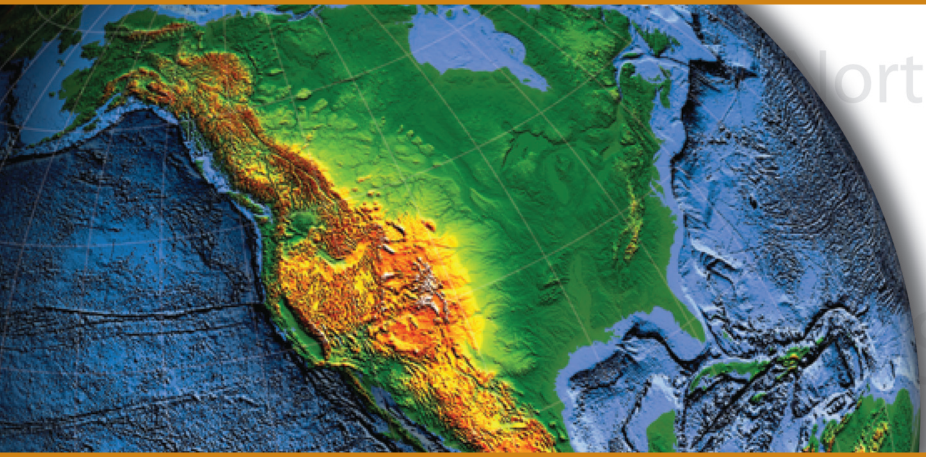
earthscope



orth American Continent
Unlocking the Secrets of the North America
Secrets of the No

# Unlocking the Secrets of the North American Continent

## An EarthScope Science Plan for 2010–2020

Please refer to this document as:
Williams, M.L., K.M. Fischer, J.T. Freymueller, B. Tikoff, A.M. Tréhu, and others, Unlocking the Secrets of the North American Continent: An EarthScope Science Plan for 2010-2020, February, 2010, 78 pp.

See page 75 for a list of workshop participants and page 78 for the writing team and other contributors.

# Unlocking the Secrets of the North American Continent

## An EarthScope Science Plan for 2010–2020

February 2010

# CONTENTS

# I. EXECUTIVE SUMMARY

EarthScope is an ambitious, multifaceted program to investigate the structure, dynamics, and history of the North American continent. Of all the bodies in our solar system, Earth is unique because of the presence of both liquid water and mobile tectonic plates. Interactions between the tectonic plates have produced the continents and ocean basins that distinguish our planet and the mineral and fossil fuel resources that support our standard of living. Active tectonic processes are also responsible for devastating hazards such as earthquakes and volcanic eruptions, and control Earth's surface topography, which fundamentally affects the climate and environment.

*EarthScope's vision is to use North America as a natural laboratory to gain fundamental insight into how Earth operates.*

EarthScope's vision is to use North America as a natural laboratory to gain fundamental insight into how Earth operates. The complexity of geologic processes requires contributions from investigators across the Earth sciences, working both as individuals and as members of multidisciplinary collaborative teams. The goal is to enable and encourage scientists to study Earth in creative new ways, allow innovative ideas to thrive, and ultimately provide new insights into the past, present, and future of the planet we live on.

EarthScope provides researchers with rich data sets to image, sample, and monitor the continent and underlying mantle at a resolution never before attempted. For example, the data are enabling multidisciplinary studies to test whether past and present-day subduction along the western margin of North America affects the entire continent (*Sidebar 1*) and are revealing new modes of slip along faults that may improve earthquake forecasts (*Sidebar 2*). In addition to the original objectives of the program, which focused on solid Earth dynamics, new objectives have emerged in the past few years related to interactions between Earth's interior and the cryosphere, hydrosphere, and atmosphere. New data processing and distribution capabilities are being developed to rapidly and freely provide researchers everywhere with raw and processed data "products," thus facilitating multidisciplinary integration of data and models.

The purpose of this science plan is threefold. First, the plan outlines a wide range of exciting scientific research directions to be explored in the coming decade. Second, it provides an overview of recent discoveries enabled by the young EarthScope program and a sampling of important questions yet to be answered. Third, it provides recommendations that will better enable the EarthScope community to answer these questions. EarthScope is a framework for discovery; just as many of the recent breakthroughs and outstanding questions were not explicitly anticipated when EarthScope was conceived, new discoveries and whole new research directions will certainly arise over the duration of the program.

## EARTHSCOPE RESEARCH OBJECTIVES

Many of the initial EarthScope investigations have focused on the active tectonic systems of the western United States. They include acquisition of the first samples from the seismogenic zone of an active fault and real-time, near-field observations during an earthquake through EarthScope's San Andreas Fault Observatory at Depth (SAFOD). The SAFOD drill hole is currently being offset by slow-motion creep along the fault, observable in detail for the first time with the SAFOD facility. These direct observations, combined with detailed reconstructions of fault histories enabled by images of high-resolution topography obtained through GeoEarthScope, are forcing researchers to re-evaluate theories about the faulting process.

# SIDEBAR 1. SUBDUCTED PLATES AND THE HISTORY OF NORTH AMERICA

Continents are shaped by their tectonic history. For North America, the dominant tectonic process over the past 200 million years has been the subduction of Pacific Ocean lithosphere beneath the western edge of the westward-moving continent. This subduction continues to the present beneath the Pacific Northwest and Alaska (A). The remnants of this subducted lithosphere appear as fast (and presumably cold) mantle velocity anomalies that extend all the way to the core-mantle boundary (B). Beneath the United States, much of this anomaly has been interpreted as the subducted Farallon plate plus fragments of adjacent plates, although the detailed trajectories of different plates are still vigorously debated.

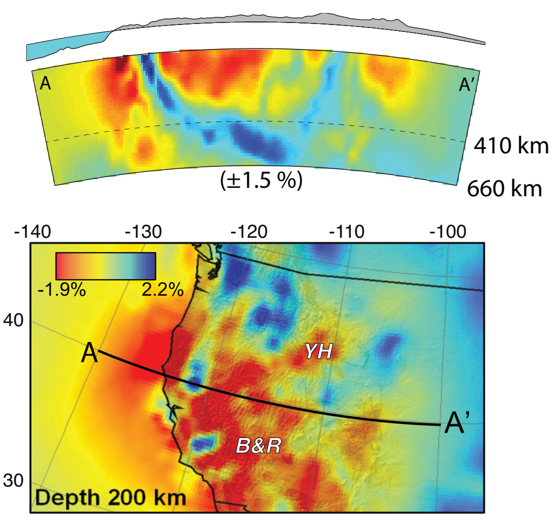
These subducted plate fragments have strongly influenced western U.S. magmatism and landform evolution. Dynamic subsidence caused by the sinking plate matches the inundation of a seaway that penetrated into the interior of the western United States during the Cretaceous (65 to 145 million years ago) and the more recent subsidence history of the eastern U.S. coastline (see *Section 3.7.2*). North America may have driven over the Farallon plate long ago, but this cold body still haunts us!

## References

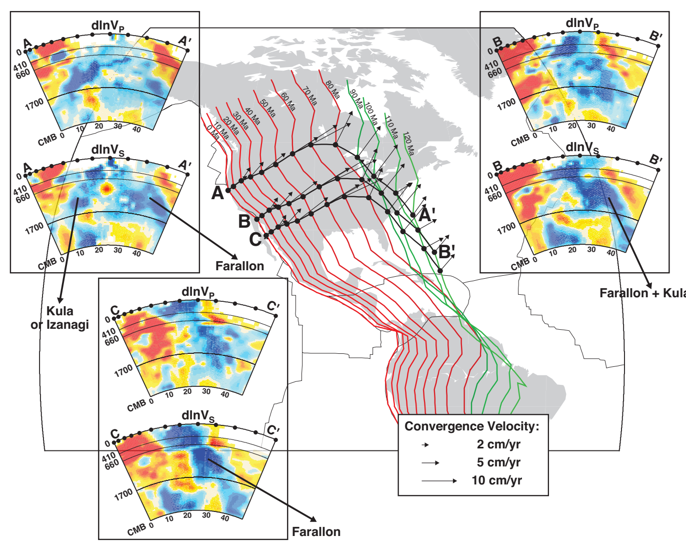

Burdick, S., C. Li, V. Martynov, T. Cox, J. Eakins, T. Mulder, L. Astiz, F. L. Vernon, G.L. Pavlis, and R. van der Hilst, Upper mantle heterogeneity beneath North America from travel time tomography with global and USArray transportable array data, Seis. Res. Lett., 79, 384–392, doi: 10.1785/gssrl.79.3.384, 2008.

Burdick, S., R.D. van der Hilst, F.L. Vernon, V. Martynov, T. Cox, J. Eakins, T. Mulder, L. Astiz, and G.L. Pavlis, Model update December 2008, Seis. Res. Lett., 80, 638–645, 2009.

Ren, Y., E. Stutzmann, R. van der Hilst, and J. Besse, Understanding seismic heterogeneities in the lower mantle beneath the Americas from seismic tomography and plate tectonic history, J. Geophys. Res., 112, B01302, doi:10.1029/2005JB004154, 2007.


**A.** Cross section (top) and map at 200-km depth (bottom) showing P-wave velocity structure from tomographic inversion of travel-times observed on USArray and other seismic stations. As the USArray Transportable Array migrates, these models are periodically updated and made publicly available (Burdick et al., 2008, 2009). Colors indicate the percent departure from a reference velocity versus depth profile. Blues (relatively high velocities) are often interpreted as anomalously cold regions. Reds may indicate higher temperatures.




**B.** Profiles through P- and S-wave velocity models derived prior to availability of EarthScope data (Ren et al., 2007). Red and green lines represent past boundary positions between Pacific Ocean seafloor and American continents since 120 million years ago. Black lines are different cross-section locations. Arrows represent velocities and directions of convergence at different ages, computed in the hotspot reference frame. Labels name plate fragments interpreted to correspond to velocity anomalies. Resolution of subducted lithosphere and the connection between anomalies in the upper and lower mantle will dramatically improve as more and more Transportable Array data are incorporated into the models.

The Plate Boundary Observatory (PBO—a network of continuous GPS sites, borehole strainmeters and seismometers, and tiltmeters) and the USArray Transportable Array (TA—a network of 400 broadband seismometers at 70-km spacing that is migrating east across the continental United States and is scheduled to move to Alaska in 2014) are measuring deformation and Earth structure associated with plate interactions across the western United States and Alaska on time scales ranging from milliseconds to millions of years. The USArray TA has now covered nearly half the contiguous United States, providing data that are being used to construct high-resolution, three-dimensional models of the continental crust and underlying mantle. The research derived from these facilities is revealing geological processes at scales ranging from continental (e.g., warping of surface topography by deeply subducted lithospheric plates), to regional (e.g., fault motion through episodic slip and non-volcanic tremor along the Cascadia subduction zone on the West Coast; newly recognized "drips" of lithosphere from the base of the continental plate), and the local (e.g., the eruptions of Mt. St. Helens and Augustine volcanoes). All of these scales are relevant to mitigating geological hazards and understanding earthquake cycles, volcanism, and their interactions.

*EarthScope provides researchers with rich data sets to image, sample, and monitor the continent and underlying mantle at a resolution never before attempted.*

The great success of EarthScope in the western United States underscores even greater potential for the future. As USArray TA continues across the mid-continent and to the East Coast, and as new collaborations between geophysicists and geologists gain momentum, EarthScope scientists will investigate and illuminate the history of the North American continent from its formation nearly four billion years ago to the present. North America has progressively grown through a punctuated history that includes two full cycles of continental collision, accretion, and rifting, and this history is written in the rocks. Understanding this geological history is critical for at least three reasons. First, the eastern United States faces seismic hazards that result from movement on geologic structures inherited from older tectonic events (e.g., major earthquakes have occurred historically in South Carolina, Missouri, and New England). Second, some past geologic events resulted in mineral or fossil fuel deposits (e.g., the zinc-lead deposits in the Midwest, which formed during formation of the Appalachian mountains approximately 300 million years ago). Third, processes currently occurring at great depth beneath the western United States cannot be directly observed but have signatures in rocks that have been uplifted and exposed in the older mountain belts of the eastern United States.

