EarthScope: Opportunities and challenges for earth-science research and education

ANNE MELTZER, Lehigh University, Bethlehem, Pennsylvania, U.S.

EarthScope is a new earth-science initiative to dramatically improve our understanding of the dynamics and evolution of the North American continent through an unprecedented exploration of its three-dimensional structure at continental scales. EarthScope will use the North American continent as a natural laboratory in which new observations from cutting-edge land and space-based technologies will image the interior at high resolution and measure deformation in real time at continental scales. By integrating complementary geophysical, geochemical, and geologic data, EarthScope will bring together the remarkable advances made in these sciences to provide a comprehensive time-integrated picture of continental structure and evolution, links between surface features and their structures at depth, and vastly improved understanding of hazards related to earthquakes and magmatic processes.

The EarthScope Program will use new observational facilities in seismology, satellite geodesy, and downhole monitoring to provide synoptic observations of plate scale processes. In turn, these observational facilities will provide a framework for broad, integrated studies across the earth sciences—such as research on fault properties and the earthquake process, crustal strain transfer, magmatic and hydrous fluids in the crust and upper mantle, plate boundary processes, large-scale continental deformation, continental structure and evolution, and deep-earth structure.

North America provides a diverse array of processes and structures for investigation; in fact, the opportunity for studies with societal relevance (investigation of earthquake and volcanic processes, hazards, and natural resource evaluations) and existing infrastructure (communication, transportation, and educational) are what make the project feasible. The North American continent’s ideal location with respect to global seismicity will lead to unprecedented views of the deep mantle, and the rich fabric of tectonic provinces in North America should provide a solid scientific rationale for a major national program to investigate in detail the relationship between tectonic processes and structures over a range of time and spatial scales within the crust, lithosphere, and mantle. The western United States contains a Mesozoic-Cenozoic mobile belt and orogenic plateau including a Cenozoic collapse structure, a developing rift system, a continental hotspot, and an ocean-continent transform fault system. The eastern United States contains a Paleozoic continent-continent collision zone, a Mesozoic rift, and a Mesozoic-Cenozoic passive margin. The passive margin along the Gulf Coast contains excellent examples of salt tectonics and large accumulations of hydrocarbons. In the interior of the continent, Proterozoic collisional belts ring the Proterozoic-Archean craton, which sits above a large upper mantle velocity anomaly. The midcontinent is also blanketed by platform sediments, a long and detailed record of what are probably mantle-controlled vertical motions. In the western United States, young tectonic activity, operating over the last few million years to tens of millions of years, is responsible for much present-day lithospheric architecture. However, this recent activity overprints older structures developed during previous plate collisions and rifting events and these pre-existing structures modulate modern processes. A systematic investigation of the North American continent provides a broad sampling of geologic processes across a range of scales and ages. In essence, moving spatially across the continent provides a snapshot of continental evolution and continental dynamics through time.

This article overviews EarthScope with an emphasis on the new observational facilities. Accompanying articles in this issue describe in more detail the instrumentation and infrastructure within the academic community supporting these facilities and highlight recent advances in imaging whole earth structure.

EarthScope facilities. Four new observation systems will be established through EarthScope: the U.S. Seismic Array (USArray), the Plate Boundary Observatory (PBO), the San Andreas Fault Observatory at Depth (SAFOD), and an Interferometric Synthetic Aperture Radar (InSAR) satellite. Data from these systems will be linked through high-speed, high-performance computing and telecommunication networks to allow open access to real-time data to scientists, educators, government agencies, industry, and the general public.

USArray—a continental scale seismic array of permanent and portable seismometers. USArray is designed to probe the three-dimensional structure beneath continental North America with a spatially dense network of high quality seismic stations. The core of USArray is a transportable telemetered array of 400 broadband seismometers designed to provide real-time data from a grid with dense and uniform station spacing of ~70 km and an aperture of ~1400 km (Figures 1 and 2). The array will record local, regional, and teleseismic earthquakes, providing resolution of crustal and upper mantle structure on the order of tens of kilometers and increased resolution of structures in the lower mantle and core-mantle boundary. (See the article by Levander in this issue summarizing pre-USArray work to define the “acquisition program” necessary to seismically resolve the
crustal and mantle features of interest. The transportable array will roll across the country with 18-month deployments at each site. As the array moves, it will systematically monitor active volcanic (yellow circles) and tectonic (magenta circles) areas susceptible to significant seismic hazards.

