crust?
- What are the dynamics of intrusion and eruption? To what extent can magma motion in the subsurface be tracked by surface deformation data? What are the size and shape of magma reservoirs and conduits, and how do they constrain the dynamics of magma flow?
- How do temporal and spatial scales of deformation vary with eruptive style and magma composition?
- Can we characterize deformation that leads to an eruption versus that which is normal "breathing," and thus predict eruptions with high confidence?
- Are there interactions between earthquakes and volcanic/magmatic behaviors, and if so, what are the controlling factors? In general, how do active tectonic and volcanic structures interact?
- What is the relationship between ongoing deformation in large calderas, such as Long Valley and Yellowstone, and structures and processes in the underlying crust and mantle?
- To what degree is the Yellowstone hot spot influencing regional tectonics and modifying the continental lithosphere, and vice versa?

Knowledge of the detailed structural, physical, and chemical properties throughout Earth's Interior—including the crust, mantle, and core—is required to understand how the solid Earth works as a globally interconnected system. Although we know that the lithosphere and mantle both play important roles in continental dynamics, their three-dimensional structure beneath continents is poorly known. EarthScope will provide the first high-resolution tomographic images of Earth's interior at the continental scale, linking geologic features on the surface to structures deep below.

To understand continental evolution, we need higher resolution information on major features such as the depth to which the roots of continental material extend beneath the craton—a continent's ancient core. Variations in the depth of global upper mantle discontinuities (near depths of 410 and 660 km) as well as the occurrence of regional discontinuities (e.g., 220 km) provide information on compositional, thermal, and chemical differences from one region to another. Knowledge of anisotropy of seismic velocities, reflecting prior strain events, can be an important tool in discerning past and present mantle flow. EarthScope will provide multidirectional source-receiver coverage so that anisotropy can be mapped beneath the continent to help unravel the link between mantle flow and lithospheric deformation.

We suspect that large-scale mantle convection is important in the development and evolution of continents and that continents, in turn, modulate convection. We

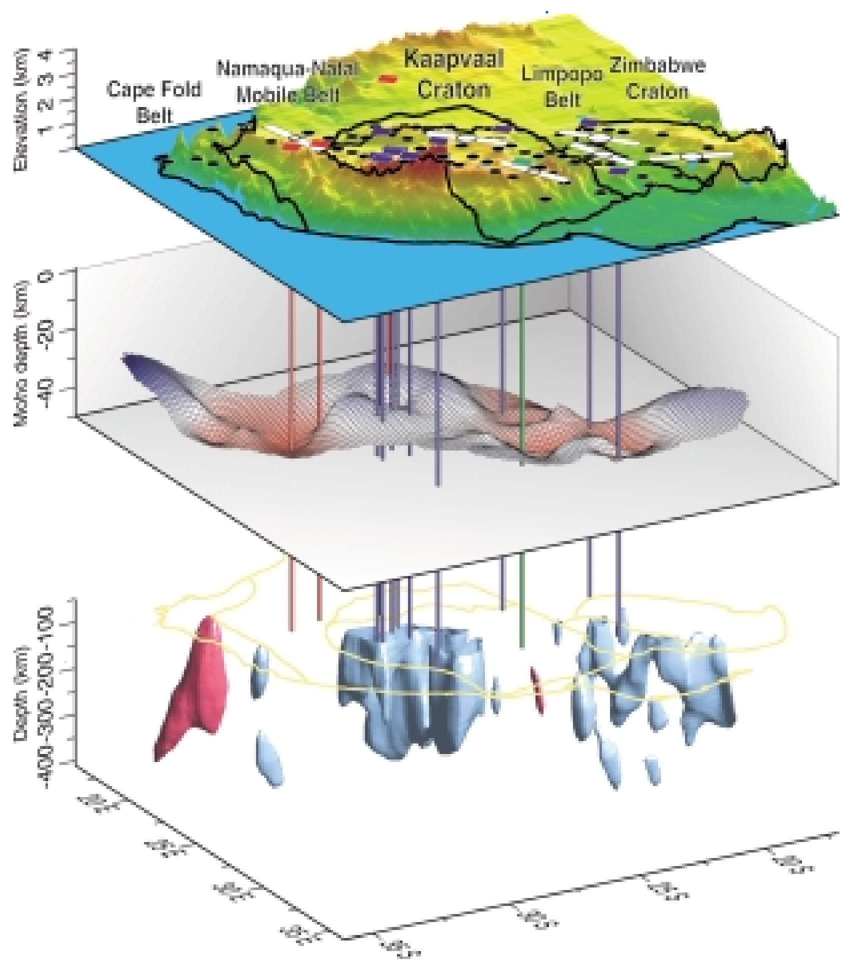


Figure 9. The Kaapvaal project in South Africa is an international program that incorporates many of the multidisciplinary geological and geophysical techniques that will characterize EarthScope investigations. This three-dimensional cross section shows a number of properties of the crust and upper mantle of southern Africa. The upper panel shows surface topography and outlines the major geologic terranes ranging from the 3+ billion-year-old Kaapvaal and Zimbabwe cratons to the 600-700 million year old Cape Fold Belt. The middle panel shows the depth to the bottom of the crust, while the lower panel shows tomographic images of high- (blue) and low- (red) velocity structures deeper in the mantle. The long vertical bars penetrating the panels show the downward extrapolation of the kimberlite pipes to their likely depths of origin. Mantle samples with ages > 2.5 Ga derive only from areas with high seismic velocity which also predominately only underlie the old crustal sections of southern Africa. Figure courtesy of M. Fouch, D. James, and R. Carlson.

know little of the properties of the mantle transition zone, including the velocity gradients at the discontinuities (which strongly depend on the mineralogical composition), lateral variations in composition and temperature, and how this region relates to large-scale mantle convection and hotspots.

A continental-scale seismic array can also be used as a downward-looking telescope to observe distant structures, not necessarily underneath North America. We do not know much about the lateral structure of the mid-mantle, partly because heterogeneities appear to be relatively small at these depths. There are occasional reports of additional discontinuities (1000, 1200, 1800 km), the potential existence of which could have a significant impact on our understanding of mixing in the mantle.

The core-mantle boundary is the most dramatic and important discontinuity in Earth's interior. Understanding the processes that occur at and across this boundary are essential to modeling the evolution of the mantle and core, the nature of flow in the mantle, and the origin of the geodynamo. These processes occur at a variety of spatial scales: there is a known large-wavelength pattern of velocity anomalies, but there is also an indication of strong variations over much shorter distances. There are indications of an ultra-low velocity zone and underplating of the core-mantle boundary, as well as both thermal and compositional variations in the lowermost 300 km of the mantle. Furthermore, there are suggestions that Earth's most remote region, the inner core, contains structure on a wide range of scales including some very strong anomalies. Using distant earthquakes as sources, USArray's highly sensitive broadband instrument coverage will be able to track seismic waves that have penetrated to and even through the inner core, providing high-resolution information on the structure and composition of Earth's deepest interior.

Scientific Issues

- What is the three-dimensional structure of the upper mantle under North America, including variations in anisotropy, composition, and temperature?
- What is the compositional and mechanical stratification of the lithosphere and sublithospheric mantle, and how does this stratification vary from young orogenic belts to the cratonic interior of the continent?
- What is the nature of mass transfer (crustal recycling) between the crust and mantle and between the lithosphere and deeper Earth during subduction and orogenesis?
- What is the relationship between deep mantle convection and plate tectonics?
- What is the nature of upper mantle discontinuities, including the velocity gradients and fine structure of the 410 and 660 km discontinuities, and how do they relate to orogenesis and rifting?
- How does mantle flow correlate with lithospheric deformation?
- Are there additional global-scale discontinuities in the mid-mantle?
- What processes are represented by very different scale anomalies observed at the core-mantle boundary?
- What is the anisotropy and heterogeneity of the inner core?