Looking further ahead, Alaska provides a rich target for EarthScope. Active plate-boundary deformation is distributed across most or all of Alaska. Its southern margin is a subduction zone that experiences extremely large earthquakes and volcanic eruptions. The region also has a well-developed continental collision belt, where the Yakutat terrane collides with coastal Alaska and forms the St. Elias Range. With peaks reaching almost 6000 m (19,500 ft), the St. Elias Range influences the atmosphere and results in a feedback loop between erosion and uplift. A large segment with a nearly flat subducted slab that underlies a large part of Alaska may be an analog for the western United States during a critical period, the Laramide orogeny (~70 million years ago), when the Colorado Plateau and present Rocky Mountains developed. The active Aleutian volcanic arc will provide essential information about the generation of arc magmas, relationships between volcanism and active faults, fluid-rock interactions, and earthquake and volcanic hazard mitigation.

While our community has defined many specific targets for EarthScope investigations, the next decade of the EarthScope experiment will also yield important unanticipated discoveries. EarthScope facilities are producing data streams that are broad, deep, and accessible to all. The facilities were designed to study the solid Earth, but the data are increasingly being used to monitor and measure a much wider variety of phenomena. Some of the most exciting discoveries, and perhaps those with the greatest impact on society, may come from scientists using EarthScope data in new ways. Examples of such uses already include monitoring soil moisture, atmospheric water vapor, and glacier collapse.

## EDUCATIONAL OPPORTUNITIES

The continent-wide footprint of EarthScope experiments and discoveries will provide unique opportunities to raise the scientific literacy of all Americans and excite a new generation of students. USArray will bring a seismometer to every county in the United States, and EarthScope models will explain natural phenomena that are of broad public interest, especially when the results have a local connection. The ability of a hometown seismometer to detect an earthquake in Haiti or a volcanic eruption in Alaska helps to connect people and countries, and highlights the importance of research that may initially seem abstract. Many important public decisions are based on Earth science. In light of statistics documenting declining public interest in science, it is essential to seize the opportunities provided by EarthScope both in formal education venues and in the informal venues of parks, museums, the worldwide web, television, and local newspapers.

*Some of the most exciting discoveries, and perhaps those with the greatest impact on society, may come from scientists using EarthScope data in new ways.*

The initial EarthScope education and outreach plan, as well as activities promoted by the EarthScope National Office and the EarthScope facilities, have made a strong start at reaching schools, colleges, and the general public through activities such as development of teaching materials for K–16 teachers and workshops to train them in the use of these materials, placement of *Active Earth* kiosks in parks and museums, involvement of college students in initial siting of new USArray sites, and a program to "adopt" seismic stations as USArray migrates. Opportunities will increase as USArray reaches the dense population centers and numerous colleges and universities of the eastern United States.

## INTERDISCIPLINARY AND TRANSFORMATIVE SCIENCE

EarthScope can have a transformative effect on the way that geoscience research is conducted. Although some key EarthScope projects involve single researchers pursuing relatively discipline-specific objectives, many projects require integration of data from a broad variety of disciplines. Integration of geological data, geophysical data, and geodynamic models, and collaboration among geologists, geophysicists, and geodynamicists, have been goals from the beginning of EarthScope. To understand the tectonic history of North America, geophysical models require the context of time and rock properties that geologic studies provide, and geological data require the three-dimensional spatial context that geophysical data provide. Geological, geochemical, geochronological, and geophysical data are all essential to achieving EarthScope's broad goals. As the USArray TA moves eastward, collaboration and integration will be increasingly important as the interpretation of geophysical models will increasingly reflect the combination of present-day mantle flow and the long history of lithospheric evolution recorded in the geology.

The recognition that aspects of surficial topography, hydrogeology, and even climate and atmospheric processes are linked to mantle flow and to the geometry of tectonic plates long since subducted greatly expands the intellectual breadth of EarthScope studies and the necessity of broad-based, collaborative research. These types of collaborations have faced challenges within existing institutional structures and funding models even though they are increasingly recognized as essential for solving many critical problems facing society. EarthScope will pioneer new methods for the physical integration of data sets and for overcoming institutional and intellectual boundaries to truly interdisciplinary research.

## RECOMMENDATIONS

The EarthScope program offers unprecedented opportunities within the geosciences because the scale of the facility allows observations that were simply not available prior to its initiation. The potential for new discoveries is a major strength of the EarthScope program, and the facilitation of creative, transformative science should remain the intellectual core of the enterprise. To foster this approach and to reflect the wide range of EarthScope science, we offer these general recommendations.

## SIDEBAR 2. TIMES SCALES OF SLIP ON FAULTS

The past decade has revealed previously unknown phenomena related to slow slip on faults.

**A.** Slow slip ranges over several orders of magnitude in duration and has a scaling relationship with seismic moment that is distinct from that of normal earthquakes. Low-frequency earthquakes (LFE) and very-low-frequency (VLF) events are recorded by broadband seismometers and show spectra deficient in high frequencies; slow slip events (SSE) and silent earthquakes (SEQ) are recorded by GPS instruments and represent slip that would be comparable to an earthquake with M>6 if the slip had occurred within seconds. In many places (e.g., Cascadia), slow slip is accompanied by an increased level of seismic tremor and occurs at quasi-regular intervals, a phenomenon commonly called episodic tremor and slip (ETS). (adapted from Ide et al., 2007)

**B.** Correlation between slow slip and seismic tremor. Slow slip is indicated by a change in the direction of motion, leading to a saw-tooth pattern over time in the GPS data. The number of hours of tremor/day increases dramatically during a slow slip event. (updated from Rogers and Dragert, 2003)

**C.** Tremor activity (left) and slip distribution (right) during a slow slip event in Cascadia (Wech et al., 2009).

**D.** Examples of tremor and an LFE that occurred at the same time on January 31, 2007 (Kao et al., 2009).

Defining the temporal and spatial migration patterns of ETS in the Cascadia and Aleutian subduction zones is a major objective of EarthScope. ETS is occurring down dip of the part of the plate boundary thought to rupture in great subduction zone earthquakes. Understanding what controls the boundaries of "patches" that slip in discrete ETS events and whether slip on one "patch" triggers slip elsewhere on the plate boundary may lead to a better understanding of megathrust dynamics and more accurate seismic hazard assessments.

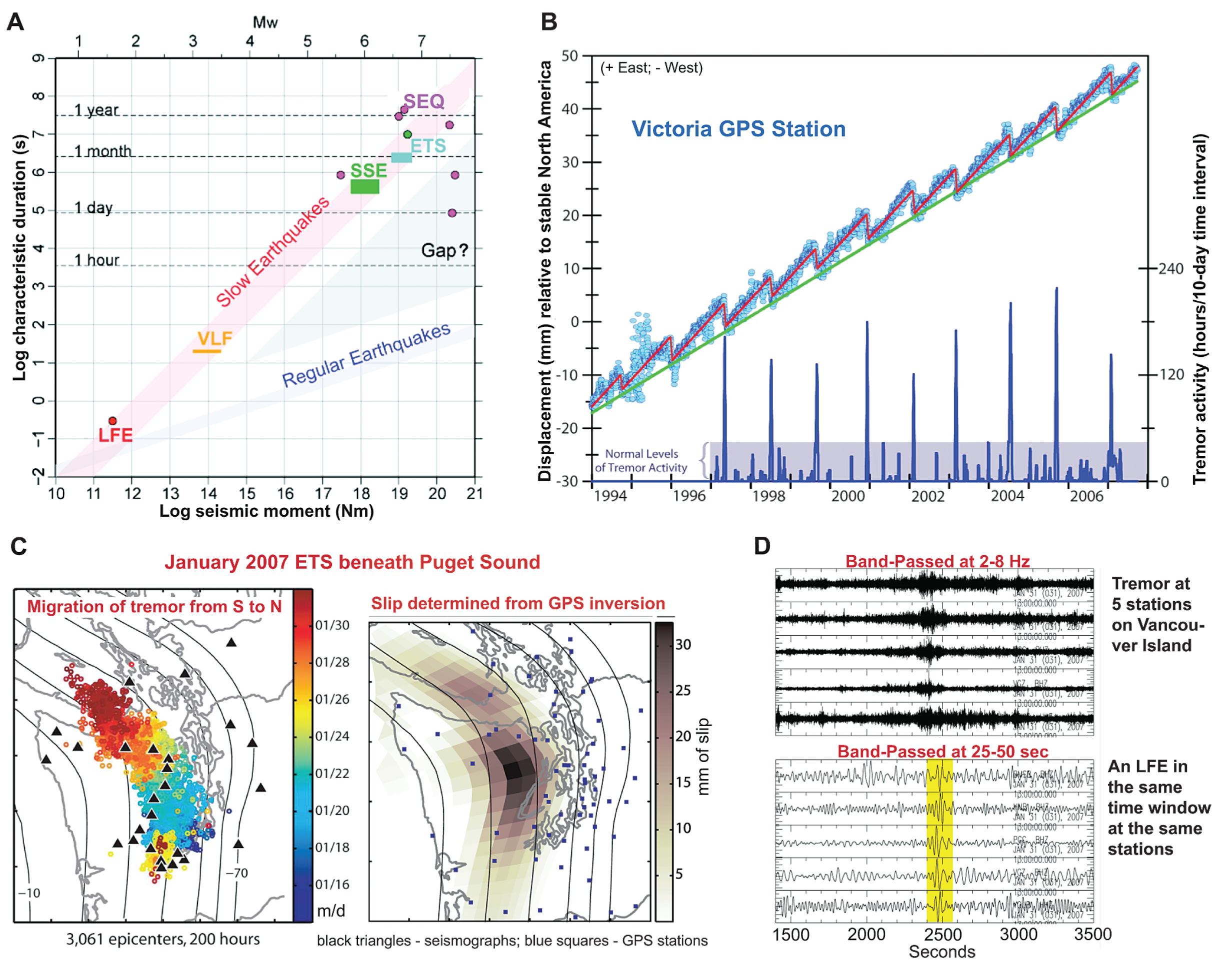
### References


Ide, S., G.C. Beroza, D.R. Shelly, and T. Uchide, A scaling law for slow earthquakes, Nature, 447, 76–79, 2007.

Kao, H., S-J. Shan, H. Dragert, and G. Rogers, Northern Cascadia episodic tremor and slip: A decade of tremor observations from 1997 to 2007, J. Geophys. Res., 114, B00A12, doi:10.1029/2008JB006046, 2009.

Rogers, G., and H. Dragert, Episodic Tremor and Slip on the Cascadia Subduction Zone: The Chatter of Silent Slip, Science, 300:5627, 1942–1943, doi: 10.1126/science.1084783, 2003.

Wech, A.G., K.C. Creager, and T.I. Melbourne, Seismic and geodetic constraints on Cascadia slow slip, J. Geophys. Res., 114, doi:10.129/2008JB006090, 2009.

**1. MAINTAIN AND ENHANCE THE EARTHSCOPE NATIONAL OFFICE.** The EarthScope National Office has helped to communicate EarthScope progress, data, and research opportunities and has expanded education and outreach efforts to include informal as well as formal education. Details of the role of the office will certainly evolve along with the program. Efforts to improve communication and integration within the research community through support of workshops, informative newsletters, and other means should be encouraged.

**2. FACILITATE INTEGRATIVE AND MULTIDISCIPLINARY RESEARCH.** It is essential to broaden the EarthScope community with the goal of encouraging integrative and multidisciplinary research. This emphasis applies to scientific communities that were not closely involved with EarthScope a decade ago (e.g., hydrologists, atmospheric scientists) as well as the more naturally related scientific communities (e.g., geologists, geochemists, petrologists, structural geologists, geodynamicists). Mechanisms to facilitate submission of multidisciplinary or exploratory proposals that integrate disparate fields and to expand access to higher-order data products are essential.

