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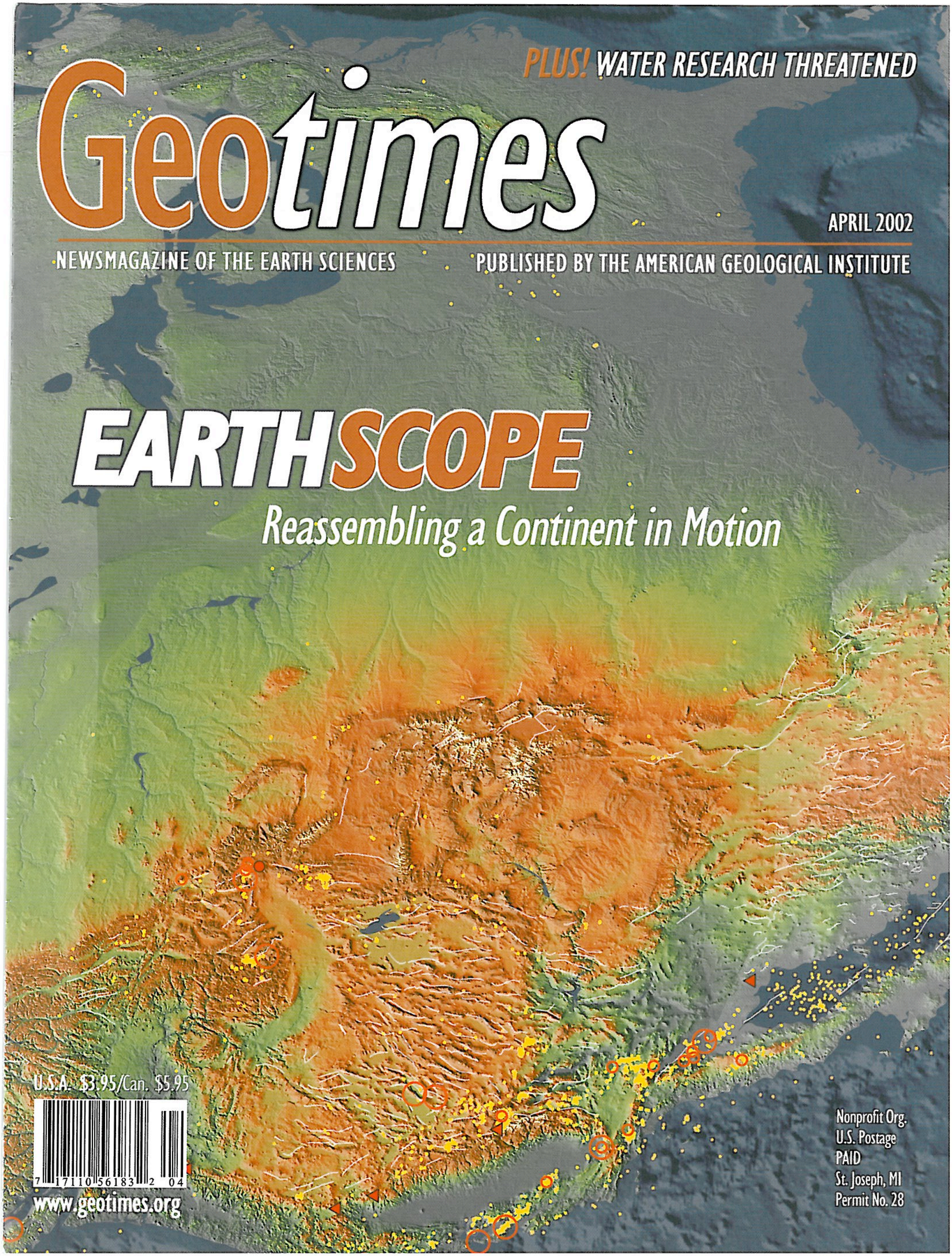
EARTHSCOPE