Integrated Observation Systems

Study of the structure and deformation of a continent requires integrated observational systems that span temporal scales from seconds to the age of Earth, and spatial scales from continental dimensions (1000s of km) to the submillimeter ground displacements in small earthquakes. EarthScope will combine the tools of modern geophysics with geological observations (Figure 10) to permit scientists to examine the dynamic Earth and its structure at the spatial and temporal scales over which geologic activity takes place.

Seismological and geodetic observations, with arrays of fixed and portable seismometers and strainmeters, will sense the short-term deformation process in individual earthquakes and volcanic eruptions. GPS observations, InSAR images, and geological data will measure strain accumulation during intra-seismic periods and long-term plate deformation. Geophysical and geological tools will be used to probe the underlying structure of the continents, which carries the record of the past and influences future episodes of deformation.

In common with all areas of observational science, the Earth sciences have benefited from the enormous advances that have taken place in recent years in sensor technology, recording systems, communications, data management, and computational power. Highly rugged, portable instruments can now be left unattended in remote environments, continuously measuring the full spectrum of ground deformation and transmitting data in real-time to centralized data collection and distribution centers. Advanced data management systems allow users to selectively mine these extensive data resources, which then provide the basis for analysis and interpretation using highly sophisticated computational resources.

With strong support from NSF, USGS, NASA, and DOE over the past decade, the U.S. Earth science community has built linked, community-based management structures and technical expertise to operate and make optimum use of these advanced technologies. EarthScope's observational components are a natural extension of these resources, extending the base established through facilities such as UNAVCO, IRIS, SCEC, and ANSS, to form a complementary and linked observational system extending across North America.

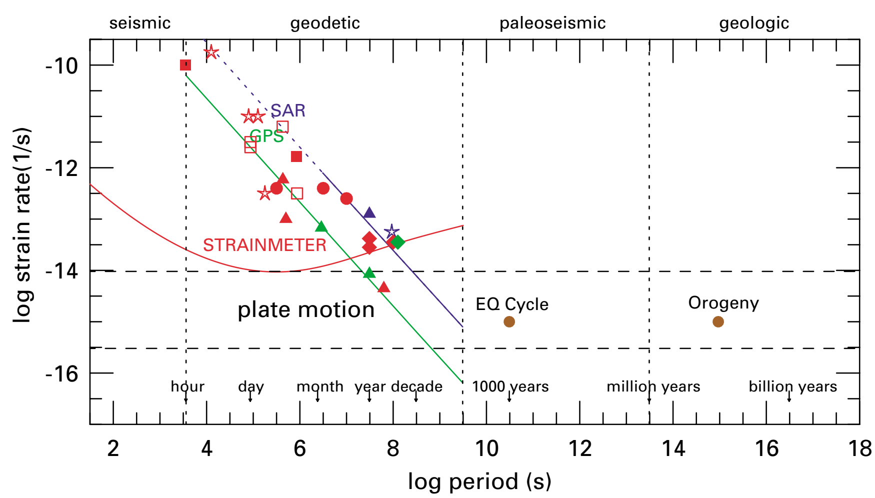


Figure 10. Components of an EarthScope Observing System. Thresholds of strain-rate sensitivity (schematic) are shown for strainmeters, GPS, and InSAR as functions of period. The diagonal lines give GPS (green) and InSAR (blue) detection thresholds for 10-km baselines, assuming 2-mm and 2-cm displacement resolution for GPS and InSAR, respectively (horizontal only). GPS and InSAR strain-rate sensitivity is better at increasing periods, allowing, for example, the detection of plate motion (dashed lines) and long-term transients (periods greater than a month). Strainmeter detection threshold (red) reaches a minimum at a period of a week and then increases at longer periods due to an increase in hydrologic influences. Post-seismic deformation (triangles), slow earthquakes (squares), and long-term deformation (diamonds), preseismic transients (circles) and volcanic strain transients (stars).

New Observational Facilities

United States Seismic Array (USArray)

Modern seismology has evolved a rich complement of tools and techniques for probing the fine-scale structure of the crust and upper mantle. Fixed and permanent arrays of seismometers, recording small local earthquakes, active sources, and large events from anywhere in the world, are used to develop high-resolution images of geological structures in the crust, upper mantle, and deepest interior.

The seismological component of EarthScope, USArray, consists of three interrelated parts. USArray's core is a transportable telemetered array of 400 broadband seismometers designed to provide real-time data from a regular grid of stations with dense and uniform spacing of 70 km and an aperture of 1400 km. The array will record local, regional, and teleseismic earthquakes, providing resolution of crustal and upper mantle structure on the order of a few tens of kilometers. Moreover, resolution of structures in the lower mantle and at the core-mantle boundary will be dramatically increased beyond that which presently exists. Fifty magnetotelluric field systems will be embedded within the array to provide constraints on temperature and fluid content within the lithosphere.

The transportable array will roll across the country with one- to two-year deployments in each region (Figure 11). Multiple deployments will cover all contiguous 48 states and Alaska over a ten-year period. When completed, the more than 2000 seismic station locations will have provided unprecedented coverage for three-dimensional imaging of the entire continental lithosphere and underlying mantle. New images of the largely uncharted lowermost mantle and core-mantle boundary will emerge. Although USArray's initial focus is coverage within the United States, extensions of the array into neighboring countries and onto the continental margins in collaboration with scientists from Canada, Mexico, and the ocean sciences community would be natural additions to the initiative.

An important second element of USArray is a pool of 2400 portable instruments (a mix of broadband, short period, and high frequency sensors) that can be deployed using flexible source-receiver geometries. These instruments will permit high-resolu-

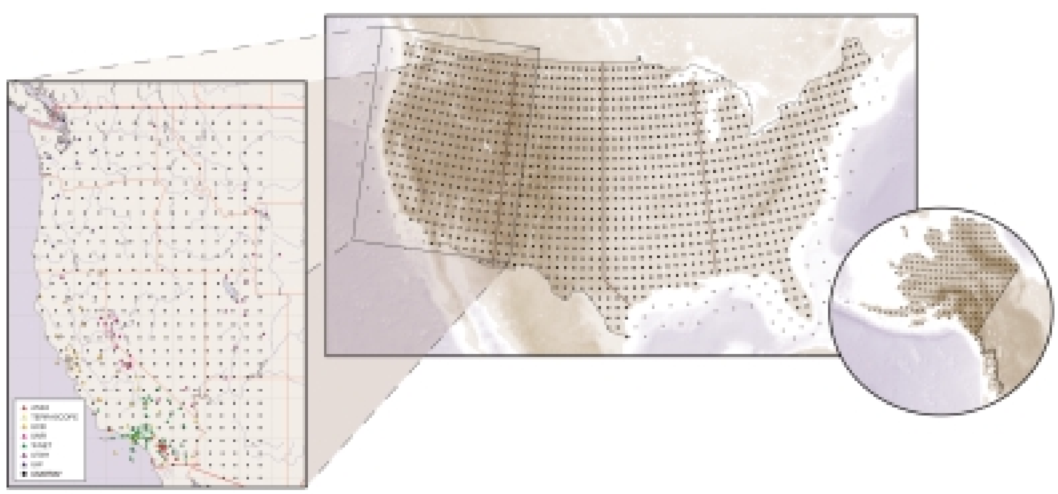


Figure 11. Deployment strategy for the transportable array. The underlying grid shows a regular spacing of 70 km, resulting in approximately 1600 sites in the lower 48 states. USArray begins operations in California, encompassing the SAFOD site at Parkfield. Western U.S. detail shows the nominal coverage for the first full deployment of the 400 instruments of the transportable array. Included in this map as colored symbols are existing sites of broadband instruments in regional networks.

tion, short-term observations of key geologic targets within the footprint of the larger transportable array, using high-density sensor spacing and both natural and artificial sources of seismic energy.