**3. ENCOURAGE EXPLORATION.** Many of the most interesting scientific results of EarthScope have been unexpected. EarthScope science should take advantage of this "discovery" aspect, and use its flexibility to build on serendipitous findings. Possible means of facilitating research include allowing rapid response to earthquakes and/or volcanic events, supporting unconventional deployments of geophysical instrumentation, and supporting work in areas of interest even if they fall outside of the onshore portions of the United States.

**4. ENHANCE OUTREACH EFFORTS.** It is critical to create a high-profile public identity for EarthScope. This will involve better coordination of EarthScope education and outreach activities and an overall assessment of the roles of the many stakeholders in these activities. Although the EarthScope National Office, facilities, and individual investigators have been active in promoting a wide variety of outreach efforts, there are many opportunities and new communities that need to be involved in these activities.

**5. DEVELOP EFFECTIVE CYBERINFRASTRUCTURE.** It is essential to develop a cyberinfrastructure framework within EarthScope to facilitate communication, dissemination, and integration of scientific findings. This includes development of tools for analysis of very large data sets, incentives for researchers to make data "products" available to the community, and coordination of efforts among the many groups investing in cyberinfrastructure for the geosciences.

**6. LINK TO OTHER PROGRAMS.** This includes international cooperation around the edges of the EarthScope footprint, co-funding of projects by multiple National Science Foundation (NSF) programs and other agencies, and collaboration with industry. Collaboration with the NSF MARGINS program along the margins of the continent and in the Great Lakes is particularly important.

**7. SUPPORT INSAR (SPACEBORNE RADAR) DEVELOPMENT AND DATA ACQUISITION.** Radar measurements of fine-resolution, spatially continuous crustal deformation are critical to many of the EarthScope science goals, as they reach inaccessible areas with frequent revisit times. A U.S. radar satellite mission is needed to provide these essential data to EarthScope investigators. Collaborations with other agencies, primarily NASA, should be pursued to realize this critical data set within the decade. In the short term, EarthScope should encourage high-level government agreements and systems to facilitate the use of data from international satellite platforms.

**8. ENHANCE THE EARTHSCOPE FACILITIES.** The community should be proactive in proposing projects that involve funding for extending or enhancing EarthScope facilities in response to evolving science needs. Key aspects of EarthScope facility enhancement could include reinstallation of the SAFOD borehole observatory and expansion of its capabilities to include additional measurements (e.g., pore pressure), acquisition of new SAFOD cores, upgrades of additional GPS stations to high-rate, real-time recording, acquisition of new USArray seismic and magnetotelluric stations for onshore/offshore deployments, and augmentation of EarthScope stations with other instruments that provide new capabilities.

It is hard to overstate the excitement that has been generated as a result of the EarthScope program. What has already been accomplished—technically, scientifically, and culturally—is truly spectacular. Interdisciplinary collaboration and broad distribution and integration of data and science results are progressively growing. This culture should be nurtured to fully realize EarthScope's promise.

# 2. EARTHSCOPE FACILITIES

EarthScope's facilities encompass a broad range of instrumentation distributed around the North American continent as well as a variety of data sets and the cyberinfrastructure and technical personnel needed to manage and distribute these data. The facilities can be grouped into three general categories, as outlined below, and are managed by the Incorporated Research Institutions for Seismology (IRIS) and UNAVCO, two non-profit corporations established and run by the academic seismological and geodetic communities, respectively. Capitalization and construction of the facilities (FY2003–2008) was enabled through the National Science Foundation's Major Research Equipment and Facilities Construction (MREFC) program. For more details about the EarthScope facilities, see Appendix 9.3 or http://www.earthscope.org.

## 2.1 USArray

USArray consists of four major observatory components: a Transportable Array (TA) of ~400 seismic stations that is rolling across North America, a Flexible Array (FA) pool of ~2100 seismic instruments for use in investigator-driven projects to achieve higher resolution over targets of special interest, a Reference Network (RN) of permanent seismic stations, and a magnetotelluric (MT) observatory with permanent (backbone) and transportable instruments. *Figure 2.1* shows the location of the USArray instrumentation in January 2010. Although the RN and MT backbone instruments do not move, TA stations spend ~24 months at each site before being moved to the eastern edge of the

### USArray Status as of January, 2010

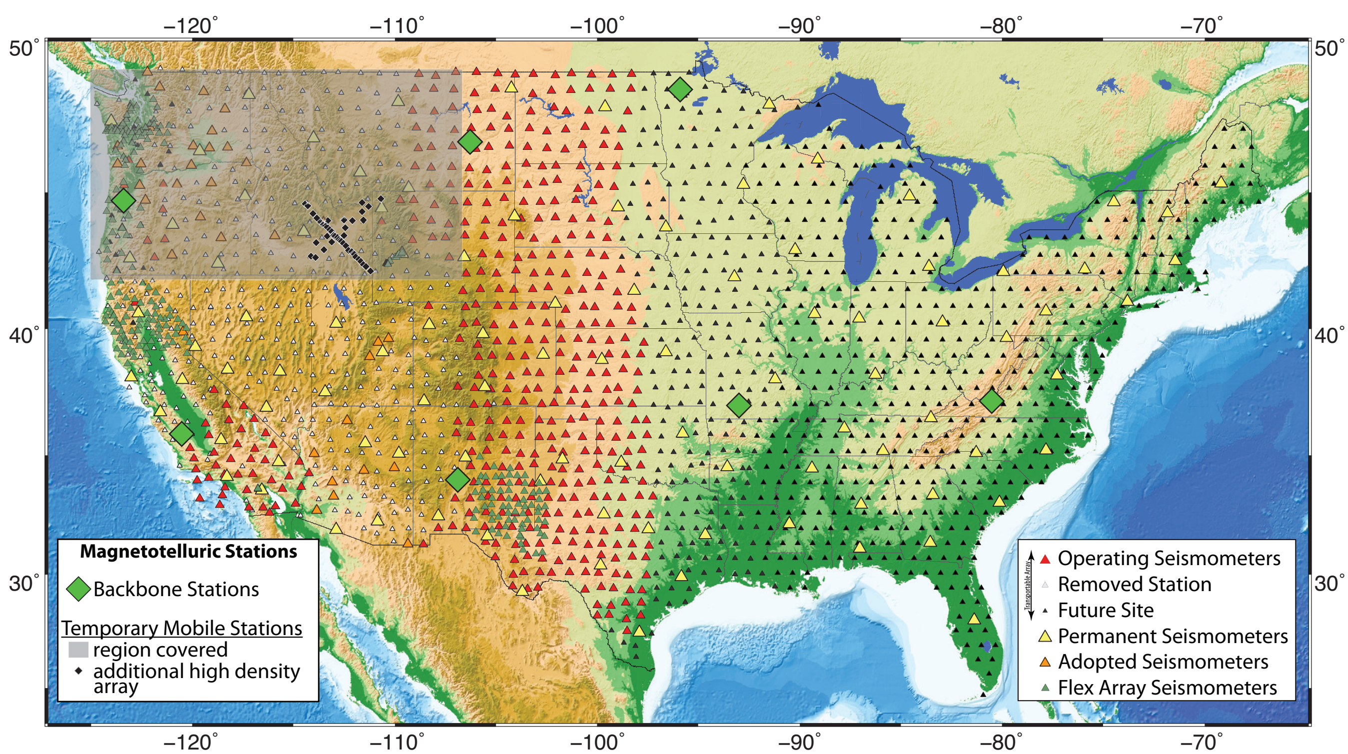



**Figure 2.1.** Map of USArray in January 2010.

active TA array; past, present, and future TA sites are shown. During the EarthScope program, TA stations will cover the entire United States, reaching the East Coast in 2012 and moving to Alaska by 2014. A number of organizations have "adopted" one or more TA stations rather than have the station(s) removed, creating a legacy of permanent stations in the wake of TA, with over 35 TA stations already adopted in the western United States. USArray also includes comprehensive data management and siting outreach efforts. USArray data are providing images of the subsurface with an unprecedented resolution and spatial coverage and are revealing new information about earthquakes and other processes that cause ground motion (e.g., propagation of oceanic and atmospheric signals into the solid Earth).

## 2.2 PBO

The Plate Boundary Observatory (PBO) consists of several major observatory components: a network of 1100 permanent, continuously operating Global Positioning System (GPS) stations, 78 borehole seismometers, 74 borehole strainmeters, 28 shallow borehole tiltmeters, and six long baseline laser strainmeters (*Figure 2.2*). These instruments are complemented by InSAR (interferometric synthetic aperture radar) and LiDAR (light detection and ranging) imagery and geochronology acquired as part of the GeoEarthScope initiative. PBO also includes comprehensive data management and outreach efforts. The ability of PBO to address its scientific goals relies heavily on continuous instrument operation to obtain uninterrupted time series of positions and strains, which are critical for rigorously quantifying measurement errors and detecting transient deformation. PBO spans the North American continent with instrumentation, providing the detailed deformation data necessary to address a wide range of scientific goals at the forefront of tectonics and earthquake science, including the modes and driving forces of distributed plate boundary deformation, time-dependent deformation and rheology of the lithosphere, and episodic tremor and slip (ETS) phenomena.

**SAFOD and PBO Station Locations**

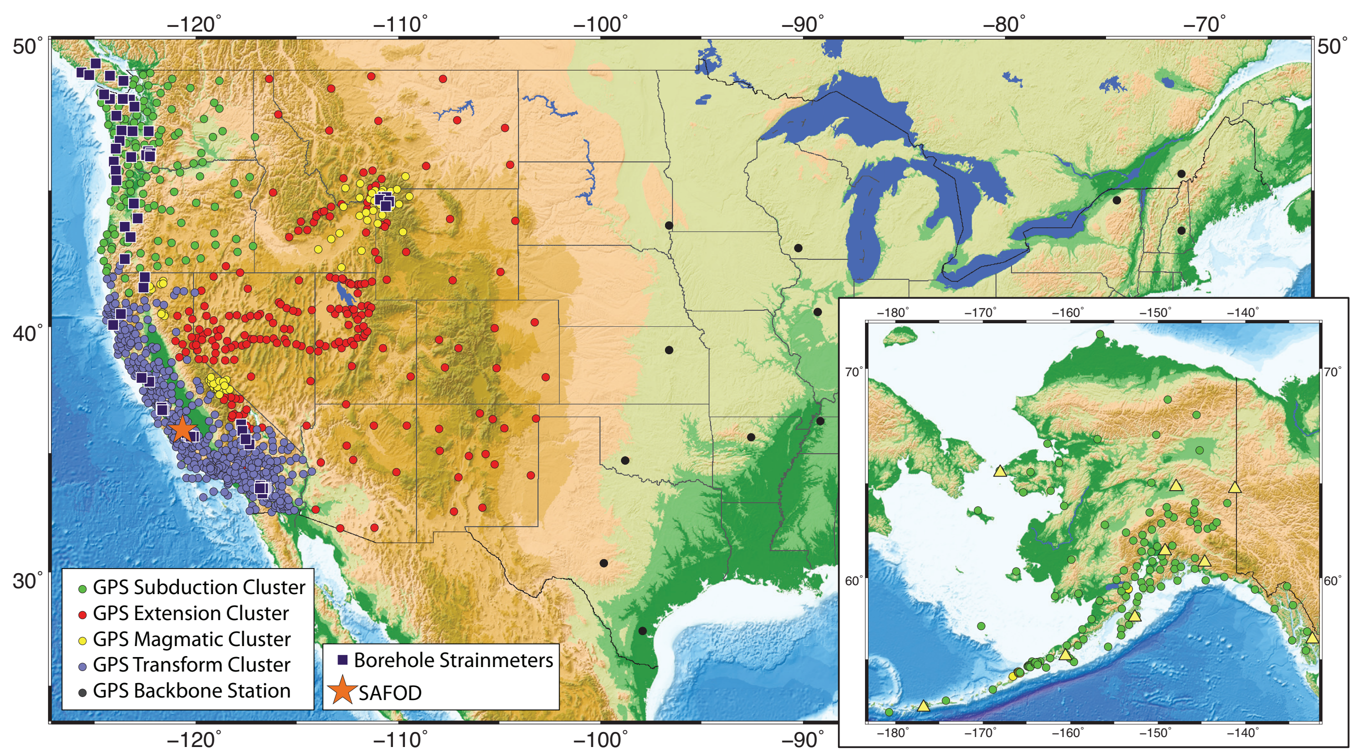



**Figure 2.2.** Map of PBO and SAFOD.

# 2.3 SAFOD

The San Andreas Fault Observatory at Depth (SAFOD) is a deep drill hole and geophysical observatory located within the San Andreas Fault in central California along the creeping segment of the fault immediately north of the Parkfield segment (*Figure 2.2, 2.3*). The main goals of SAFOD are to address fundamental questions about physical and chemical processes controlling faulting and earthquake generation within a major plate-bounding fault. The facility currently includes a cased borehole that terminates within the active trace of the San Andreas Fault at a depth of 2.6 km. It also includes physical samples extracted from the fault zone and adjacent formations during 2004, 2005, and 2007. Over