A second component of USArray is an additional pool of ~2400 instruments (200 broadband, 200 short period, and 2000 high frequency) that can be deployed using flexible source-receiver geometries. (See the accompanying article by Owens and Fowler in this issue for details on instrumentation.) These additional portable instruments will allow for high-density, shorter-term observations of key targets within the footprint of the larger transportable array using both natural and active sources. This flexible component of USArray offers exciting opportunities for a variety of focused investigations requiring higher resolution images imbedded within the context of the larger array. Depending on the detailed deployments of specific experiments, the resolution provided by this flexible array will vary from the 60-km scale provided by the transportable array to the tens of meters scale, making it ideal for tying surface geology to deeper structures in the crust and upper mantle.

A third component is an augmentation of the permanent seismic network in the United States operated by USGS. Permanent observations from a uniform, high-quality network provide fixed reference points for calibration of the transportable array and a platform for continuous long-term observations. Relatively dense, high-quality observations from a network with uniform spacing of 300-350 km across the continent are important for tomographic imaging of deep-earth structure and will provide a continent-wide unalised wavefield for long-period surface wave traveltime and diffraction tomography. Some or all stations of the permanent component of USArray will be equipped as expanded geophysical observatories, with GPS receivers to provide direct real-time data on crustal deformation. The permanent component of USArray will be undertaken in coordination with USGS, complementing the initiative under way at the survey to install an Advanced National Seismic System (ANSS) to improve seismic monitoring in urban areas susceptible to significant seismic hazards.

Plate Boundary Observatory (PBO)—a plate boundary scale network of permanent and portable GPS receivers and strain meters. GPS has revolutionized tectonic geodesy. Over the past 10 years, positional accuracy has increased and instrument costs have dropped to the extent that continuously recording installations are now feasible. Recent advances in GPS monuments coupled with improved data processing strategies have significantly reduced positional errors and changes in baselines so that GPS networks can routinely track plate tectonic and fault-related crustal motions that range from a few millimeters to several centimeters per year.

The geodetic component of EarthScope, PBO, is designed and uniformly image structure beneath the continental United States. Continuous redeployment will cover the entire conterminous United States (lower 48 states) over a period of 10 years. The final result will be the first coherent, high-resolution, plate-scale image of the lithosphere and underlying mantle. After completing coverage in the lower 48 states, the array is scheduled to move to Alaska. Approximately 50 magnetotelluric field systems will be embedded within the array to provide constraints on conductivity, which translate into temperature and fluid content within the lithosphere. The magnetotelluric method is most sensitive to conductors in the crust and upper mantle. Silicate minerals at subsolidus temperatures in the crust are very resistive, so natural electrical currents are attracted to regions of low resistivity. These conductive regions can be caused by solid phases such as graphite and metallic sulfides or oxides, aqueous fluids (especially brines), and partial melt.

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The geodetic component of EarthScope, PBO, is designed
to study the three-dimensional strain field resulting from plate tectonic deformation of the western portion of the North American continent. PBO consists of three elements. The first is a backbone network of ~100 continuously recording GPS receivers deployed at approximately 200-km spacing throughout western United States and southern Alaska to provide a long-wavelength, long-period synoptic view of deformation of the entire plate boundary zone (Figure 3a).

The second element of PBO consists of focused dense deployments of continuously recording instruments (“clusters”) in tectonically active areas requiring greater temporal resolution than that provided by the GPS backbone (Figure 3b). Each GPS cluster consists of an integrated network of GPS receivers and borehole strain meters with nominal spacing of 5-10 km. Approximately 875 permanent GPS receivers and 175 strain meters will be installed around the most active tectonic regions in western United States and southern Alaska, including the San Andreas fault system, and around several magmatic centers (Yellowstone and Long Valley calderas, and volcanoes in Alaska and the Pacific Northwest). Existing geodetic networks in the western United States and Alaska will be fully integrated into PBO forming a single network to monitor strain.

A third element of PBO is a pool of 100 portable GPS systems for deployment in areas not covered by continuous GPS, and for rapid response capability following an earthquake or volcanic activity. Further details on PBO objectives, instrumentation and deployment can be found in the article by Jackson in this issue.

San Andreas Fault Observatory at Depth (SAFOD)—a deep observation well in the San Andreas Fault. 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 many kilometers. Subsurface measurements of material properties and other in-situ conditions provide ground truth information for seismic and geodetic data acquired at the surface. Integration of surface and subsurface data is required to properly characterize zones of deformation such as major fault systems.