The third element of USArray will be an augmentation of the fixed National Seismic Network operated by the USGS. Relatively dense, high-quality observations from a continental network with uniform spacing of 300 to 350 km is important for tomographic imaging of deep Earth structure, providing a platform for continuous, long-term observations, and establishing fixed reference points for calibration of the transportable array. This USArray component is being undertaken in collaboration with the USGS and represents an EarthScope contribution to complement the initiative underway by the USGS to install an Advanced National Seismic System (ANSS) for earthquake monitoring.

Plate Boundary Observatory (PBO)

The Global Positioning System (GPS) has revolutionized tectonic geodesy. Over the past ten years, positional accuracy has increased and instrument costs have dropped to the extent that continuously recording installations for measuring movements of Earth's crust are now the norm. Recent advances in field monumentation coupled with the best data processing strategies have reduced positional errors and changes in baselines of hundreds of kilometers to approximately one millimeter. Thus, GPS networks can routinely track plate-tectonic and fault-related crustal motions in many parts of North America from a few millimeters to a couple of centimeters per year.

The geodetic component of EarthScope, PBO—an observatory designed to study the three-dimensional strain field resulting from plate-tectonic deformation of the western portion of the continent—consists of two elements (Figure 12). The first is a backbone network of 100 continuously recording GPS receivers sparsely deployed throughout conterminous western U.S. and southern Alaska to provide a long-wavelength, long-period synoptic view of deformation of the entire plate boundary zone. Receiver spacing will be approximately 200 km, and the data will be integrated with InSAR (see next section), when and where available, to define the regional component of the strain field.

PBO's second element consists of focused, dense deployments of continuously recording instruments ("clusters") in the

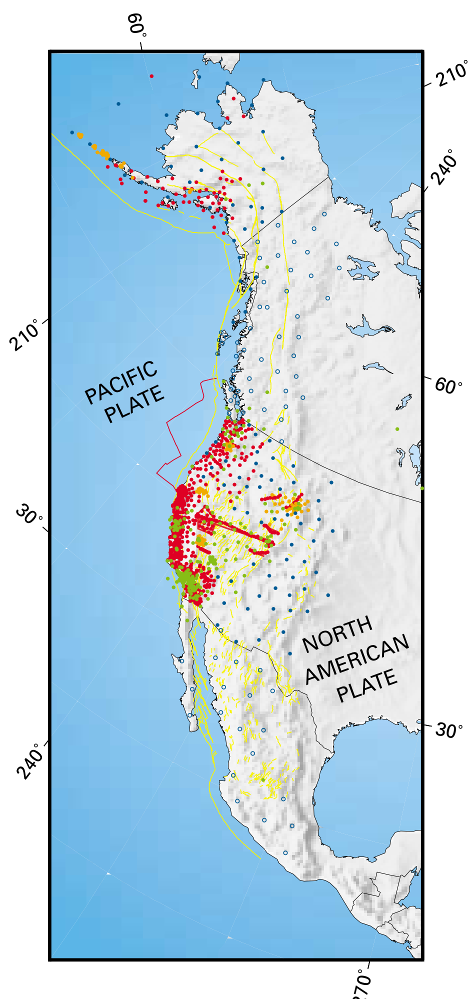


Figure 12. Map of GPS sites. Backbone stations are solid blue; existing stations are green; volcanic clusters are red; fault/tectonic-related clusters (excludes volcanic, e.g. San Andreas Fault system) are orange. Anticipated stations through international collaboration with Canada and Mexico are open blue.

most tectonically active areas requiring the greatest temporal resolution. Each cluster consists of an integrated network of GPS receivers and borehole strainmeters. These instruments, with a nominal spacing of 5 to 10 km, will provide nanometer strain sensitivity. On the order of 800 observing sites (GPS receivers plus strainmeters in a 4:1 ratio) will be installed around the most active tectonic regions of western conterminous U.S. and southern Alaska, including the San Andreas fault system, Yellowstone and Long Valley calderas, and several Alaskan and Cascade volcanoes.

Existing geodetic networks in the western conterminous U.S. and Alaska will be fully integrated into PBO thereby forming a geodetic facility spanning the plate boundary from the coast across the Basin and Range and Rocky Mountains. Moreover, combining all permanent GPS stations into a single network will avoid siting redundancies, maintain instrumental compatibility, provide for free and rapid data access, and permit uniform operation and maintenance.

Interferometric Synthetic Aperture Radar (InSAR)

Although GPS has proved a powerful way to study the deformation of Earth's surface, these measurements lack spatial continuity and require field equipment at each study site. Recent technological advances in space-borne radar interferometry permit observation of mm-level surface deformation at 25-m resolution with worldwide accessibility. Derivation of the first interferometric maps of the co-seismic displacement field of the 1992 Landers earthquake by French scientists was arguably one of the most exciting results in earthquake geodesy. More recently, InSAR has been applied to post-earthquake relaxation phenomena, volcano-magmatic inflation (Figure 13), land subsidence, and fault creep, further emphasizing the importance of this technique to the EarthScope initiative.

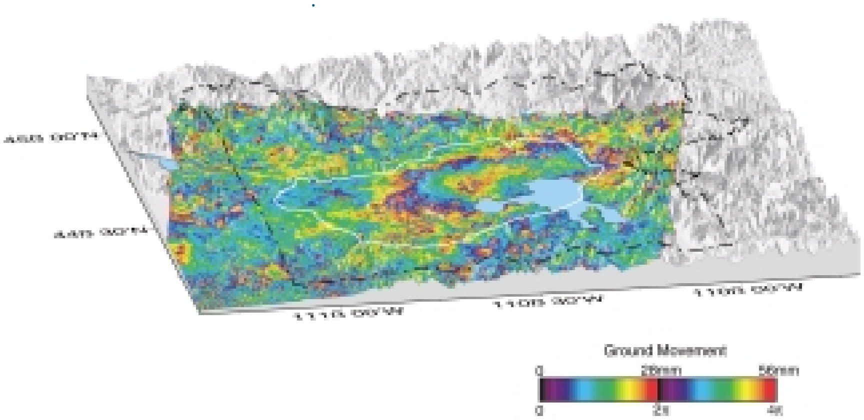


Figure 13. InSAR image for 1992-1993 draped over topography of Yellowstone National Park (boundaries of park shown by dashed line, outline of caldera boundary is white). Subsidence is located beneath the northeastern resurgent during 1992-93, but from 1993-95, deformation migrated to the southwest, indicating outflow of magmatic fluids for a source about 8 km beneath the caldera.

A dedicated InSAR satellite mission carried out jointly among NASA, NSF, and the USGS will provide spatially continuous strain measurements over wide geographic areas. These InSAR images will be an essential contributor to understanding crustal deformation, complementing the continuous GPS point measurements made by PBO. The optimum characteristics are dense spatial (100 m) and temporal (every 8 days) coverage of the entire plate boundary with vector solutions accurate to 1 mm over all terrain types. Existing and planned international SAR missions cannot deliver the required data.

InSAR will enable mapping of surface displacements before, during, and after earthquakes and volcanic eruptions, as well as charting strain accumulation across broad, actively deforming zones of conterminous western U.S. and Alaska, thereby highlighting regions of highest risk for future earthquakes and volcanic eruptions. It also will provide a tool for mapping subsidence induced by petroleum production and ground water withdrawal.

San Andreas Fault Observatory at Depth (SAFOD)

SAFOD will be EarthScope's first subsurface observatory. It will be drilled to a depth of 4 km, directly into the San Andreas fault zone through a cluster of microearthquakes and close to the nucleation point of a 1966 M6 earthquake near Parkfield, California. SAFOD will directly sample fault zone rocks and fluids, measure a wide variety of fault zone physical and chemical properties, and monitor the creeping and seismically active fault zone at depth.