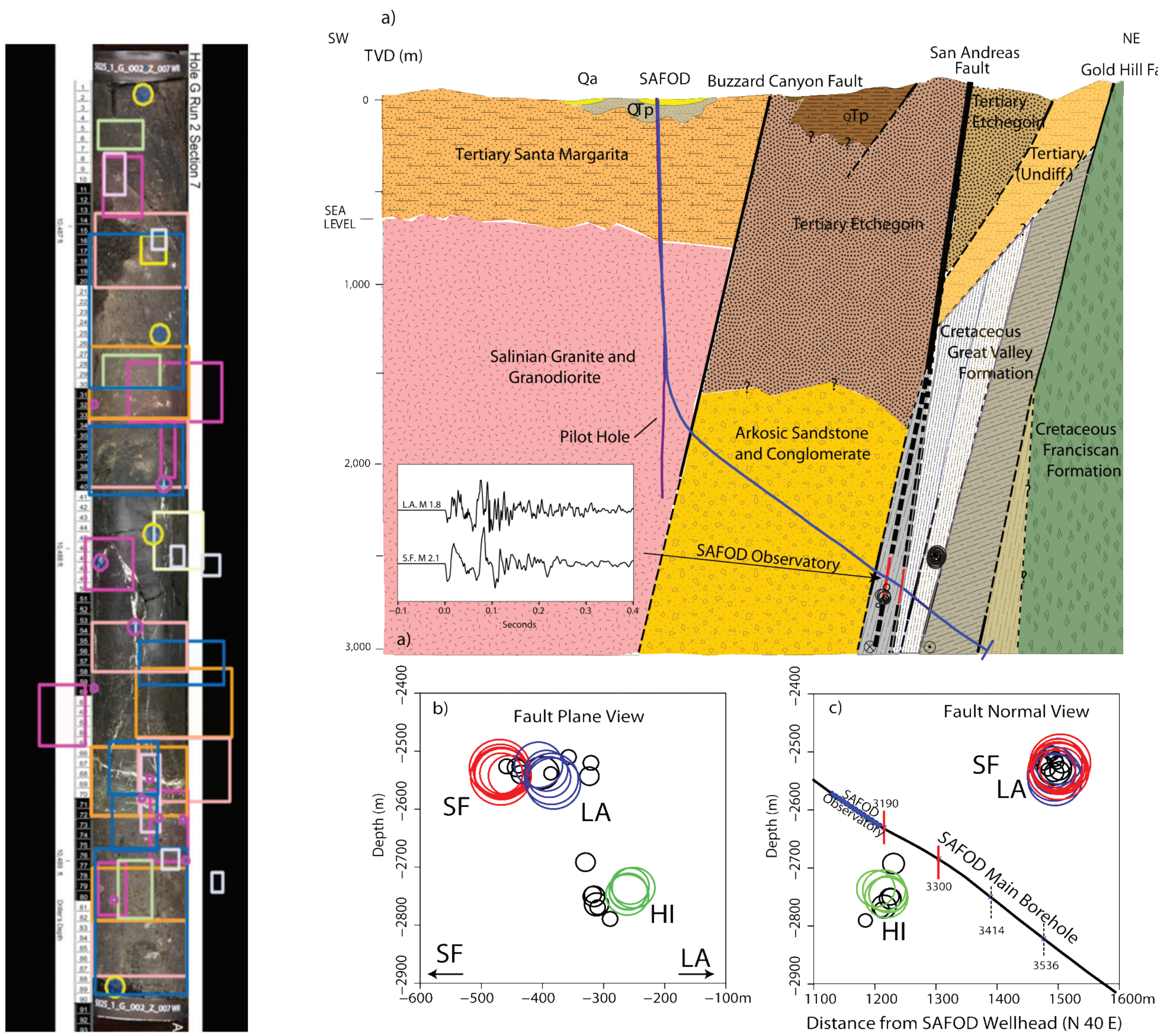



**Figure 2.3. (left)** Requests for core samples from the "10,480" fault zone (a core obtained 10,480 ft from the surface from within a 100-m-wide zone of active slip in the San Andreas Fault). Investigators from around the world can view the core and select samples using a tool developed by EarthScope. Because each sample is unique (unlike the geophysical data, which can be reproduced at will), equitable distribution of core requires a well-defined protocol. **(right)** (a) Simplified geologic cross section along the trajectory of the SAFOD borehole as constrained by surface mapping (courtesy M. Thayer and R. Arrowsmith) and subsurface information. (b) View of the plane of the San Andreas Fault at ~2.7-km depth looking to the northeast. The red, blue, and green circles represent seismogenic patches that produce regularly repeating target microearthquakes. (c) Cross-sectional view of the target earthquakes looking to the northwest, including the trajectory of the SAFOD borehole and some of the most significant faults encountered during drilling (denoted by depths as measured along the borehole). The faults in red at 3190 and 3300 m (measured depth) are actively deforming the casing (see *Sidebar 14*).

40 m of drill core were collected in the fault zone and at other locations, along with a comprehensive suite of cuttings from the entire drilling operation. The core is currently stored at the International Ocean Drilling Program (IODP) Gulf Coast Repository at Texas A&M University. A web-based "core viewer" tool provides high-resolution photographs of the cores to the scientific community and is used by the community to request samples for further study (*Figure 2.3*). Comprehensive geophysical logs collected during and following the drilling phases are available on the web through the International Continental Drilling Program. The geophysical observatory currently consists of a fiber optical laser strainmeter installed inside the vertical portion of the SAFOD main hole. Seismometers were operated during breaks in the drilling activity at depths of up to 2.7 km from 2004–2007. Seismometers and tiltmeters installed near the bottom of the drill hole in 2008 failed shortly after installation, and efforts are underway to reestablish a borehole observatory. SAFOD management was based at Stanford University and at the USGS during the MREFC phase, and moved to UNAVCO for the Operations and Management (O&M) phase.

## 2.4 Data Management

All EarthScope data (except core samples) are available via the EarthScope data portal, which provides a resource for students, researchers, and others interested in scientific data to simultaneously explore EarthScope's various instrument networks. The portal enables seamless downloads of data from multiple stations and instrument types. The intuitive Google Maps-based user interface provides a familiar means to filter stations by geography, data class, or station identifier. Additional temporal and spatial filters give users the ability to further refine their searches as needed.

Data can also be downloaded directly from the facilities. Roughly 300,000 discrete data requests are serviced per year, with a cumulative shipment of more than 11 terabytes of EarthScope data via traditional (non-streaming) request mechanisms. *Figure 2.4* shows the total EarthScope data holdings through September 2009.

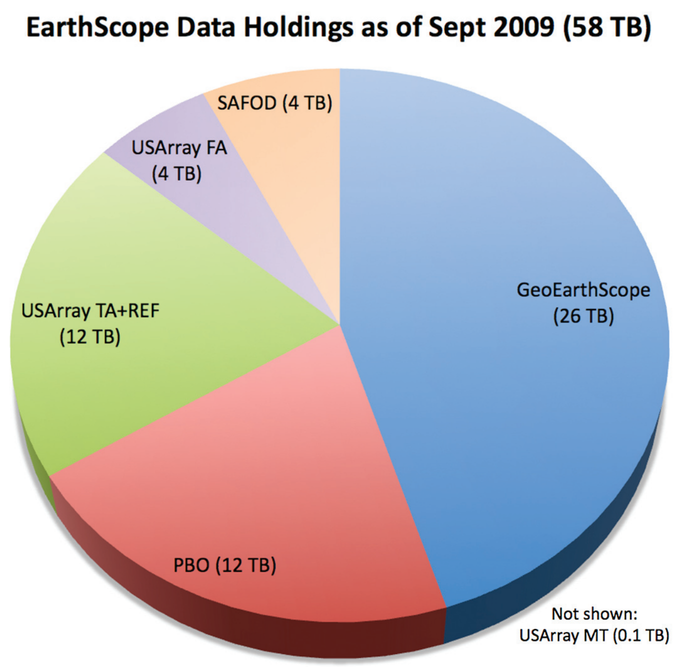



**Figure 2.4.** EarthScope data archived through September 2009.

# 3. SCIENTIFIC TARGETS FOR EARTHSCOPE

The continental lithosphere bears the tectonic scars of over 4 billion years of Earth history, and North America provides one of the most complete records of episodic continental growth, modification, and breakup. While the continental crust and mantle are known to be chemically and rheologically distinct from adjacent oceanic lithosphere and the underlying mantle, much remains to be learned about how the crust and mantle interact. EarthScope researchers are examining the geologic processes that result in continental growth and evolution on scales ranging from microscopic rock structures to tectonic plates. One exciting theme that recently has emerged is the interplay between flow in the mantle and deformation at Earth's surface, with zones of coupling and decoupling at different levels. EarthScope's geological and geophysical data sets are providing the means to test a new generation of 4D (space plus time) models for lithospheric evolution, plate boundary processes, and mantle circulation. Lessons learned from SAFOD, PBO, and USArray are also revolutionizing our understanding of fault properties and fault-slip processes, with implications for the evaluation of seismic hazards.

## 3.1 Imaging the Crust and Lithosphere Beneath North America

The high density and broad sweep of EarthScope data, coupled with advances in analysis methods, are leading to images of the continental crust and upper mantle of the North American continent with resolutions not possible even a decade ago (*Sidebar 3*). EarthScope will systematically produce high-resolution images of the lithospheric mantle in the western United States and Alaska (where the lithosphere is being destabilized by active tectonism), the Archean and Proterozoic craton in the continental interior (where a thick lithospheric root promotes long-term continental stability), and the eastern United States (where large-scale tectonism has not occurred since the rifting that produced the Atlantic Ocean ~200 million years ago). Comparisons among the mantle lithospheres of these regions (*Sidebar 4*) will help to resolve the competing roles of crust and mantle buoyancy and rheology in preserving or destroying the continental lithosphere. A particularly intriguing finding from EarthScope studies in the western United States is the observation of multiple zones of apparent mantle delamination or downwelling (*Sidebar 5*). As the TA rolls eastward, it will reveal whether these downwellings are confined to the active tectonic environment of the western United States or whether they are ubiquitous beneath the continent. The distribution and characteristics of such downwellings will provide new insights into the internal properties of the continental lithosphere and its interactions with the deeper mantle. A clearer picture of how the properties of the mantle lithosphere vary with age will also inform models for how the continental lithosphere was formed and stabilized.

## 3.2 Active Deformation of the North American Continent

All of the processes that lead to growth, modification, preservation, and destruction of continents have contributed to the geologic evolution of North America, and many are active today. These processes include subduction in Cascadia and Alaska, terrane collision in southern Alaska, extension in the Basin and Range province, rifting in the Gulf of California, and transcurrent movement in the San Andreas and Walker Lane fault systems.