SAFOD is designed to be subsurface observatory (Figure 4). It will be drilled to a depth of 4 km, directly into the San Andreas Fault zone through the location of a cluster of frequent microearthquakes and close to the nucleation point of the 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.

Drilling will begin west of the San Andreas Fault. At a depth of 3 km, advanced directional-drilling technologies will be used to guide an inclined hole through the entire fault zone until relatively undisturbed rock is reached on the other side (Figure 4b). 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 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 earthquakes, seismic wave radiation patterns, and rupture mechanics, and to help determine the positions of active fault strands. Fluid pressure will be monitored continuously at carefully chosen depths, and the hole will be logged repeatedly to identify places where the casing may be deforming due to active shear zones. For further information on SAFOD, please see: http://www.icdponline.de/html/sites/sanandreas/index/index.html.
Interferometric Synthetic Aperture Radar (InSAR)—a dedicated satellite capable of providing spatially continuous strain measurements over wide geographic areas. Although GPS has proved a powerful way to study deformation of the 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. InSAR has provided spectacular images of deformation associated with earthquakes and volcanoes. As part of EarthScope a dedicated InSAR satellite mission will provide spatially continuous strain measurements over wide geographic areas. This new capability will enable synoptic mapping of surface displacements before, during, and after earthquakes or volcanic eruptions; imaging of the time evolution of these geologic systems; unique insights into the mechanics of fault loading and earthquake rupture; mapping of strain accumulation across broad tectonic zones potentially highlighting zones of strain concentration; insight into sources, migration, and dynamics of magma movement through a volcanic system leading to eruption; and improve understanding of the rheology of the crust and upper mantle. It is also useful for monitoring subsidence.

**Funding and implementation.** EarthScope is an interagency initiative led by the U.S. National Science Foundation in partnership with USGS and NASA. Funding for the USArray, PBO, and SAFOD facilities will come from NSF through the Major Research Equipment and Facilities Construction (MREFC) account. Funding for an InSAR mission in support of EarthScope science would come through NASA. The NSF MREFC account is used for funding large equipment needs that are beyond the capability of a single division or directorate within NSF. Projects funded through this account go through an extensive review process within the NSF and by the National Science board. Examples of other types of instrumentation funded through this mechanism include radio telescopes, airplanes for atmospheric research, and ships for ocean sciences.

EarthScope is the first earth science project funded through the U.S. NSF MREFC process and represents a significant achievement for the earth science community. Funding for EarthScope facilities is anticipated to begin in fiscal year 2003. If funded, facilities will be constructed over a five-year time frame. Support for scientific research and related activities will be funded through the typical peer review process within the Geosciences Division of the Geoscience Directorate at the NSF. While the initial focus of EarthScope is within the United States, coverage may include portions of Canada, Mexico, and the submerged continental margins in cooperation with United States and international partners and the ocean science community.

**Challenges and opportunities.** EarthScope’s challenges include manipulation of large data volumes, integration and distribution of diverse data types, and development of new visualization/analysis tools, challenges faced routinely within the petroleum and environmental industry. EarthScope provides new avenues and opportunities for collaboration between industry and the academic community and we welcome industry participation and expertise.

In addition, EarthScope offers an unprecedented opportunity to improve science literacy in the United States and to reinvigorate interest in geoscience in elementary through college education. EarthScope should also increase public awareness of science in general, and earth science and geophysics in particular, and improve communication between elementary and secondary schools, community colleges, research institutions, and industry.

A highly visible, science-driven initiative such as EarthScope can capitalize on the public’s natural interest and excitement in earthquakes, volcanoes, and geology, and make these subjects relevant on a region-by-region basis as EarthScope and USArray in particular moves across the country. Over a 10-year period, EarthScope can highlight regional geology, natural resources, and hazards and provide an emerging and changing continental scale image of the subsurface. We anticipate a comprehensive education and outreach program will develop in concert with the research and facility components of EarthScope. This aspect provides an excellent opportunity to collaborate with the SEG K-12 and college initiatives.

**Acknowledgments:** The EarthScope initiative represents the efforts of a broad spectrum of the earth science community working in partnership with NSF, USGS, and NASA. The scientific justification, rationale, and technical requirements were developed through a series of community workshops and are described in a number of white papers and reports. This article draws heavily from these white papers and reports. For further information on EarthScope, additional references, and additional contact information refer to www.EarthScope.org. For further information on ANSS refer to: www.anss.org.

**Corresponding author:** ameltzer@lehigh.edu