Modern drilling and borehole instrument technology, pioneered by both the oil and gas industry and the scientific community, now permit detailed sampling, characterization, and observation of the upper crust to depths of several kilometers. Subsurface measurements of material properties and other *in-situ* conditions must be integrated with seismic and geodetic data acquired at the surface to properly characterize zones of deformation such as major strike-slip faults and magmatic systems, thereby moving us closer to predictive understanding of these processes.

Drilling will begin west of the San Andreas fault. At a depth of 2 km, advanced directional-drilling technologies will be used to drill an inclined hole through the entire fault zone until relatively undisturbed rock is reached on the other side (Figure 14). During drilling, the hole will be logged, spot cores and cuttings collected, and fluids and gases continuously sampled. After conducting side-wall coring and open-hole geophysical logs, the completed hole will be cased and cemented. Fluid sampling, permeability, and hydraulic fracturing experiments will be made through perforations in the casing.

An array of seismometers will be deployed in the hole to make near-field observations of earthquake locations, seismic wave radiation patterns, and rupture mechanics, and to help determine the positions of active fault strands. Fluid pressure will be monitored continuously at a carefully chosen depth and the hole will be logged repeatedly to identify places where the casing may be deforming due to active shear zones.

SAFOD will be the focal point for the real-time earthquake physics experiment going on at Parkfield. It will supplement the densest surface fault monitoring network in the world with direct *in situ* physical and fluid property measurements within the seismically active fault zone. The effort to build a real-time and predictive model of an active fault zone will take advantage of the knowledge base developed over the past 15+ years in the area through the collaborative efforts of hundreds of scientists from the USGS, universities throughout the United States, and U.S. government laboratories.

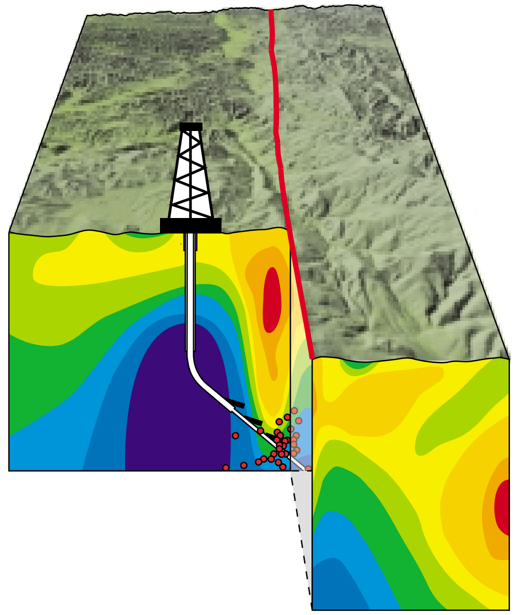


Figure 14. Schematic cross section of the SAFOD drill hole showing small target earthquakes (red dots) at 3-4 km depth. The colored patterns show electrical resistivity at depth as determined from surface surveys; the lowest resistivity rocks (red) lie beneath and to the southwest of the surface trace of the San Andreas fault (red line) and may represent a highly fractured and fluid-filled fault zone.

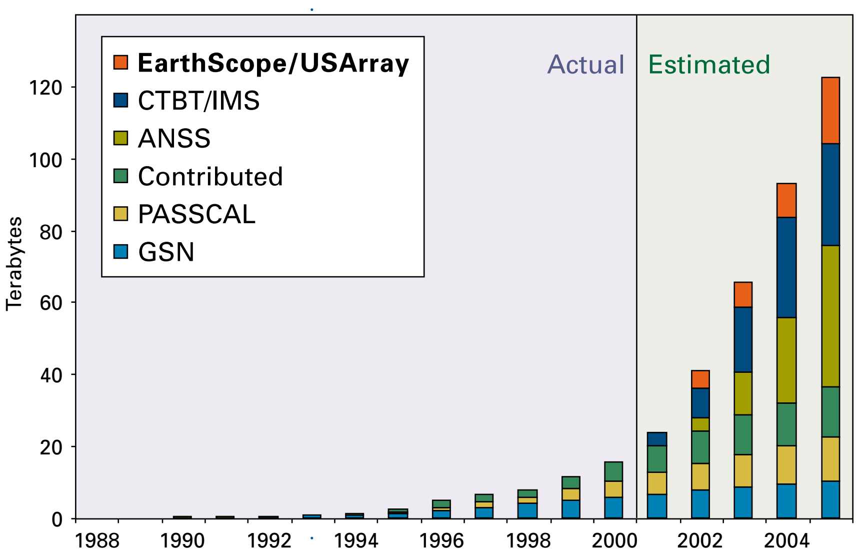
Data Management and Information Technology

Tools from modern data management and information technologies will be applied throughout EarthScope—in collecting data from the field, creating and accessing data bases and archives, developing and processing data products, and analyzing and visualizing multidimensional data. The information infrastructure established to meet EarthScope's data needs is also expected to stimulate the growth of a much broader effort in Geoinformatics and Earth Information Systems, incorporating multidisciplinary data resources that extend well beyond those produced by EarthScope facilities alone.

EarthScope facilities will produce data at a rate that only a decade ago would have overwhelmed the technical capabilities of the geoscience community (Figure 15). USArray alone will produce almost 5 terabytes of data per year—eight times that produced by the Global Seismograph Network. The volume of data in the image archive created by InSAR will be even larger. Over the past decade, the geosciences have embraced modern advances in computer, communication, and information technology in ways that have not only overcome earlier technical limitations, but also fundamentally changed the manner in which data are treated as a community resource, strongly encouraging data exchange and communication. The use of powerful data management tools for coordinated data collection and distribution from large observational systems, for example, seismic networks (IRIS, ANSS), regional networks, and geodetic arrays (UNAVCO, SCIGN), is now widely accepted as an essential component of the geophysical research infrastructure. EarthScope will build on these traditions and established mechanisms (Figure 16).

Three aspects of EarthScope data management are:

Figure 15. Current and projected data holdings at the IRIS Data Management Center. The current (2001) data archive of over 15 terabytes is increasing at four terabytes per year. It is estimated that USArray would add approximately five terabytes per year. Total archive requirements are expected to be over 100 terabytes by 2005.



Primary Data

The challenges of data collection, archiving, and distribution for EarthScope's observational systems are significant, but well within current capabilities. While data quantities are large, they represent less than an order of magnitude increase over that which is presently being handled by the IRIS Data Management System and regional networks. Raw data from the primary instrument components of EarthScope—seismometer arrays, strainmeters, geodetic receivers, and other geophysical instruments—will be treated as an open community resource. These raw data can be relatively simply classified as time-series (seismograms, strain records, and geodetic data from USArray, PBO, and SAFOD), and images (InSAR). All data will be collected and distributed in real time. An annotated