Reassembling a Continent in Motion



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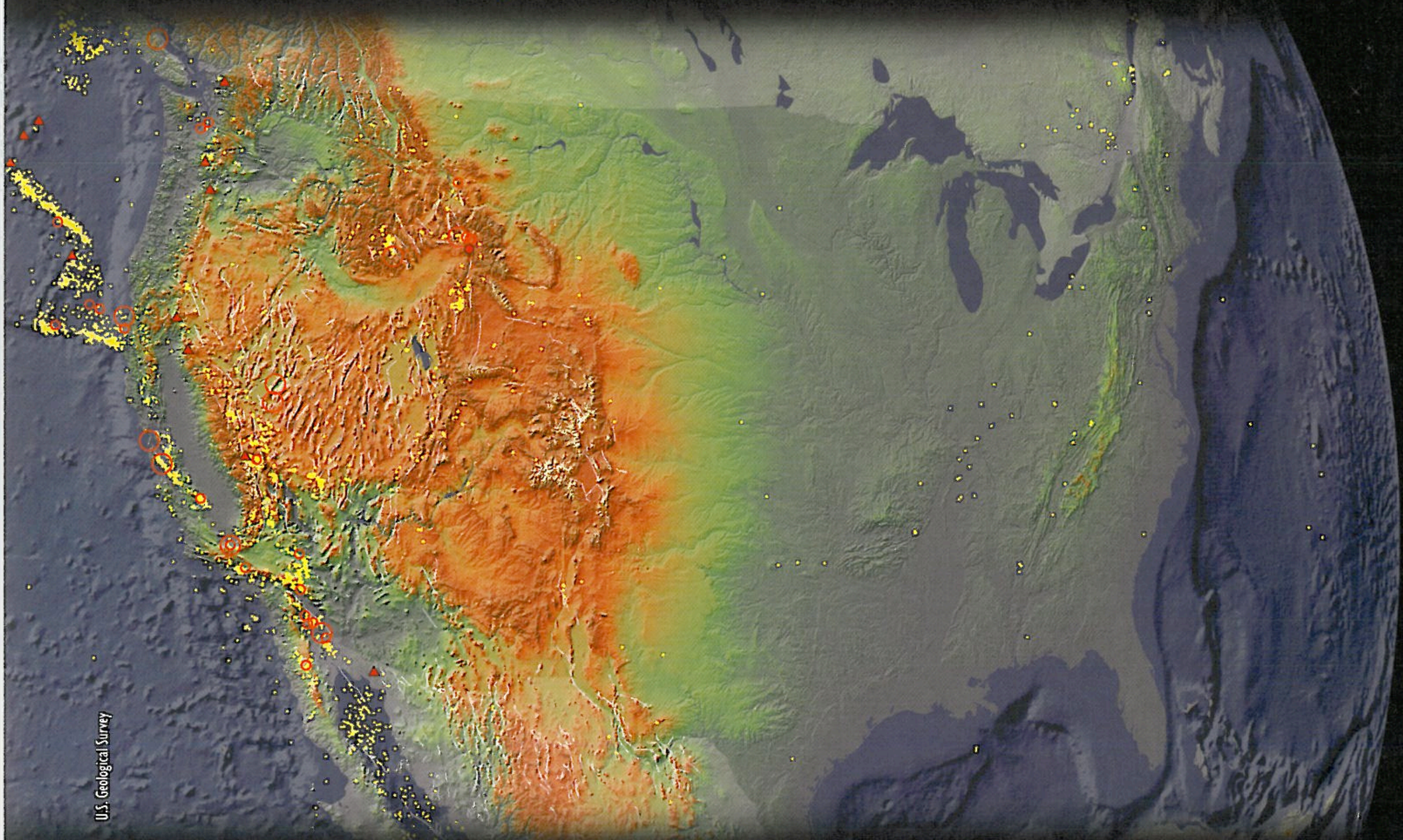
EarthScope

Reassembling a Continent in Motion


U.S. Geological Survey

Gregory van der Vink for the EarthScope Working Group and steering committees

When Thomas Jefferson asked Congress to fund the Lewis and Clark expedition in 1803, we knew little then about western America. The discoveries the expedition made, many unpredicted, led us to appreciate our nation's natural resources, to settle the West and, eventually, establish our national parks.

Now, exactly two centuries later, President Bush is asking Congress to fund an expedition to survey the continent. This time, however, instead of bringing guns, sextants and compasses to map the surface, we will bring seismometers, satellites and GPS receivers to map Earth's interior. Bush is recommending that Congress fund EarthScope, a scientific survey that will "investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions."