## SIDEBAR 3. IMAGING CRUSTAL VELOCITY STRUCTURE AND THICKNESS

**A.** Ambient noise tomography represents a new imaging technique that takes advantage of the TA's dense, regular spacing to determine the shear wave velocity structure of the crust and upper mantle with unprecedented resolution on a continent-wide scale. The two images show horizontal slices at two different depths within the crust extracted from a 3D model of the western United States (Yang et al., 2008).

**B.** Pn tomography (right) is another technique used to determine important parameters of the crust and uppermost mantle. The map on the right shows crustal thickness across the western United States (Buehler and Shearer, in review).

**C.** Higher-resolution studies, using instruments from the FA and both manmade and natural sources, are needed to tie mapped geologic structures to subsurface processes. The cross section on the left shows a velocity model around the SAFOD drill hole derived by waveform inversion and migration of active source data. The middle section shows details of the model at SAFOD. White dots show earthquake hypocenters. The white line shows the top of the Salinian granite. SAF – San Andreas Fault; BCF – Buzzard Canyon Fault; GHF – Gold Hill Fault; WCF – Waltham Canyon Fault. Graph on the right shows the starting (blue dashed) and final (red) velocity models compared to a SAFOD sonic log (grey) (Bleibinhaus et al., 2007).

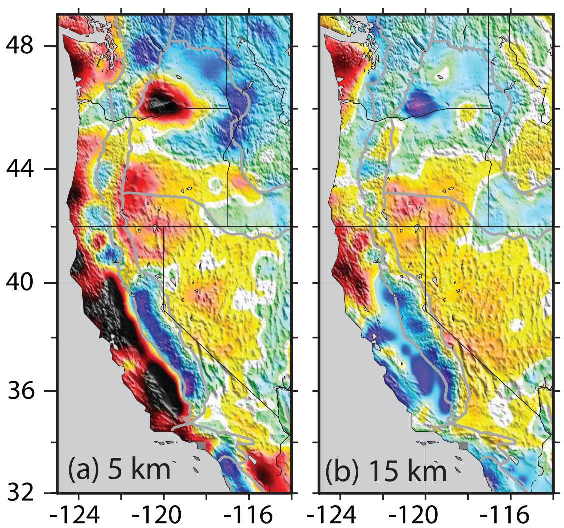
### References


Bleibinhaus, F., J.A. Hole, T. Ryberg, and G.S. Fuis, Structure of the California Coast Ranges and San Andreas Fault at SAFOD from seismic waveform inversion and reflection imaging, J. Geophys. Res., 112, B06315, doi: 10.1029/2006JB004611, 2007.

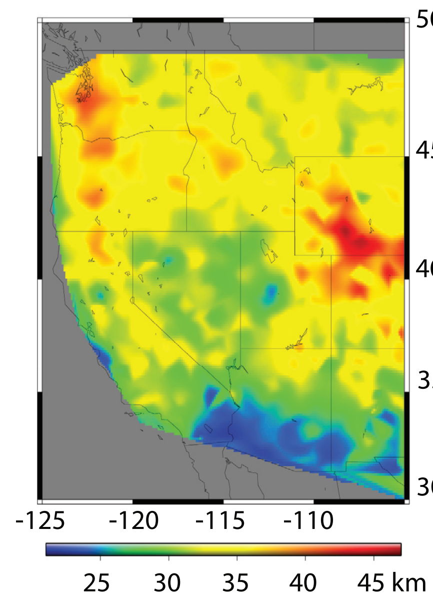
Buehler, J., and P. Shearer, Pn tomography of the western United States using USArray, J. Geophys. Res., in review.

Yang, Y., M.H. Ritzwoller, F.-C. Lin, M.P. Moschetti, and N.M. Shapiro, Structure of the crust and uppermost mantle beneath the western United States revealed by ambient noise and earthquake tomography, J. Geophys. Res., 113, B12310, doi: 10.1029/2008 JB005833, 2008.

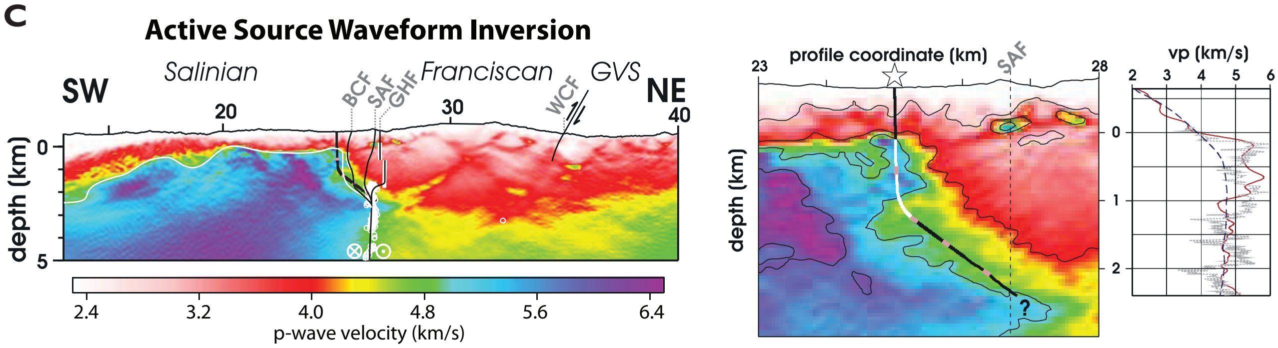

**A** Ambient Noise Tomography




**B** Crustal Thickness from Pn Tomography




**C** Active Source Waveform Inversion

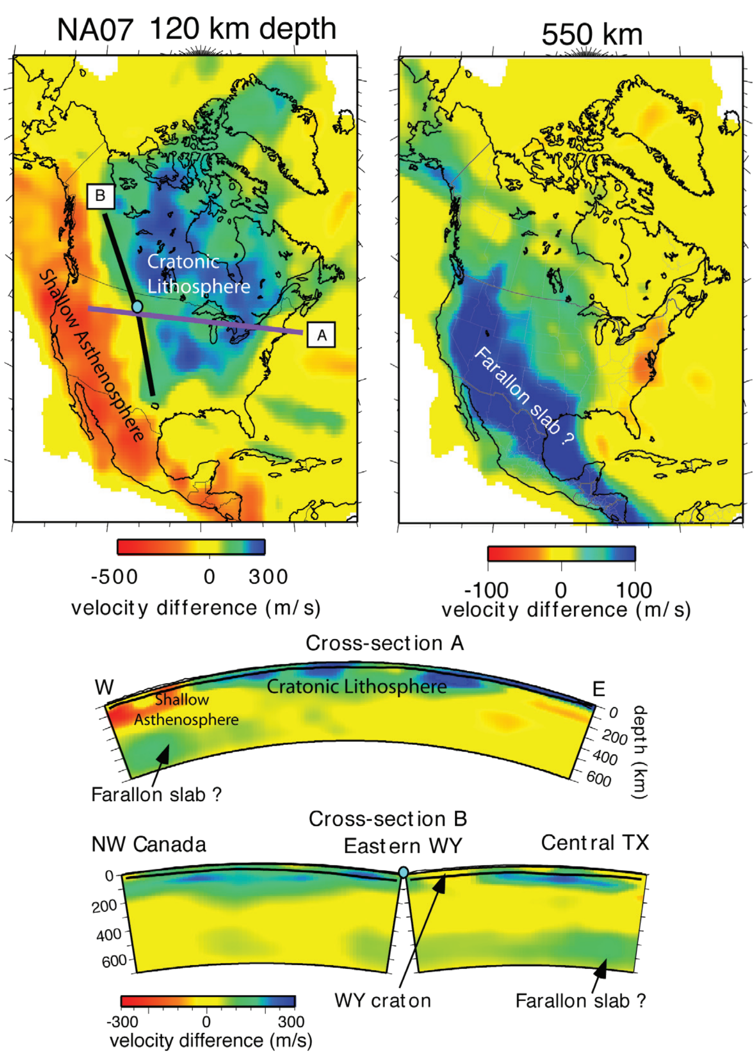


Active plate boundary deformation is distributed across the western part of the contiguous United States, most or all of Alaska, and a large part of Canada's northern cordillera. Studying active deformation processes provides new insight into the underlying mechanisms and dynamics of continental deformation, elucidates the history of the North American continent, and allows better recognition and assessment of natural hazards and their associated risk. EarthScope measures this deformation directly through PBO's continuous geodetic measurements, and indirectly through USArray's seismic data. Interferograms produced from synthetic aperture radar images acquired by EarthScope or WInSAR (Western North American Synthetic Aperture Radar Consortium) augment the GPS measurements. Campaign GPS data can provide critical information on steady tectonic motions where PBO continuous sites are too sparse. Seismicity and other modes of fault slip are monitored by USArray's FA and TA components as well as by regional seismic networks run by other agencies.

### 3.2.1 CONVERGENT MARGINS

Convergent margins are the most dynamic tectonic environments on the planet. Over human time scales, subduction of oceanic lithosphere produces the world's largest earthquakes and leads to potentially hazardous volcanic eruptions. Over

## SIDEBAR 4. SEISMIC IMAGES OF THE NORTH AMERICAN LITHOSPHERE




Slices through a shear-wave velocity model obtained from regional S and Rayleigh waves beneath North America. Colors represent departures from a reference model. The lithosphere beneath the craton appears as a 200-km-thick "lid" of fast seismic velocities. The tectonically active western United States appears as a zone of low-velocity asthenospheric material at <200-km depth. Beneath some cratonic provinces, such as the Wyoming craton (Profile B), thick lithosphere is missing. The processes that create, modify, and destroy continental lithosphere are a primary scientific target of the EarthScope program.

A fast anomaly at 500–700-km depth beneath western North America (horizontal slice at 550 km) has been interpreted to be the subducted Farallon plate. Correlations between this feature and the subducted slab shown in *Sidebar 1* will be refined as the TA moves east. Denser data combined with new techniques for joint inversion of different types of seismic waves will lead to higher-resolution images of the entire mantle.

#### Reference

Bedle, H., and S. van der Lee, S velocity variations beneath North America, J. Geophys. Res., 114, B07308, doi:10.1029/2008JB005949, 2009.

## SIDEBAR 5. LITHOSPHERIC INSTABILITIES: DELAMINATION AND DRIPS

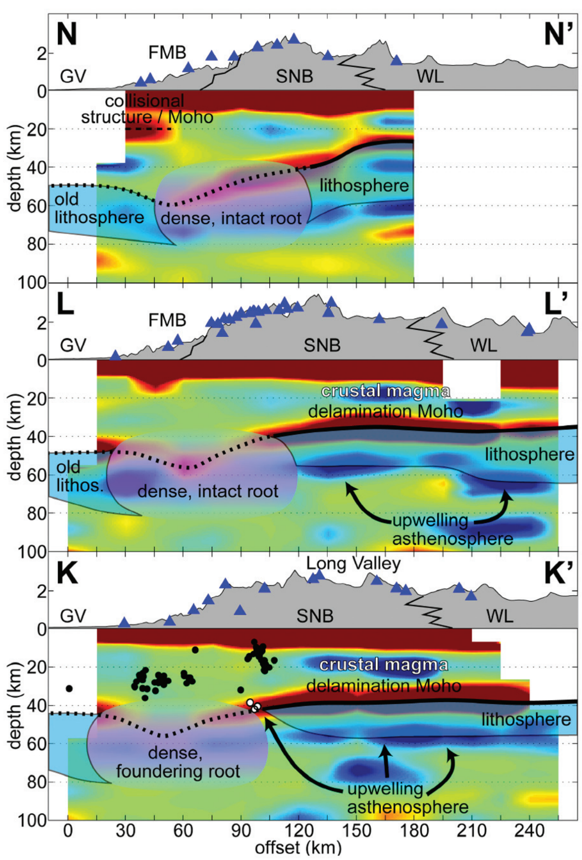
Sierra Nevada (left): A longstanding hypothesis that has been supported by a wide range of geophysical and geological data is that the subducted Farallon plate foundered beneath the Sierra Nevada, removing the lithospheric mantle and dense lower crust, which were replaced by hot, buoyant asthenosphere. The Sierra Nevada EarthScope Project (SNEP) employed TA and FA stations to produce a high-resolution image of the crust and upper mantle that is consistent with this hypothesis. A series of transects across the Sierra Nevada shows this process in action, with delamination occurring in the south and an intact root in the north (Frassetto et al., 2009).