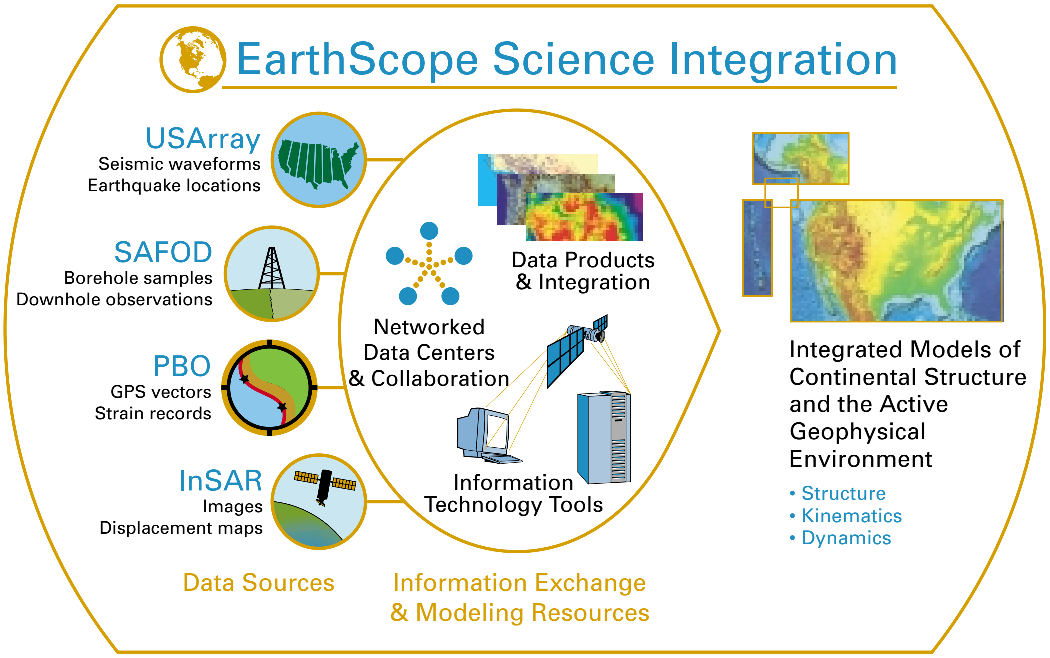


Figure 16. Coordinated data management and integration from all EarthScope components and the application of information technology tools will provide a rich environment for research and modeling. Documented and open data and software resources will encourage multidisciplinary investigations of continental structure and the active geophysical environment with applications in education, seismic hazard assessment, and resource management.

archive of all data will be created and maintained, and free and open access will be provided to national and international research and education communities.

Derived Products

A growing realization in information systems is the need to provide end users with access to data, and software to aid data integration and manipulation. For many in the research community, the raw data from EarthScope instruments will be the most direct and critical products from this initiative. For other researchers, and especially for the public, it will be important to convert these primary data into products that are accessible and interpretable by the layperson, teacher, resource manager, or policy maker.

The seismic and geodetic data from EarthScope will be a powerful tool for focused studies of natural hazards such as earthquakes and volcanic eruptions, and natural resources.

Integrated Earth Information System

A far greater challenge, and one that holds promise for fundamental changes in the way we do science, is the merging of disparate data sets from diverse disciplines. EarthScope provides a forum to aid the development of an Integrated Earth Infor-

> These proposed facilities and the resultant open data sets will have an egalitarian effect of broadening the accessibility of science; a small-college researcher with a workstation can do first-rate science with resources that were previously limited to major universities.
>
> Frank Press, GSA Annual Meeting, 1999

mation System that can be accessed easily by the Earth science community, educators, government agencies, and the interested public. A considerable amount of information already exists from decades of geological, geochemical, and geochronological studies of North America. A large portion of these geological data, however, are in forms that are not readily compared with other information and exist only in print-published tables and maps, or in electronic format on an individual scientist's computer. For several large categories of Earth science data, there are no data exchange standards to facilitate information sharing. An important part of EarthScope's data management mission is to facilitate the adoption of data exchange standards by the geologic community and to facilitate the transcription of existing data into these standards. EarthScope will provide a forum to coordinate and work with the USGS, state geological surveys, and other agencies to establish data exchange formats and protocols. This will ensure that data access and management are facilitated for the benefit of the entire scientific community.

Education and Outreach

Although the primary motivation for EarthScope is grounded in fundamental advances in scientific discovery, the initiative also provides a spectacular opportunity for a focused education and outreach program that will reach the general public, K-16 students and faculty, and Earth science professionals. EarthScope will capitalize on the public's natural curiosity about our dynamic planet by providing all Americans with new insights into how Earth works. The national scope of instrument deployments will provide education and outreach opportunities across the country for many years, while the local nature of the deployments will make the initiative's scientific investigations and discoveries relevant for educational efforts on a region-by-region basis.

Figure 17. Children gather around IRIS' hands-on seismology exhibit at a museum.

EarthScope is emerging at a time when there is growing national awareness of the need to improve science education, coupled with an appreciation of the opportunities offered by Earth sciences to engage students at all levels in the exploration of the world around them. The nature of the decade-long experiment will provide many opportunities for citizens of all ages to participate in scientific inquiry and discovery along with EarthScope scientists. With strong encouragement and support from NSF and other federal agencies, education programs are becoming an integral part of Earth science facilities and research programs. The Earth science community—from major research facilities to professional societies, government agencies, and individual scientists—is building educational links to resources primarily established for research. In addition, a growing number of Earth scientists are actively pursuing educational initiatives as a formal part of their research. Providing real-time access to the rich data sets, along with tools and materials that create opportunities for citizens to explore and understand these data, will be an important EarthScope activity.

EarthScope's national scale and breadth of associated research is unprecedented in the Earth sciences. It has the potential to spawn new areas of discovery in ways similar to the Human Genome project for the biological sciences. We anticipate an education and outreach program that conveys both the exciting results that emerge from EarthScope's national scientific effort, and perhaps as importantly, the nature of our scientific method. For example, as USArray moves from region to region, the education and outreach efforts will highlight both important regional questions and an emerging (and changing) continental-scale picture. This process will provide a genuine example of how our scientific thinking often changes as new data become available. In addition, the rich data sets will provide new ways to help students make their own discoveries, thereby understanding Earth more deeply. EarthScope will be able to capitalize on the excitement created by a huge science experiment in one's own backyard.

EarthScope will foster education and outreach coordination among individuals and organizations in the Earth science community by providing opportunities for participation at two levels: (1) developing a core of information and resources appropriate for national-scale outreach to a broad audience and (2) providing more focused educational efforts for specific audiences or regions.

Figure 18. Students visit an active GPS site in southern California.

The first level of EarthScope E&O will focus on high-profile information (and data) dissemination that facilitates the science initiative and is consistent with education of a broad audience. A significant component of this outreach effort will include providing real-time access and tools necessary to manipulate, analyze, and view EarthScope data. Disseminating information on project goals, initiatives, activities, key geoscience concepts, and discoveries will help media representatives, community leaders, educators, students, scientists, and the general public understand the project and stay abreast of new developments. All resources and information will be available on-line as well as in posters, brochures, and occasionally as video. By coordinating on-line information by region, it will be possible to link communities to EarthScope activities and show how data recorded in their region merges with data from other regions to provide a coherent picture of Earth.

EarthScope facilities will provide the infrastructure for principal-investigator (PI)-driven scientific research; similarly, a core of EarthScope education and outreach efforts will provide a basic foundation for PI-driven education and outreach activities. Thus, the second level of EarthScope E&O will focus on PI-driven educational activities for specific audiences and regions and will include small to large-scale projects such as informal science programs in museums and schools, regional and national citizen or student directed scientific investigations, instructional materials development, and professional development workshops for K-16 faculty. To help individual efforts build upon one another for maximum impact, individual PIs or organizations will work with teachers, scientists, colleges, museums, and state geological surveys to develop materials that apply to the initiative as a whole and materials that highlight hazards, natural resources, and the geologic structures and history that are region-specific. These materials will effectively translate and communicate both scientific results and the scientific method to all audiences and will be critical for education and outreach efforts when the instrument deployments are under way.