Studies of geology have enabled us to infer the geological processes that shaped and continue to shape our continent. Now technology can allow us to watch these processes on a human time scale, even as short as an academic school year. EarthScope will create a dataset that many researchers can use. The work we do with this data will not only help us to advance our understanding of how the North

American continent formed. It will also make it possible to map the continent's structure and how that structure is changing.

The president's fiscal year 2003 budget request for the National Science Foundation (NSF) asks Congress to approve $35 million for EarthScope within NSF's Major Research and Facilities Construction Account. Through this account, the EarthScope infrastructure will be constructed over five years. NSF and other agencies will fund individual EarthScope research projects, which will draw on the comprehensive EarthScope dataset.

Ten years in development, EarthScope has grown from unprecedented, multidisciplinary cooperation among hundreds of scientific and educational institutions. It capitalizes on new broadband seismic sensors developments in GPS technologies, reduced telecommunication costs, and a data distribution infrastructure. It will collect and integrate scientific information derived from geology, seismology, remote sensing and geodesy, the science of measuring Earth's surface features.

An array of 400 seismometers will move across the contiguous 48 states and Alaska, occupying 2,000 locations over 10 years to assemble an image of the internal structure of the continent and underlying mantle from "crust to core." The array will investigate earthquakes, volcanoes, and active mountain-building in Alaska and the West. In the eastern United States, the array will study the early development and roots of our continent, imaging the deep Earth for clues about the origin of our magnetic field and the driving mechanisms of plate tectonics.

A network of GPS receivers will continuously record their positions on the surface relative to the GPS satellites orbiting Earth. Sensitive bore-hole strain meters will measure the change in stress along the plate boundary of the western United States and Alaska. These sensors will measure how the North American crust is deforming, what motions occur along faults, how earthquakes start and how magma flows beneath active volcanoes.

EarthScope will work with NASA to monitor the continent from space with Synthetic Aperture Radar. These data will map changes in Earth's surface before, during and after major earthquakes and volcanic eruptions.

An observatory that will be placed 4 kilometers deep into the San Andreas fault will provide the first opportunity to watch directly the conditions under which earthquakes occur, to collect fault rocks and fluids for laboratory study, and to monitor continuously an active fault zone at depth.

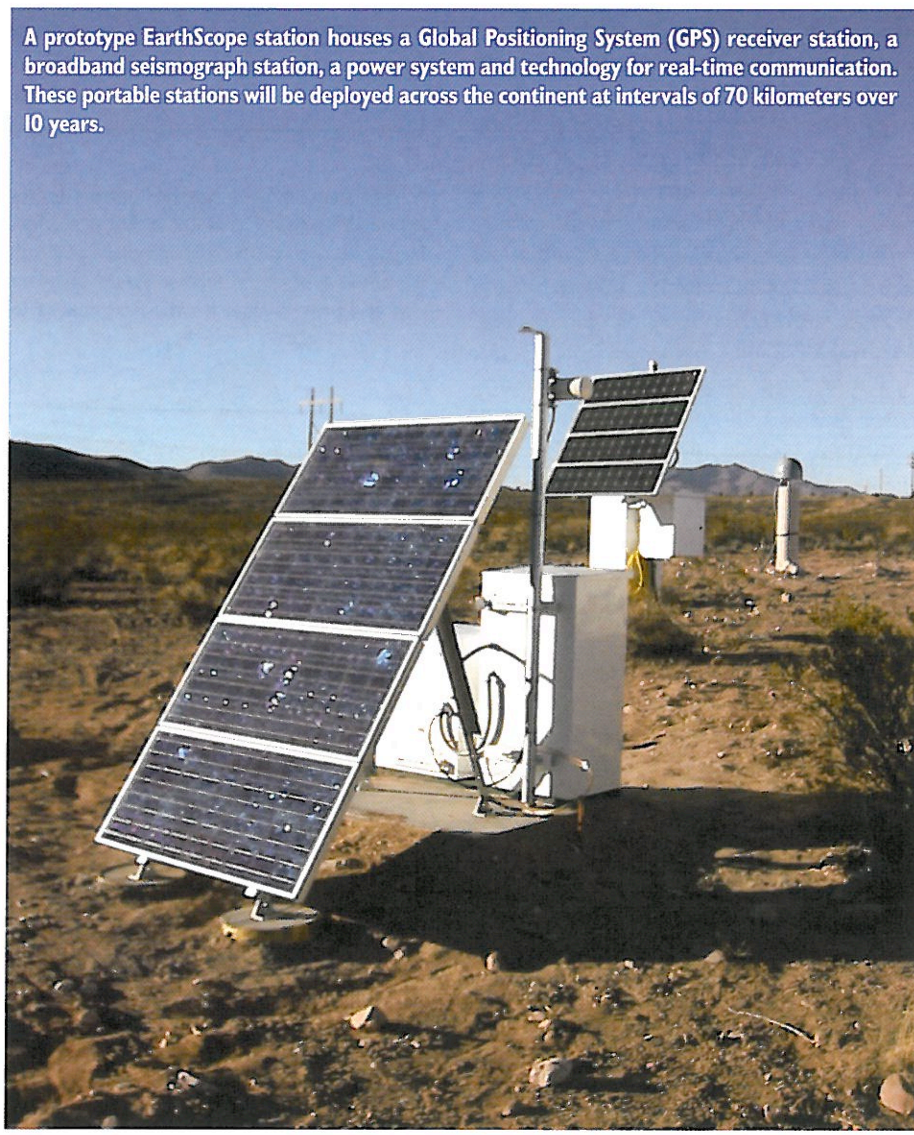
Data from all EarthScope components will be integrated to produce models of continental structures and to determine how those structures evolve. The seismological and drilling components will yield detailed images of Earth below the surface. The GPS, strain meter and radar images will allow us to view changes in those structures through time.