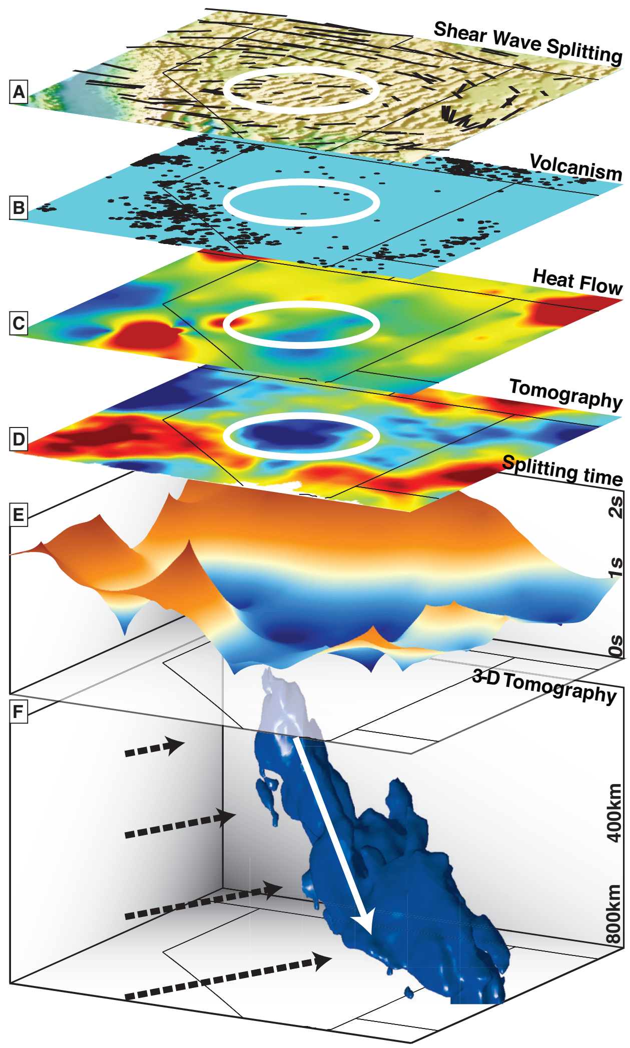
The Nevada "drip" (right) is an apparent cold downwelling that was unknown until illuminated by the TA (West et al., 2009). Geodynamic models and observations of shear wave splitting times suggest that the "downwelling," which appears in the 3D tomographic model, is actively descending, drawing lithospheric material deep into the mantle. The drip underlies an anomalous part of the Great Basin, where volcanism and crustal extension are attenuated. These results suggest that lithospheric drips are an important tectonic process in continental evolution.

### References


Frassetto A., G. Zandt, H. Gilbert, T.J. Owens, and C. Jones, Lithospheric structure of the Sierra Nevada from receiver functions and implications for lithospheric foundering, submitted to Geosphere, 2009.

West, J.D., M.J. Fouch, J.B. Roth, and L.T. Elkins-Tanton, Vertical mantle flow associated with a lithospheric drip beneath the Great Basin, Nature Geosc., doi: 10.1038/NGEO526, 2009.

geologic time scales, arc magmatism and the collision of lithospheric fragments have added to North America's continental crust. EarthScope will continue to provide exciting new information on the structure and active deformation of two distinctly different subduction zones: Cascadia and Alaska. These subduction zones both feature forearc blocks (upper plate lithosphere between arc and trench) that are moving relative to the North American plate, but they differ in the age of subducting crust, convergence rate, and sediment influx.

The contrasting geometry, subduction history, and driving forces between Cascadia and Alaska will provide unique tests for a wide variety of subduction-related hypotheses during the next decade of EarthScope studies. The opportunity to compare two major subjection systems also underscores the importance of the Alaska TA deployment, proposed to begin in 2014.

**CASCADIA:** The Cascadia subduction zone is unusual in at least three ways: very young lithosphere is being consumed, a relatively thick sedimentary section, largely from the erosion of North America, is being carried into the trench, and subduction is strongly influenced by interactions with the adjacent San Andreas fault system and Basin and Range extension. The last feature is apparent in Cascadia motions relative to stable North America. GPS vectors show a clockwise rotation in northern California and Oregon (*Sidebar 6*) that results from a combination of long-term motion of forearc blocks and elastic deformation associated with the seismogenic subduction zone. As PBO data are further analyzed, including those from longer time series, these motions can be used to constrain strain accumulation and transient slip in the subduction zone, the kinematics of the deforming upper plate, rheology of the plate margin, the downdip limit of the locking zone on the plate interface, and transient records of magmatic processes associated with the arc volcanoes. Cascadia is the focus of a new joint initiative between EarthScope and the NSF MARGINS program that will deploy onshore/offshore arrays of GPS and seismometer stations to more fully characterize the subduction system (*Section 7.1*).

**ALASKA:** The Alaska-Aleutian subduction zone is different in many respects from the Cascadia subduction zone. This arc-trench system contains along-strike transitions from an ocean-ocean subduction zone (Aleutian islands), to an ocean-continent subduction zone (Alaska Peninsula), to a flat-slab subduction region (Gulf of Alaska) associated with the subduction of oceanic crust of different thickness (Pacific and the Yakutat terrane), to collision and underplating of the eastern Yakutat terrane beneath coastal Alaska (St. Elias Range). The Alaska-Aleutian subduction zone also displays convergence directions that range from trench-normal (Alaska Peninsula) to nearly trench-parallel (western Aleutians). This subduction zone has been the site of numerous M>8 earthquakes over the past century, including the 1964 Alaska earthquake, which continues to produce significant postseismic transient deformation (*Figure 3.2.1*). Alaska has also experienced the largest coseismic uplifts ever observed (~14 m during the 1899 Yakutat earthquakes) and is the home of the highest coastal mountain range on Earth (St. Elias Range).

The Alaska margin is uniquely suited to geodetic studies of strain accumulation in different phases of the earthquake and volcanic cycles, processes of flat-slab subduction associated with terrane collision, and tectonic and magmatic processes in volcanoes (*Section 3.6*). Campaign GPS studies together with PBO continuous stations document pervasive deformation of the overriding plate reflected in the motion of crustal blocks relative to North America.

**EPISODIC TREMOR AND SLIP (ETS):** EarthScope data have provided new insights into the temporal and spatial patterns of ETS events in Cascadia (*Sidebar 2*). Future studies will certainly refine our understanding of these intriguing events; they will provide the information needed to distinguish between earthquake-cycle deformation (*Section 3.5*) and long-term deformation of the North American continent, and will perhaps eventually reveal features indicative of temporal evolution of the great earthquake cycle. Tremor and slow slip also occur in Alaska, although to date only a single very large ETS event has been studied in detail.

### 3.2.2 TERRANE BOUNDARIES AND COLLISIONAL MARGINS

The Alaskan component of EarthScope enables direct investigation of mountain-building processes in southern Alaska east of the Alaska Peninsula, where the Yakutat microplate is colliding with southern Alaska. This collision results in intriguing complexities, including flat-slab subduction with a gap in the magmatic arc, a magmatic arc segment (the Wrangell mountains) developed away from the main Alaskan-Aleutian arc, a tear in the subducting plate east of which the Yakutat terrane is too buoyant to subduct, reactivated interior strike-slip faults (e.g., the Denali Fault), and complex feedbacks among sediment subduction, uplift, and the surface processes of erosion and deposition. The buoyancy of the flat slab almost certainly plays a major role in southern Alaskan mountain building. In particular, scattered seismicity and active deformation observed by GPS throughout northern Alaska and into the Yukon appear to be directly related to flat-slab subduction and the associated Yakutat collision (*Sidebar 7*). The scale of this far-field deformation is similar to that of the subduction and mountain-building episode that affected North America from Alaska to its southern reaches roughly 65 million years ago (the Laramide orogeny). One of the most powerful aspects of EarthScope will involve comparison of ancient and active tectonic systems.

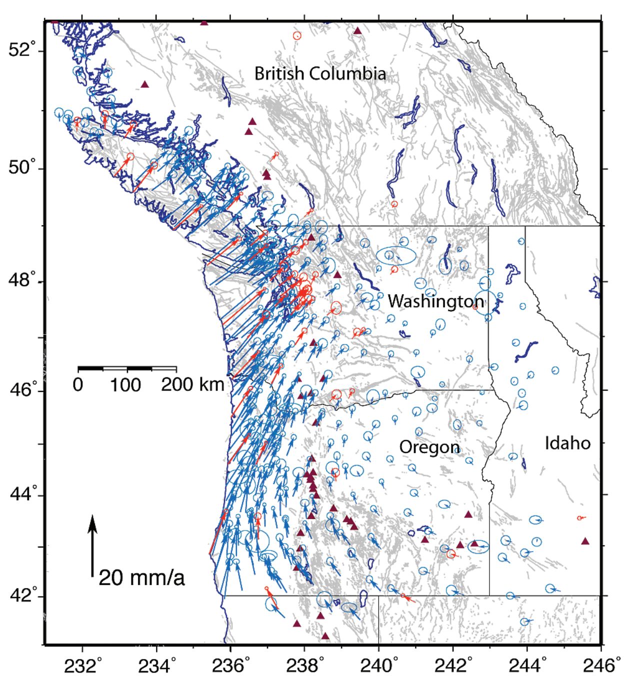
## SIDEBAR 6. ROTATION OF THE CRUST AND MANTLE IN THE WESTERN U.S.

Geoscientists have long known that the southwestern North American plate boundary is characterized by a broad zone of active deformation that extends from the Pacific coast eastward to the Rocky Mountains. EarthScope data are inspiring new hypotheses about possible interactions between the lithosphere and underlying asthenosphere. For example, clockwise rotation of the surface in northern California and Oregon (left) is similar to but offset by ~1000 km from clockwise rotation of the upper mantle beneath Nevada as inferred from shear-wave splitting. Modeling of the surface rotation indicates that this results from rotation of discrete blocks caught between the Cascadia subduction zone, shear between the Pacific and North American plates, and Basin and Range extension (McCaffrey et al., 2007). The observed anisotropy is consistent with asthenospheric flow around the edge of the subducting lithosphere, which corresponds to the slab-like high-velocity anomaly. Geodynamic modeling is needed to evaluate the relationship between mantle flow inferred from the shear-wave splitting and surface block rotations determined from GPS data. In addition, new seismological techniques are needed to constrain 3D flow patterns because shear-wave splitting constrains mainly the horizontal component.

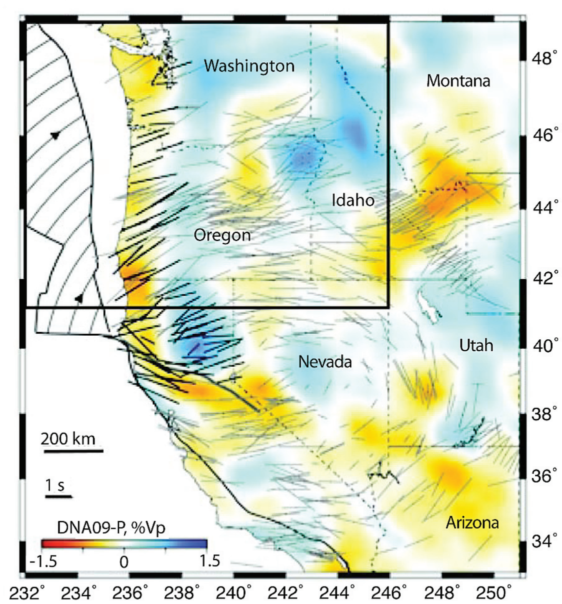
### References


Eakin, C.M., M. Obrebski, R.M. Allen, D.C. Boyarko, M.R. Brudzinski, and R. Porritt, Seismic Anisotropy beneath Cascadia and the Mendocino Triple Junction: Interaction of the Subducting Slab with Mantle Flow, in review.