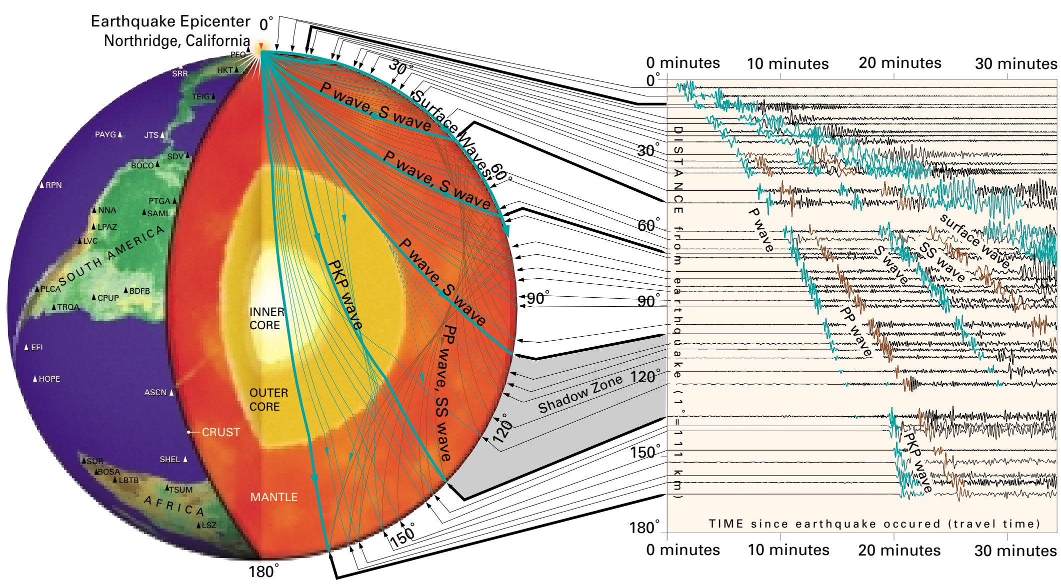


Figure 19. Concise explanations of scientific topics, in the form of posters and "one-pagers," are one way to develop links between research topics and the classroom. Distributed in printed form at workshops and available via the web, these materials provide high school teachers with supplemental materials to enhance standard curriculum and establish direct contacts between educators and researchers. This figure is from, "Exploring the Earth Using Seismology," and describes how analysis of seismic waves from earthquakes permits seismologists to explore Earth's deep interior. (See www.iris.washington.edu/EandO/onepager.htm)

Implementation

Management Structure and Coordination

An undertaking as broad and complex as EarthScope requires management and coordination at several intersecting levels.

- As a facilities program the various EarthScope components will need to build on the strengths of the individual communities they represent. During all phases of development, however, decision-making and implementation of all components will be closely coordinated, including 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 have an impact on 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.

NSF uses a variety of methods to select and fund both research and facilities. The individual investigator research grant remains at the core of NSF support of fundamental research. For larger, interdisciplinary programs, multi-institutional collaborative funding arrangements are used. Large-scale facilities are often operated by nonprofit consortia through cooperative agreements with NSF. These consortia have been established by the research community to help develop and advance the observational needs of their science. NSF Science and Technology Centers, often multi-campus "institutions without walls," have proven extremely successful in bringing together the best of the nation's scientific expertise to focus on specific research topics. The research community will work with NSF and other federal agencies to match the most appropriate of these management and funding mechanisms with the wide range of programmatic requirements necessary for EarthScope to succeed.

Evolution of EarthScope Programs and Integration

Many individuals and groups within the U.S. Earth science community have contributed to planning and developing the EarthScope concept.

The SAFOD concept of instrumenting the San Andreas fault has arisen many times over the past several decades. The current SAFOD project had its origin in December 1992 at an NSF workshop attended by 113 scientists and engineers from seven countries. Its purpose was to initiate a broad-based scientific discussion of the issues that could be addressed by direct experimentation and monitoring within the fault at depth, to identify potential sites, and to identify technological developments required to make the construction and drilling possible. The fundamental scientific issue addressed in this effort, obtaining an improved understanding of the physical and chemical processes responsible for earthquakes along major fault zones, is clearly of global scientific interest. Throughout the planning process leading to the development the SAFOD project, the U.S. scientific community has invited participation by scientists from around the world, principally through the International Continental Scientific Drilling Programme (ICDP). A proposal was submitted to NSF in January 1999 to accomplish SAFOD goals.

USArray concepts were developed in a series of workshops, including the 1994 ILIAD Workshop (Investigations of Lithosphere Architecture and Development). Two workshops, in March and September of 1999, established the specific scientific, technical, and educational objectives of USArray. A report describing USArray's scientific rationale, defining its operational components, organizational partnerships, and management structure, and developing time lines for the acquisition of USArray instrumentation and their deployment, was submitted to NSF in December 1999. The implementation plan and budget estimates for USArray are based on results of the first USArray workshop. Two subsequent USArray workshops have addressed refinements of the science and integration of USArray results with the other EarthScope elements.

PBO community support was demonstrated by a January 20, 1998 letter signed by eleven top U.S. Earth scientists urging the initiation of a program to investigate plate-boundary processes. The first PBO workshop of October 1999 developed the scientific, technical, and educational objectives of the PBO facility. The workshop had 123 participants, representing a broad spectrum of Earth scientists from the U.S., Canada, Mexico, Japan, and Australia. A workshop report was submitted to NSF describing the scientific rationale of PBO, defining its operational components, organizational partnerships, and management structure, and developing time lines and budgets for PBO instrument acquisition and deployment. A second PBO workshop was held on October 2000, with 150 participants, to refine the target areas.

InSAR is a technology that has recently come of age for active tectonic studies, and represents a major advance in spatially continuous geodesy. InSAR complements the PBO suite of instruments; PBO provides continuous time series at discrete locations while InSAR provides spatially continuous maps at discrete times. This complementary nature is an essential reason for making InSAR an integral part of EarthScope, with NASA as the lead agency. The priorities concerning the use of InSAR have been examined in the course of a workshop held in June 2000. Participants at the workshop agreed that a mission featuring a single-polarized L-band (24 cm wavelength) radar with both left- and right-pointing capability, in a precisely controlled orbit, would offer the best opportunity for outstanding scientific return.

EarthScope as a Major Research Equipment Initiative

In May 1999, discussions between NSF and leaders from SAFOD, USArray, PBO, and InSAR lead to the merging of these developing initiatives as a proposal for a single national program called EarthScope. An EarthScope Working Group was formed that has planned workshops, interacted with NSF and other federal agencies, developed coordinated program plans, and encouraged broad community support. This Working Group is preparing for the transition to a more permanent management structure under which the funded EarthScope project would operate.

EarthScope facility components have now been approved by NSF and the National Science Board for inclusion as a project in NSF's Major Research Equipment (MRE) account. This account supports the acquisition of facilities and equipment that are beyond the resources of any individual Foundation directorate. Once EarthScope is approved by Congress as part of NSF's budget, the Foundation will issue project solicitations for EarthScope elements USArray, SAFOD, and PBO. Under this solicitation, proposals will be submitted for the initial construction and acquisition phases as well as the operation and maintenance over the facility's first ten years. An overall management plan for EarthScope integration is designed to closely coordinate and integrate with other EarthScope elements and with the national and international Earth sciences research and educational communities.

Science Support

In a manner consistent with their usual modes of research funding, NSF and other agencies will issue Program Announcements to support the science activities using EarthScope data. NSF expects to make individual-investigator and group grants for all aspects related to the science and integration of EarthScope data, educational and outreach activities, and planning and science-coordination activities. Planning and coordination will involve participation by a broad segment of the U.S. scientific community in EarthScope working groups and workshops.

Management Structure

The proposed oversight and management structure of EarthScope facilities is shown in Figure 20. This management structure is intended to combine consensus-building, grass-roots direction from the research community with a strong, centralized management structure and financial oversight and control from NSF, the primary funding agency. The management structure should be able to formulate priorities and guide overall facility operations, consistent with decisions of a broad community and guidance from the funding agencies.