For the first time, we will be able to measure geological processes at the continental scale within the time frame of human life. All data from EarthScope will be available to the public in real-time to maximize participation from the scientific community and to provide ongoing educational opportunities for students of all ages.

Our national infrastructure is growing at an exponential rate in many areas of high seismic risk.

Unanswered questions

While plate tectonics has provided us with a strong framework for our general understanding of Earth, many questions persist about the structure of the North American landmass, how it was formed and what forces are acting upon it. How are the complex fault systems of the western



A prototype EarthScope station houses a Global Positioning System (GPS) receiver station, a broadband seismograph station, a power system and technology for real-time communication. These portable stations will be deployed across the continent at intervals of 70 kilometers over 10 years.

United States organized to accommodate overall tectonic plate motions between the Pacific and North American plates? To what extent is mantle underplating responsible for relatively thick crust in the Basin and Range (30 kilometers), despite 200 to 300 kilometers of crustal extension? How did the Rocky Mountains form and what role does mantle flow play in supporting them? Is earthquake activity in the "stable" mid-continent region near New Madrid, Mo., related to the early development of the North Atlantic Ocean more than 500 million years ago?

Seismic and geodynamic models of the mantle suggest that a major feature beneath the North American plate is the Farralon plate, a piece of oceanic lithosphere that was subducted beneath the continent. Images derived from EarthScope seismic data will make it possible to determine more precisely the effect the subducted Farralon plate has on North American geology. Preliminary GPS measurements suggest little deformation in the North American continent east of the Rocky Mountains. EarthScope GPS measurements will address the apparent discrepancy between the lack of strain accumulation east of the Rockies and the historic record of large earthquakes in areas such as New Madrid, Mo., and Charleston, S.C.

The tectonic history of North America spans at least 3 billion years. Models for its formation include plate tectonic mechanisms, such as the collision of island arcs; and non-plate tectonic mechanisms, such as large-volume magmatism associated with mantle-plume eruptions. The formation of continents, the mechanical response of continents to the forces of mantle convection and plate tectonics, and the long-term survival of continents at Earth's surface are intimately linked to crustal properties, and to interactions between the crust and the underlying mantle. EarthScope will provide the first continuous, high-resolution images of the lithosphere at the continental scale to allow us to determine the structure, deformation and evolution of the North American continent.

Quakes: More people, more risk

Our national infrastructure is growing at an exponential rate in many areas of high seismic risk. The cost of earthquakes — and the federal government's liability — is growing proportionally. For example, the ten-fold increase between the cost of the 1971 San Fernando earthquake ($2 billion) and the 1994 Northridge event ($20 billion) in southern California mostly can be attributed to the region's increase in wealth density over that time. A repeat of the magnitude-8.0 earthquakes that hit along the Mississippi River in the central United States from 1811 to 1812 today would result in losses exceeding $100 billion.