McCaffrey, R., A.I. Qamar, R.W. King, R. Wells, G. Khazaradze, C.A. Williams, C.W. Stevens, J.J. Vollick, and P.C. Zwick, Fault locking, Block Rotation and Crustal Deformation in the Pacific Northwest, Geophys. Jour. Int., 169, 1315-1340, 2007.


Velocity vectors in the Pacific Northwest relative to stable North America. Data are from several permanent and campaign GPS networks that predate EarthScope (McCaffrey et al., 2007).




Shear-wave splitting measurements from TA and other seismic stations superimposed on a map of P-wave velocities averaged over 100–400-km depth. The curved lines show trajectories of the Juan de Fuca and Gorda plates relative to North America. Box outlines region shown on left (Eakin et al., in review).

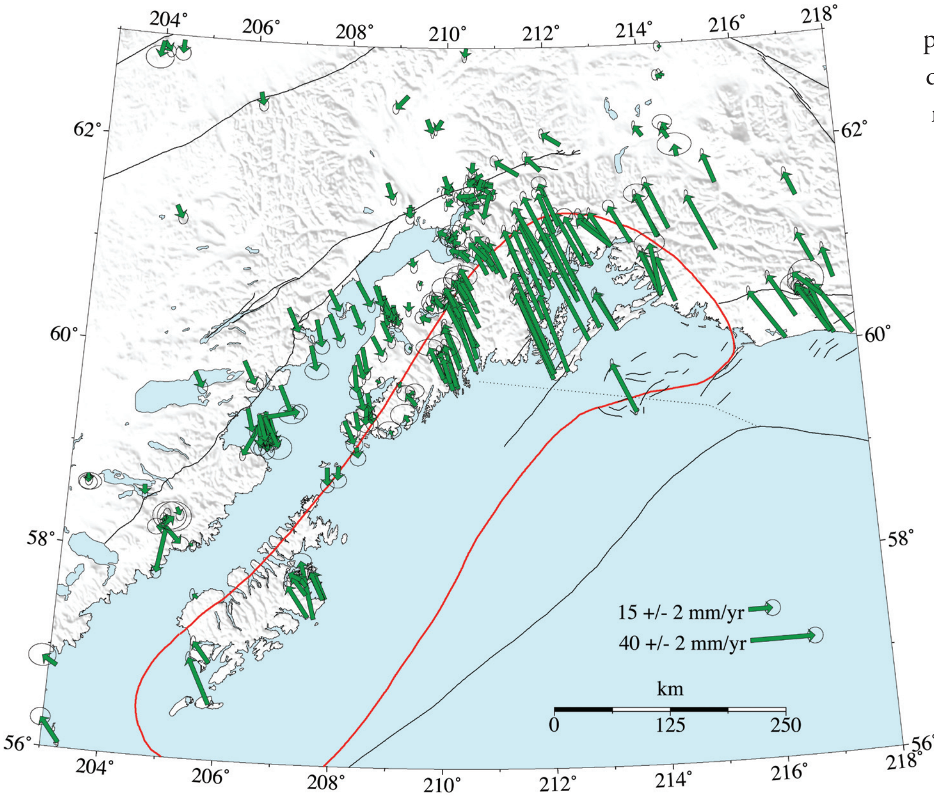



**Figure 3.2.1.** GPS velocities from southern Alaska in the region of the 1964 Alaska earthquake, primarily from pre-EarthScope campaign data. The earthquake rupture zone, based on aftershocks, is outlined in red. GPS velocity vectors relative to North America show the effects of multiple processes. Trenchward motions in the western part of the figure result from ongoing postseismic deformation following the 1964 earthquake. The large motions away from the trench in the eastern part of the figure result from elastic deformation due to the locked region on the plate interface. They are not uniform along strike because the pattern of locked and creeping behavior of the plate interface varies along strike, matching the distribution of slip in the 1964 earthquake.

*Freymueller, J.T., H. Woodward, S.C. Cohen, R. Cross, J. Elliot, C.F. Larsen, S. Hreinsdottir, C. Zweck, Active deformation processes in Alaska, based on 15 years of GPS measurements, in Active Tectonics and Seismic Potential of Alaska, Geophysical Monograph Series 179, Am. Geophys. Un., 2008)*

## 3.2.3 TRANSCURRENT, TRANSPRESSIONAL, AND TRANSTENSIONAL MARGINS

With PBO and USArray data from western North America, EarthScope scientists now have an excellent view of ongoing tectonic processes along a major continental transform margin. The San Andreas fault system and related structures pose one of the clearest seismic hazards in North America because of the potential impact on large population centers in California. New understanding of this margin through EarthScope-enabled research is of major societal importance.

Overall slip along the San Andreas fault system is coupled with Basin and Range extension and the movement of apparently rigid tectonic blocks (Sierra Nevada, Great Valley, and parts of Oregon and Washington), but the dynamic drivers of this large-scale deformation system remain the subject of hot debate. In the south, the plate boundary consists of a series of right-stepping strike-slip faults in the Gulf of California and Salton Trough, with intervening spreading centers. The San Andreas Fault is the northernmost of these strike-slip faults. It undergoes a marked left bend in the Transverse Ranges, partly in response to Basin and Range extension (*Figure 3.2.3*). At its northern end, as the Mendocino triple junction migrates northward, the San Andreas fault system appears to evolve from reactivated subduction-related structures, resulting in a broad zone of crustal slivers separated by faults. The present kinematic pattern and its relation to crustal structure as well as the long-term evolution of the plate boundary are major research targets for EarthScope.

Over much of its length, the San Andreas fault system consists of three or more major subparallel strands. Elastic deformation from closely spaced parallel faults overlaps, making it difficult to determine individual fault slip rates unless the locking depth or seismogenic limits of the faults are also known, even where geodetic data are dense. There are well-documented geological examples of transpressional deformation (strike-slip combined with contraction) adjacent to the San Andreas Fault. The deformation requires a small but permanent (non-elastic) component of transcurrent motion (pure strike-slip). Additional insight requires more sophisticated earthquake-cycle models that can integrate geodetic, seismological, thermal, and geological information. Despite considerable work on this topic, these models remain in their infancy and further theoretical development and data are needed. Spatially continuous deformation data from InSAR will help to distinguish between competing deformation models (*Sidebar 8*). On thousand-year times scales, intriguing anticorrelations in the timing of slip are observed between neighboring strands of the southern San Andreas Fault (*Sidebar 9*), which challenge assumptions that fault slip rates are consistent over time.

Alaska will provide two excellent opportunities to investigate transcurrent boundaries: the Queen Charlotte-Fairweather Fault, which is a continent/ocean transform fault, and the Denali Fault, which is a major intracontinental strike-slip fault (*Sidebar 7*). Comparison between these faults and the San Andreas Fault is critical for understanding transform plate boundary processes because different segments of these faults vary widely in the amount of deformation that is transcurrent, transpressional, and transtensional (strike-slip combined with extension).

## SIDEBAR 7. TECTONIC BLOCK MOTIONS IN THE NORTHERN CORDILLERA

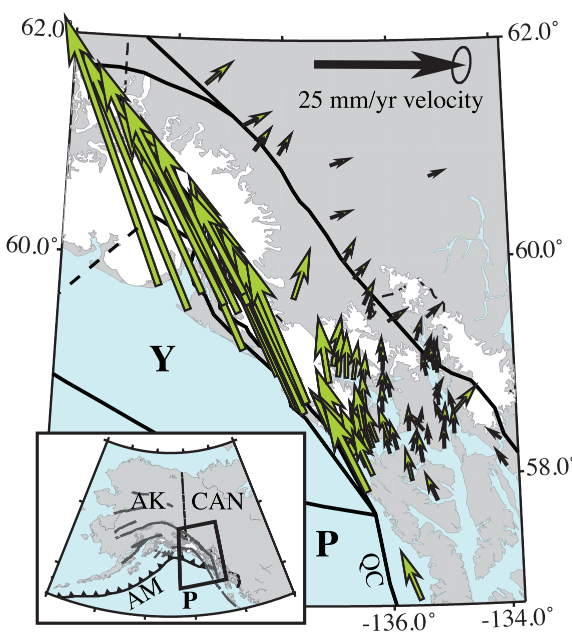
Southeast Alaska and adjacent Canada make up part of the Northern Cordillera, an important part of the Pacific-North America plate boundary marking the transition from transform to subduction along the Aleutian megathrust. The region's tectonics are driven by ~50 mm/yr Pacific-North America motion and the Yakutat block's collision with and accretion to North America. The entire coastal region is subject to active deformation, which also extends northward to the Arctic coast.

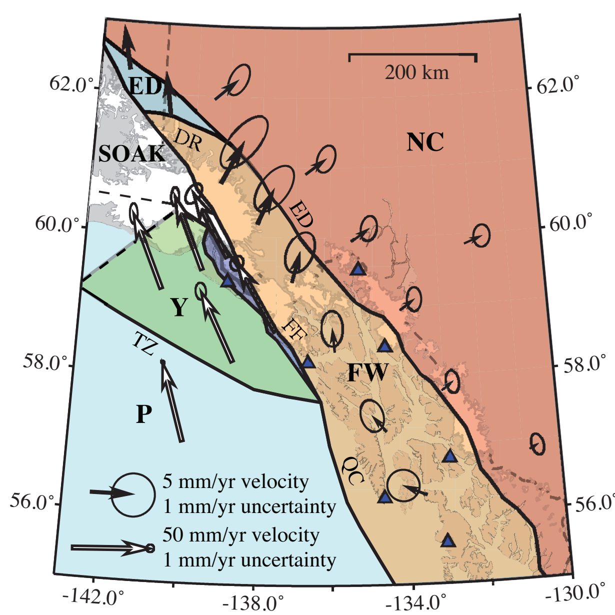
Observed GPS velocities relative to North America (left panel, green arrows) show rapid motion along the coast and a rotational pattern inland. Inverting the velocities to determine a rigid block model results in the predicted long-term motions (with no elastic deformation component) shown in the panel at right. The Yakutat block (Y) moves 51 ± 3 mm/yr toward N22 ± 3°W relative to North America, almost identical in rate to the Pacific plate (P) but in a more westerly direction. The Fairweather Fault (FF) is almost pure strike-slip with fault-normal convergence confined to faults close to the coast or offshore. The Fairweather block (FW) rotates clockwise relative to North America causing transpression at its northern end. There is clear strain transfer from the coast eastward into the Northern Cordillera (NC), which moves northeastward relative to North America. Yakutat-Pacific relative motion is accommodated by left-lateral oblique slip on offshore faults such as the Transition fault zone (TZ). Yakutat block collision with southern Alaska results in 45 mm/yr shortening across the St. Elias Range, resulting in some of the steepest coastal mountains globally.

The PBO sites south of the Fairweather-Queen Charlotte (QC) junction will provide additional insights about the plate boundary zone. However, the network is sparse, making coastal Alaska and Northwest Canada a promising target for future PBO densification.

### Reference


Elliott, J.L., C.F. Larsen, J.T. Freymueller, and R.J. Motyka, Tectonic Block Motion and Glacial Isostatic Adjustment in Southeast Alaska and Adjacent Canada Constrained by GPS Measurements, submitted to J. Geophys. Res., Nov. 2009.

## 3.2.4 DIVERGENCE AND REGIONAL EXTENSION

The western United States contains the best-known post-orogenic extensional province in the world—the Basin and Range—in a broad band that extends from Oregon-Idaho southward into Mexico. This extensional province has a long history that began tens of millions of years ago, but continues today in a broad belt between the Sierra Nevada mountains and the Wasatch front. Although divergence rates on individual faults in the Great Basin are low compared to typical interplate velocities, they nevertheless add up to divergence of ~10 mm/yr across the entire ~500-km-wide region. PBO Nucleus stations installed across this region clearly resolve this motion.