The key elements provided by this management structure are:

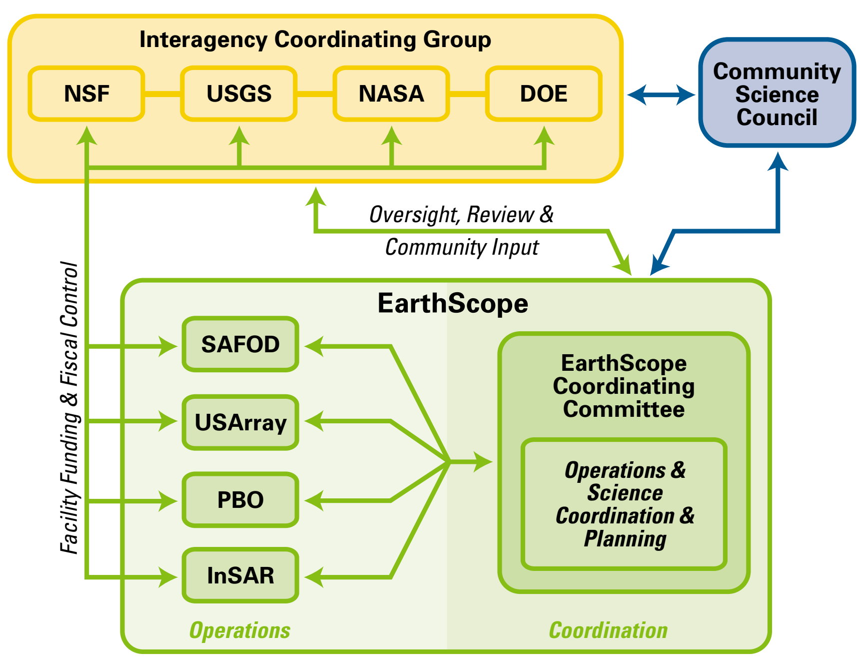
Interagency Coordination. An Interagency Committee will provide funding coordination and define the responsibilities of federal partnerships in support of EarthScope. This committee will also establish the broad goals for the project and the guidelines under which it will operate.

Oversight. A high-level Community Science Council will interact with the funding agencies and EarthScope Coordinating Committee (next page) to provide scientific direction, review technical accomplishments, and evaluate EarthScope's success in achieving its scientific objectives.

Facility Operations. Implementation of EarthScope facilities will be carried out by organizations with proven capabilities in operating large, complex observational systems.

Fiscal Reporting and Controls. The facility operators will be funded through cooperative agreements with NSF that define specific tasks to be carried out with EarthScope support. These cooperative agreements provide the legal and fiscal controls to ensure effective and appropriate use of federal funds. The tasks as defined under the cooperative agreements are

Figure 20. Proposed structure for oversight and management of EarthScope facilities.



established by NSF based on input from the user community and in collaboration with facility operators.

Management, Coordination, and Community Input. The EarthScope Coordinating Committee, with representatives from the research community and facility operators, will be a primary conduit for community input to EarthScope management and key to the success of both EarthScope facilities operations and its scientific objectives. The committee will be composed of two members from each of the EarthScope facility components, to be selected by each of their governing entities, plus four at-large members to be selected by the committee. It is anticipated that of the two members from each of the facility components, one will represent governance and the other, operations. The four at-large members will ensure an appropriate multidisciplinary balance with respect to EarthScope objectives. The committee will be tasked to:

- provide coordination among facility components;
- facilitate science and science integration;
- conduct workshops for the EarthScope community at large;
- foster education and outreach activities;
- act as a sounding board for, and provide a mechanism for input to, the funding agencies;
- coordinate and oversee the reporting and review processes;
- encourage interagency coordination of EarthScope-related activities.

National and International Partnerships

EarthScope is a multi-agency, national program with important roles being played by NSF, USGS, NASA, DOE, and NOAA. Partnerships are being developed with state agencies, regional seismic networks, organizations in Mexico and Canada, and the ICDP. EarthScope activities are built on a number of existing interactions between university research groups and federal agencies and a wide range of current and planned research projects involving numerous scientists at national and international institutions. In particular, resources from Earth observing and monitoring programs at the USGS and NASA will be extensively used to maximize EarthScope's scientific return.

As PBO instruments are installed and USArray systematically traverses the continent, there will be numerous opportunities for a wide variety of interactions between academic researchers and federal and state agencies involved in research, education, public policy, and resource assessment. Much of the data and results from EarthScope will be of interest to state geologists in hazard evaluation (seismic, volcanic, landslides), and assessment of mineral and water resources. Lithospheric imaging will add to our fundamental knowledge about Earth structure and provide data directly to, and benefit from, state geological mapping projects. EarthScope—especially as manifested in USArray and PBO—is intended to provide an evolving regional framework for a broad spectrum of Earth science investigations.

The PBO array will depend on regional networks being installed or already in place: 400 continuous GPS and 45 borehole strainmeters. Their installation was done under support by NSF, USGS, NASA, and the W.M. Keck Foundation. Support for operation and maintenance of these systems is currently done through a partnership of NSF, USGS, and NASA, and will continue as a contribution to PBO. A further NASA contribution is support of the International GPS Service (IGS), which provides precise satellite positions essential for PBO data analysis. The PBO community has been working with NOAA/National Geodetic Survey to formally develop GPS references as legal benchmarks for the surveying community in regions of active crustal deformation such as southern California. This invaluable civil-use concept will be applied to the entire PBO GPS array.

USArray scientific goals complement the initiative underway at the USGS to install ANSS. The USGS is developing ANSS to meet its mission in earthquake-hazard assessment and mitigation. A significant component of ANSS focuses on urban areas with high seismic hazard. USArray goals are to illuminate structure and understand dynamics of the lithosphere and deeper mantle, which requires densification of the USGS National Seismic Network and uniform coverage of the continent. There is clear synergy between ANSS and USArray. The coordination between ANSS and USArray will create a single, integrated network of ~115 high-quality, permanent broadband seismic stations across the country to meet the goals of both constituencies. All data from this integrated network will be available in a single data stream to both communities. Coordination of these two initiatives is an excellent example of interagency cooperation and cost sharing and continues the longstanding working relationship between NSF and the USGS on permanent seismic stations.

The SAFOD community has been working with USGS, LLNL, DOE, and ICDP to develop a prototype downhole instrument package that will be an integrated multiple sensor system within a single re-deployable module. A 3-km hole in Long Valley, California will be used as a test bed for downhole instrument development. The SAFOD community is also developing a 2-km-deep pilot hole near the main SAFOD site. In addition to serving as an instrument test site, this pilot hole will facilitate precise earthquake hypocenter determinations that will guide subsequent SAFOD investigations and coring in the active fault zone. The pilot-hole project is being carried out in partnership with the USGS and the ICDP. SAFOD will be closely integrated with the extensive seismological and geodetic observation systems deployed by the USGS at the surface in the region. Together, SAFOD and existing USGS facilities at the surface will result in an unparalleled and comprehensive monitoring system.

While EarthScope is focused primarily on the development of facilities to probe the continental lithosphere of the United States, the structures and processes to be studied are not limited by geographical or political borders. Discussions have been initiated with Canada and Mexico to extend the observations north and south of the U.S. border and links to the ocean community are being pursued to provide offshore observations on the continental shelf and beyond. The Canadian Earth science community is completing a national project, Lithoprobe, that has served, in part, as a model for EarthScope. Collaborative U.S.-Canadian projects were carried out as part of Lithoprobe and provide a basis for future interactions. A recently funded project, "POLARIS," is based on scientific targets and technologies that are similar to USArray and discussions have already been held to combine resources and merge observations. Observations in Canada will be essential to a full study of the western North America plate boundary and Canadian representatives have been included in the planning workshops for PBO.