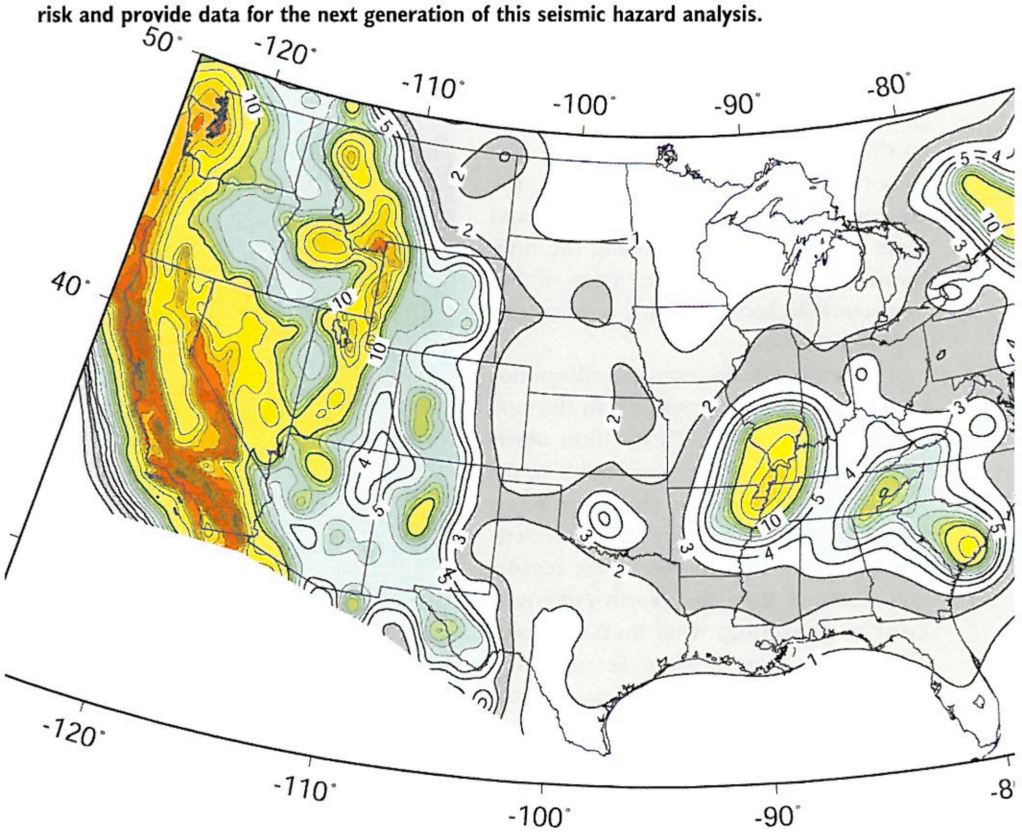
Our cities and towns are being built over complex fault systems consisting of hundreds of independently moving sections, many of which remain unidentified. These systems are not just along the plate boundary of the western United States and Alaska. Zones of weakness prone to earthquakes are known to exist along the Mississippi River, the coastal regions of the southeastern United States, and in parts of New England and the North American seaboard. The historical record of North America's earthquakes is short, and other such zones may have been subject to large, but as yet unrecognized, pre-historical earthquakes.

It now lies within our grasp to forecast the critical aspects of earthquakes.

We have seen major progress over the past decade in understanding how faults rupture and what ground motions earthquakes generate. But what remains remarkably incomplete is our understanding of what controls an earthquake's size, why great earthquakes occasionally strike plate interiors, and when and where the next major events might occur.