Budget and Planning Overview

The tables (opposite page) provide an overview of estimated EarthScope costs to be supported by NSF for equipment, installation, operations, and science support. As described below, these estimates are based on planning activities and input from the university research community and the extensive experience of NSF-supported facilities programs in geophysical instrumentation and data management. The core equipment and operational costs are identified as supported by the NSF Major Research Equipment program. The budget for ongoing operations and science support would be provided by the NSF Earth Sciences Division and Geosciences Directorate. The budgets indicated for EarthScope-related science support are consistent with the recommendations of the recent National Academy report on "Basic Research Opportunities in Earth Science" (NRC, 2001).

USArray planning began over six years ago and the portable seismic instrument development and techniques have been under development for eleven years. All of this has been done through the NSF-supported university consortium, IRIS. IRIS's 96 member institutions include virtually all the U.S. academic institutions with significant research and education programs in seismology. Keys to USArray's success will be the community's development of instrumentation and reference networks, data management facilities and software, and management experience in fielding and maintaining large portable seismic arrays. Three major community workshops have developed seismic and cross-discipline science plans.

SAFOD planning has been underway for approximately ten years through a series of community workshops, proposals, panels, and expert evaluations. These events have been open to all scientists with an interest in deep fault observations. The scientific drilling community, including DOSECC, USGS, DOE, and ICDP, has extensive experience in successfully managing other deep-drilling projects such as Cajon Pass, California, and the current Hawaii Drilling Project. The cost and technical feasibility of the SAFOD drilling plan has been reviewed and approved by an independent technical drilling expert.

PBO planning has been underway for approximately four years with workshops representing a broad spectrum of Earth scientists from the United States, Canada, Mexico, Japan, and Australia. These workshops addressed the specific scientific, technical, and educational objectives of PBO and generated the fundamental science plan as a critical element of the EarthScope effort. Detailed reports describing the scientific rationale of PBO, defining its operational components, organizational partnerships and management structure, and developing time lines for the acquisition of PBO instrumentation and its deployment have been submitted to NSF. Budget estimates are based on the results of PBO workshops and the community's experience in pilot projects using GPS and borehole strain measuring systems.

InSAR planning has just begun with discussions between NSF and NASA, in consultation with the space geodetic community for a dedicated InSAR mission. A proposal to NASA's Earth Systems Science Pathfinder Program is being prepared for submission in early 2002.

Constant FY2001 M$							
EarthScope Costs	**YR1**	**YR2**	**YR3**	**YR4**	**YR5**	**YRs6-10**	**Total**
NSF Major Research Equipment Request							
USArray	14.16	21.52	16.87	10.96			**63.51**
PBO	13.78	19.06	20.91	19.03	18.50		**91.28**
SAFOD	4.67	9.12	0.31	3.26			**17.36**
MRE Totals	**32.61**	**49.70**	**38.09**	**33.25**	**18.50**		**172.15**
Operations	0.25	1.22	2.45	3.95	8.83	55.00	**71.70**
Science & Management	5.70	10.00	9.50	10.60	11.30	65.00	**112.10**
Total	**38.56**	**60.92**	**50.04**	**47.80**	**38.63**	**120.00**	**355.95**

MRE Facilities – Cost Detail Costs in FY01 K$					
	Type	**Quantity**	**Unit Cost**	**Cost**	**Total Cost**
PBO	Strainmeters	200	51	10,200	
	GPS Continuous	875	26	22,750	
	GPS Survey	100	15	1,500	
	Installation			56,830	
					91,280
USArray	Permanent NSN	25	50	1,250	
	Permanent GSN	10	190	1,900	
	Transportable	400	50	20,000	
	Flexible, BB	400	31	12,400	
	Flexible, SP	2,000	6	11,800	
	Installation			16,160	
					63,510
SAFOD	Drilling			15,800	
	Downhole Instruments			1,560	
					17,360
	Total MRE Cost				**172,150**

Appendix 1
Implementation Milestones

Pre-EarthScope Phase (Year 0)

Year 0
- Community planning workshops for the selection of permanent sites and geologic targets.
- NSF issues project solicitation; proposal review; approval and awards for EarthScope acquisition and operation. NSF awards cooperative agreements.
- NSF issues first annual Program Announcement and competition for science aspects of EarthScope.

MRE Phase (Years 1-5)

Year 1
- Compete and award contracts for broadband and short-period seismic systems.
- Community planning on permanent seismic sites and first array deployment.
- San Andreas Fault Observatory at Depth main hole drilling contract competed and awarded. Drilling begins at end of year.
- Downhole monitoring equipment constructed.
- Acquisition begins for GPS and borehole strain systems.
- Airborne imaging of potential study sites.
- Delivery of 50 portable GPS systems.
- Delivery and installation of 100 GPS and 20 borehole-strain systems.
- NSF conducts first annual review of EarthScope.

Year 2
- Delivery and installation of 50 transportable array sites.
- Delivery of 500 flexible pool short period systems.
- Delivery and installation of 5 GSN and 10 NSN permanent stations (in cooperation with ANSS).
- Main hole completed at San Andreas Fault Observatory. Downhole monitoring instrumentation installed.
- Airborne imaging of potential study sites.
- Delivery and installation of 175 GPS and 30 borehole-strain systems.
- Delivery and deployment of 50 portable GPS systems.
- NSF conducts annual review of project status.

MRE Phase (Years 1-5) continued...	
Year 3	• Delivery and installation of 200 transportable array sites. • Delivery of flexible pool systems: 200 broadband and 1000 short period seismic systems. • Delivery and installation of 5 GSN and 10 NSN permanent stations (in cooperation with ANSS). • San Andreas Fault site characterization studies carried out. • Delivery and installation of 200 GPS and 50 borehole-strain systems. • Deployment of 50 portable GPS systems. • NSF conducts annual review of project status.
Year 4	• Delivery of 150 and installation of 200 transportable array sites. • Delivery of flexible pool systems: 200 broadband and 500 short period. • Delivery and installation of 5 NSN permanent stations (in cooperation with ANSS). • Use site characterization and monitoring data to chose four coring intervals at depth in San Andreas Fault Observatory. Commence coring operations. • Delivery and installation of 200 GPS and 50 borehole-strain systems. • NSF conducts annual review of project status.
Year 5	• Redeployment of USArray. • Install permanent monitoring instrumentation in four core intervals and main hole of San Andreas Fault Observatory at Depth. • Delivery and installation of 200 GPS and 50 borehole-strain systems. • NSF conducts annual review of project status.
Operational Phase (Years 6-10)	
Years 6-10	• Redeployment of USArray on a continual basis. • Complete analysis of San Andreas Fault cores, cuttings and logs. Continue monitoring at depth. • Ongoing operation and maintenance of the PBO. • NSF conducts biennial reviews of project status.

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Acronyms

ANSS .... Advanced National Seismic System
DOE .... Department of Energy
DOSECC .... Drilling, Observation, and Sampling of the Earth's Continental Crust
GPS .... Global Positioning System
GSN .... Global Seismic Network
ICDP .... International Continental Scientific Drilling Programme
IGS .... International GPS Service
InSAR .... Interferometric Synthetic Aperture Radar
IRIS .... Incorporated Research Institutions for Seismology
LLNL .... Lawrence Livermore National Laboratory
NASA .... National Aeronautics and Space Administration
NEHRP .... National Earthquake Hazards Reduction Program
NSF .... National Science Foundation
NSN .... National Seismic Network
PBO .... Plate Boundary Observatory
SAFOD .... San Andreas Fault Observatory at Depth
SCEC .... Southern California Earthquake Center
SCIGN .... Southern California Integrated GPS Network
UNAVCO .... University NAVSTAR Consortium
USArray .... United States Seismic Array
USGS .... United States Geological Survey

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