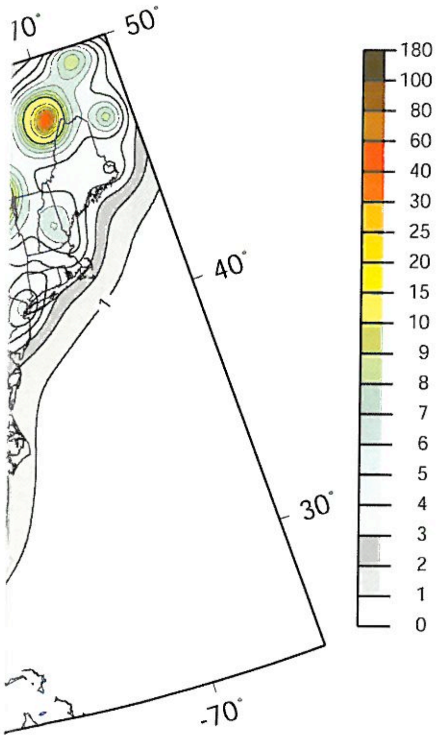
Seismic hazard analysis is a strong benefit of EarthScope's multidisciplinary, integrative approach. Seismic data will provide fault locations, fault geometries, seismic velocities and subsurface structure. Geodesy, coupled with geochronology and

A USGS map showing possible ground motion during earthquakes, specifically the peak ground acceleration that has a 10 percent probability of being exceeded in 50 years. Such maps, based largely on the relatively brief record of North American seismicity, are used for developing building codes and other seismic safety standards. EarthScope data will help identify new areas of risk and provide data for the next generation of this seismic hazard analysis.



paleoseismology, will provide regional deformation patterns and fault slip rates. Drill-hole data, combined with seismic recordings, will be tools for developing fault rupture scenarios needed for ground-motion simulations. Ground motion measurements are key for designing structures that can withstand earthquakes. Individuals and groups of scientists will have access to a large, integrated dataset for new research programs and activities.

It now lies within our grasp to forecast the critical aspects of earthquakes, including probable locations of future, major events, and characteristics of the ground motions they could generate. EarthScope will help us identify areas where earthquakes are likely to occur and zones of deformation that contribute to regional seismic hazards. The EarthScope dataset will help us measure rates of deformation, install measuring stations on an active fault, and search for evidence of sudden changes in strain or precursors that may presage potentially damaging events. EarthScope may reveal whether slow stress waves from one earthquake 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 created by past geological events.



U.S. Geological Survey

Volcanoes: Watching magma

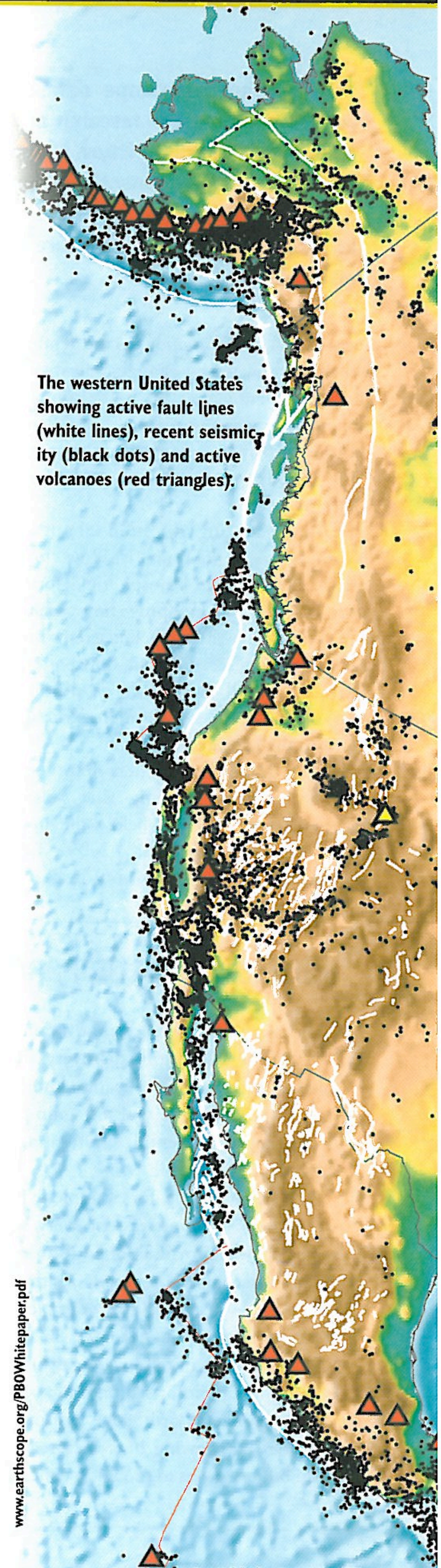
Volcanic eruptions threaten more than 10 million people in the Pacific Northwest and Alaska, and can endanger airline routes by choking jet engines with ash. Volcanism also builds new continental crust either *in situ* or through the development of island arcs on oceanic crust that are later accreted onto a continent. In addition, the melt chemistry and xenoliths (fragments of the lower crust and mantle rocks) of volcanic systems offer a window into the lower crust and upper mantle.

We can use EarthScope's seismic and geodetic data to quantify how quickly magma accumulates in the upper crust beneath the several active volcanoes in the Aleutian and Cascade arcs. Using these data, we will be able to determine whether the accumulation is steady — over the time-scale of a few years — or episodic. Does new magma move in a continuous trickle or as discrete blobs?

Along the active subduction zones of Cascadia and Alaska, EarthScope's seismic data will be used to construct 3-D tomographic images of the down-going slab, the asthenospheric wedge and the crust of the overriding plate. Changes in velocity and attenuation are sensitive indicators of temperature and the presence of melt. EarthScope may also detect vibrations induced by the flow of magma and the breaking of rock as magma flows through it.

A map beneath the surface

Although we know that the lithosphere and mantle both play important roles in continental dynamics, we still know little about the structure beneath continents. EarthScope will provide the first high-resolution, tomographic images of Earth's interior at the continental scale, linking geologic features on the surface to struc-



The western United States showing active fault lines (white lines), recent seismicity (black dots) and active volcanoes (red triangles).

www.earthscope.org/PBOWhitepaper.pdf

Through the EarthScope dataset, we can combine our research and create an integrated picture of the North American continent's formation and structure and, more importantly, how that structure is deforming and changing.

tures deep below. Variations in the depths at which seismic waves change velocities in the upper mantle are clues to the composition, temperature and chemistry of different tectonic provinces. EarthScope data will allow us to map these regions at a high resolution.

A long-standing question about the North American continent is: How closely are mantle flow and lithospheric deformation linked? By mapping how seismic waves change as they travel different directions, we can discern mantle flow patterns. EarthScope will give us the multi-directional data we need to map structures beneath the continent.

Going deeper, researchers have occasionally reported finding that seismic waves change velocities below the upper mantle at depths of 1,000, 1,200 or 1,800 kilometers. Such discontinuities could have a significant impact on our modeling of convection and flow within the mantle. Understanding the processes that occur along the boundary between the mantle and core is essential to modeling the mantle, the geodynamo and Earth's magnetic field. Some studies of the deep Earth have suggested that the structure of the inner core varies at differing scales. Measuring how fast and in what form seismic waves from distant earthquakes travel through inner core, EarthScope provide high-resolution information about the structure and composition of our planet's deepest interior.

The work of many

If Congress approves funding for EarthScope, NSF will issue project solicitations through its Major Research and Equipment and Facilities Construction Account for constructing and operating EarthScope. NSF will fund ongoing operations and research through its Earth Sciences Division and Geosciences Directorate. Consistent with their usual mode of research funding, NSF and other agencies will announce funding opportunities for individuals and groups. EarthScope will be a large dataset for all researchers. Through the EarthScope dataset, we can combine our research and create an integrated picture of the North American continent's formation and structure and, more importantly, how that structure is deforming and changing.

Just as the Lewis and Clark expedition blazed the trail for future settlers and traders, we will collect the dataset for the next generation of geoscientists and educators. EarthScope will directly address many questions about the structure and evolution of the continent. But perhaps one of the most exciting outcomes of EarthScope will be the discoveries that at this point remain unpredictable.

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van der Vink is Director of Planning for the Incorporated Research Institutions for Seismology, a consortium of universities dedicated to exploring Earth's interior by collecting and distributing seismic data.

The EarthScope program plan and the ideas presented in this article have been developed by a broad segment of the U.S. university community — in collaboration with NSF, the U.S. Geological Survey and NASA — through a series of steering committees and workshops. For more information about the EarthScope program and participants see www.EarthScope.org.

Data for Education and Outreach

Although the primary motivation for EarthScope is the fundamental advance of scientific discovery, the initiative is also a unique opportunity for earth science education and for reaching out to the general public. EarthScope will be a tool for communicating both the results that emerge from a national scientific effort, and perhaps as importantly, the nature of the scientific method.

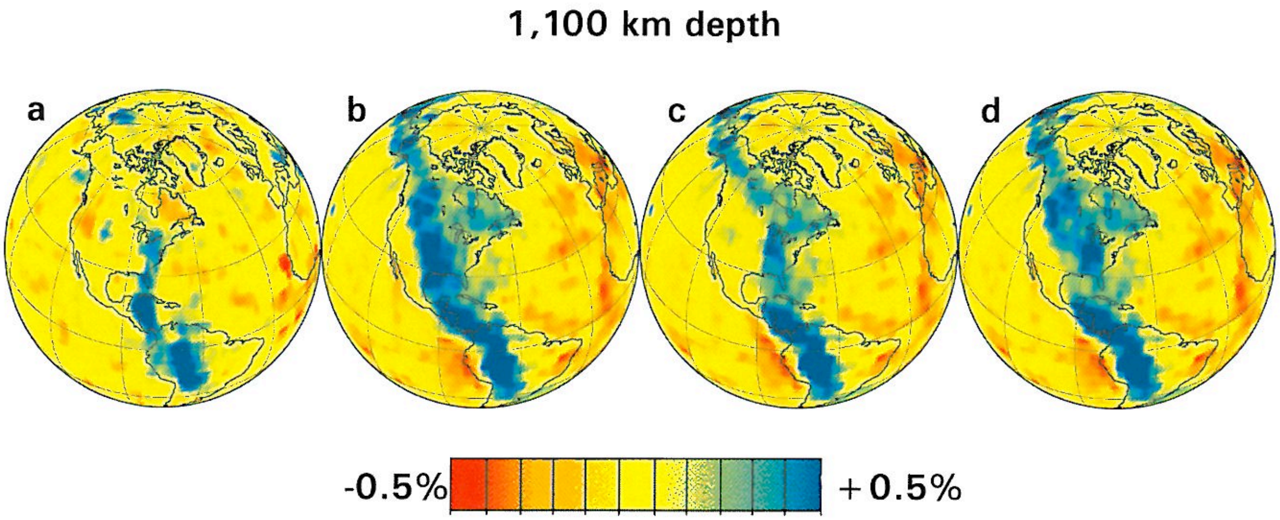
The seismic array, for example, will move across the nation with station spacing of 70 kilometers. In every state, local education institutions will serve as hosts, providing opportunities for students to participate directly in a national science experiment occurring in their own backyard. The process will provide a compelling example of how our scientific understanding advances as new data become available and new hypothesis are tested.

EarthScope will publicize real-time access to all data as they are collected and provide information on experiment goals, key geoscience concepts and discoveries. EarthScope will provide educational links between communities by showing how data recorded in one region merges with data from other regions to provide a coherent picture of the continent and Earth.

G. Van der Vink

IRIS Consortium

Students learn about earthquakes at the IRIS Consortium headquarters in Washington, D.C.



Modified from an article by Hans-Peter Bunge and Stephen P. Grand in the May 18, 2000, Nature

Data suggest that old ocean lithosphere exists in the mantle about 1,100 kilometers below North America. This old lithosphere was once part of the Farralon Plate. EarthScope images can be tools for determining the structure and composition of this subducted material and its effect on the geology of the North American continent.

EarthScope in Review

Last year, the National Research Council published a report on the proposed EarthScope project. The report, entitled Review of EarthScope Integrated Science, *was requested and funded by the National Science Foundation. It was produced by a committee led by George Hornberger of the University of Virginia. The following excerpts are reprinted with permission from the National Academy of Sciences.*

"The committee concludes that EarthScope is an extremely well articulated project that has resulted from consideration by many scientists over several years, in some cases up to a decade. During that time, the proponents have become experts, not just in the observing technology but in the data handling and retrieval systems that are necessary to manage information on this vast scale."

"EarthScope has the potential of providing scientific and technological leadership to the world's seismological community. This integrated system for looking into the subsurface realm of a significant part of the North American continent could be used as a model for the other continents — Africa, Asia, Europe, Australia, South America and Antarctica."

"The committee concludes that EarthScope will have a substantial impact on earth science in America and worldwide. It will provide scientists with vast amounts of data that will be used for decades."

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

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

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

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

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

Read the National Academies report online at www.nap.edu/catalog/10271.html