Extension is currently concentrated within two broad corridors: the eastern California shear zone/Walker Lane belt, where deformation is transtentional (*Figure 3.2.3*), and the eastern Great Basin (intermountain seismic belt). Seismicity in the eastern Great Basin is concentrated at the eastern edge (Wasatch Fault). On the longer time scales recorded in the geologic record, however, extension has been even more dispersed, including active structures throughout the Great Basin and eastward to the Rio Grande Rift in Colorado, New Mexico, and West Texas. Collectively, this ongoing deformation may pose a significant seismic hazard for several large urban centers (Salt Lake City, Reno, Albuquerque, and El Paso-Juarez) as well as many smaller cities in the intermountain area.

Existing geodetic velocities in this region show evidence of time-dependent, postseismic deformation following earthquakes in the western half of the Great Basin. Because the background tectonic extension rates are so slow, conclusions about long-term tectonics can be affected by even very small (~1 mm/yr) postseismic transient deformation, which may remain from earthquakes that occurred decades ago. Although this effect causes confusion in the limited time series collected to date, ultimately as EarthScope studies continue, this region may provide critical clues that will help us understand the relative rheologies of the lithosphere and asthenosphere.

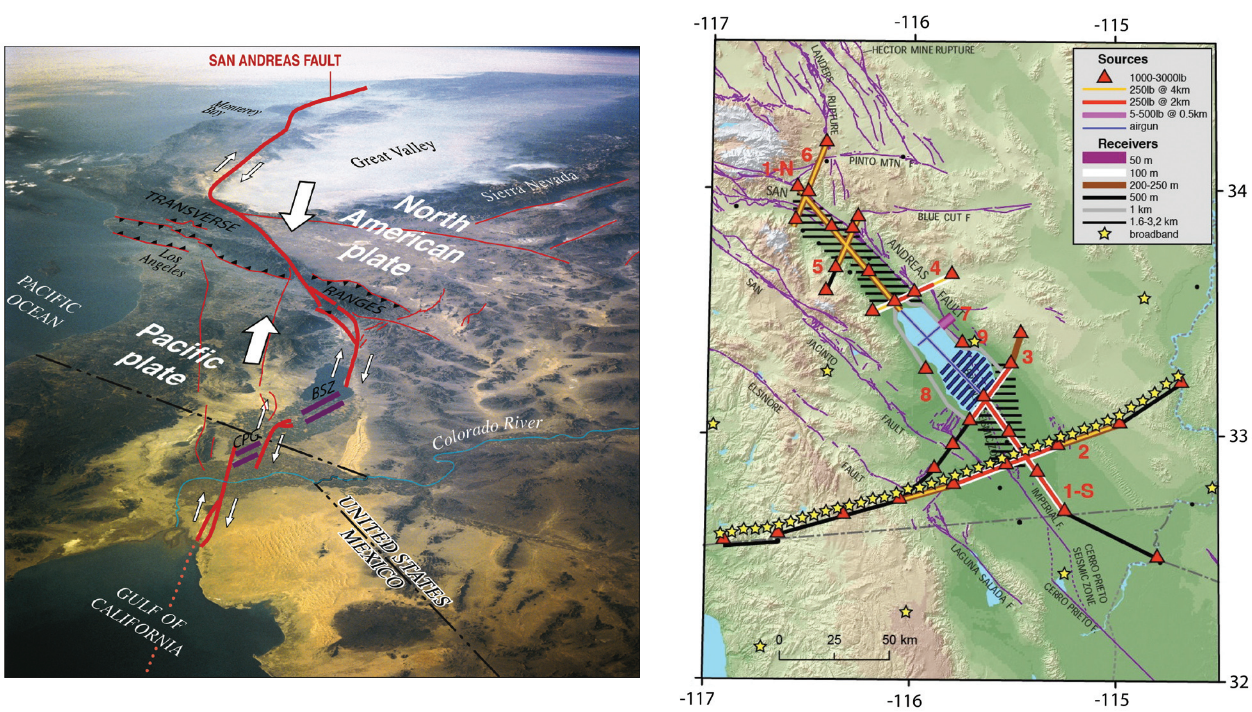



**Figure 3.2.3.** A major controlled-source and broadband seismic survey will soon be acquired across and along the Salton Trough to study rift processes and earthquake hazards (http://www.geophys.geos.vt.edu/hole/salton/). This project is jointly funded by EarthScope, MARGINS, other NSF-EAR programs, and the USGS and is an example of the type of project needed to link mantle structure to surface geology. (left) Space Shuttle photograph of southern California and northern Mexico showing the plate boundary as it changes from a right-stepping transtensional system in the Gulf of California and Salton Trough to the transpressional San Andreas Fault in the large left bend in the Transverse Ranges. Heavy red lines are strike-slip plate boundary faults; thin red lines are other strike-slip faults of the San Andreas fault system; thin red lines with black teeth are thrust faults; purple lines are spreading centers (CPG – Cerro Prieto geothermal area; BSZ – Brawley seismic zone); small white arrows show relative fault slip; large white arrows show relative plate convergence in the Transverse Ranges (schematic). (right) Schematic illustration of the Salton Seismic Imaging Project (SSIP). (courtesy of John Hole)

# SIDEBAR 8. RESOLVING STRAIN RATE ON THE SAN ANDREAS FAULT SYSTEM

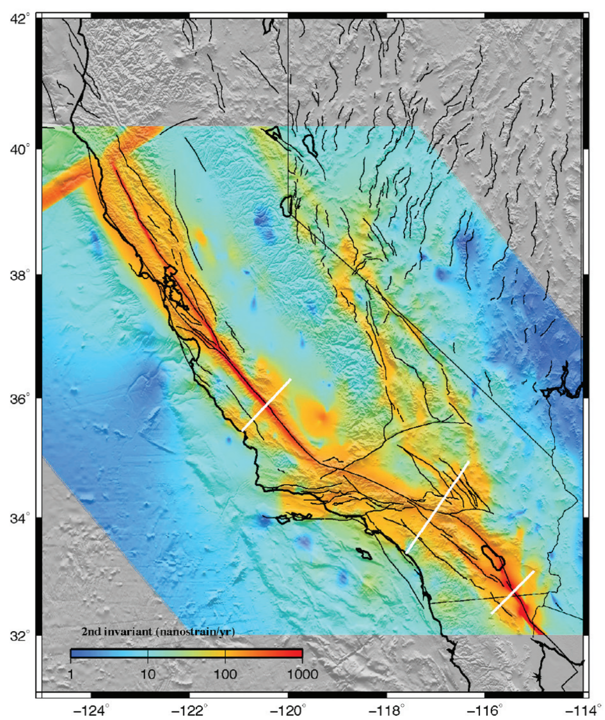
Strain rate, combined with the shear modulus of the crust and earthquake history, provide an estimate of the accumulated stress that is available for release in a future earthquake. Several geodetic research groups have used point GPS velocity measurements to construct maps of crustal strain rate for the San Andreas fault system (left panel). Because the typical spacing of GPS stations is 10 km or greater, an interpolation method or physical model must be used to compute a continuous strain-rate map. Four approaches are used to develop strain maps: isotropic interpolation, interpolation guided by known faults, interpolation of a rheologically layered lithosphere, and computed strain rates derived from a geodetically constrained block model. Strain rates vary by a factor of three to eight among the 10 models, mostly near faults. The important conclusions are that the PBO GPS array has insufficient density to measure strain rate directly, and that the range of permissible physical or interpolation models remains too broad.

Improving the accuracy and resolution of measured crustal strain will require dense GPS surveys across faults or continuous deformation images from radar interferometry (InSAR). The currently archived InSAR data have made limited contributions, because C-band radar interferograms do not retain correlation for more than about six months except in a few arid or urban areas (*Sidebar 13*), but L-band radar data lessen this problem. Although there will be no U.S. L-band mission for a decade, current and planned Japanese InSAR missions can precisely measure strain rates over lengths scales of 0.2–10 km, as long as sufficient observations are acquired.

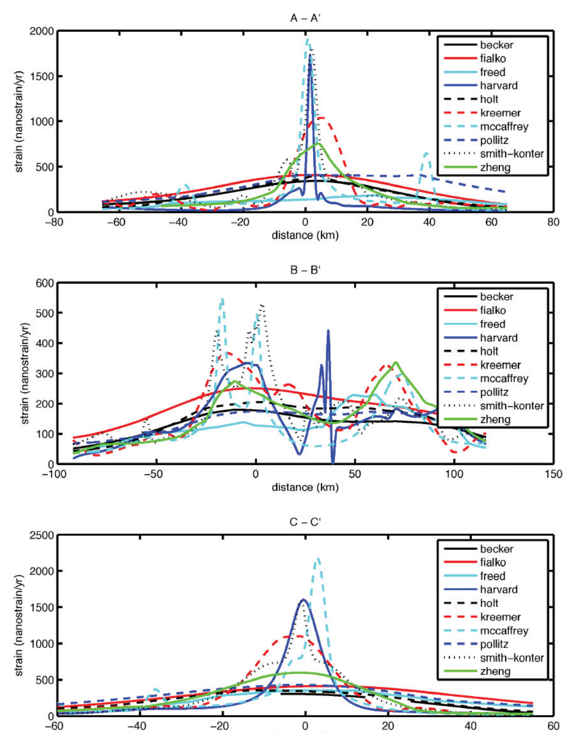
Improvements in the models used to derive crustal strain from sparse observations will require careful testing of model predictions against observations of steady interseismic velocities, and integration of additional data from seismicity, fault structure, and earthquake slip distributions. In areas with uniformly dense data coverage, model predictions are closer to each other than in sparsely instrumented areas (see right panels), but in all cases model predictions show unacceptably high variance from each other. Correct physical models are critical for determining strain and stress rates at depth from surface observations.

## References


Smith-Konter, B., and D.T. Sandwell, Stress evolution of the San Andreas Fault System: recurrence interval versus locking depth, Geophys. Res., Lett., 35, L13304, doi:10.1029/2009GL037235, 2009.


An example of one of the 10 strain-rate maps (Smith-Konter and Sandwell, 2009). In this example, 610 GPS velocity vectors were used to estimate model parameters. Deep slip occurs on 41 major fault segments where rate is largely derived from geological studies. The locking depth is varied along each fault segment to provide a best fit to the GPS data.




Profiles of strain rate across the San Andreas Fault at three locations show major disagreements especially within 15 km of the major faults. (upper) Profiles cross the Parkfield area where there is dense GPS coverage. (middle) Profiles across the Los Angeles Basin, and Mojave region where GPS spacing is highly non-uniform. (lower) Profiles across the Imperial Fault where campaign GPS coverage is very dense.

# SIDEBAR 9. MIGRATION OF THE LOCUS OF DEFORMATION ON THOUSAND-YEAR TIME SCALES

Thatcher and Politz (2008) summarize evidence for different deformation processes at different time scales. For example, well-resolved continuous GPS data indicate an extension rate that differs from geologically determined slip rates at Yucca Mountain, one of the most intensely studied sites on Earth. Using paleoseismology to examine seismic moment release vs. time for fault systems in southern California, Bennett et al. (2004) and Dolan et al. (2007) describe thought-provoking examples of the migration of the locus of deformation from one strand to another of the San Andreas fault system on time scales of thousands of years. Similarly, Thatcher (2003) notes that many continental areas show plate-like behavior based on geodetic data, yet geologic structure suggests more distributed deformation on longer time scales. Studies in southern Alaska suggest shifting deformation patterns on even longer time scales (Berger et al., 2008 and Chapman et al., 2008), where intense erosion and nearby deposition during the Pleistocene modified the topography faster than tectonics can rebuild it, producing shifts in deformation that apparently reflect this mass redistribution. San Andreas/San Jacinto example from Bennet et al. (2004); Eastern California Shear Zone from Dolan et al. (2007).

## References


Bennett, R.A., A.M. Friedrich, and K.P. Furlong, Codependent histories of the San Andreas and San Jacinto fault zones from inversion of fault displacement rates, Geology, 32:11, 961–964, doi: 10.1130/G20806.1, 2004.

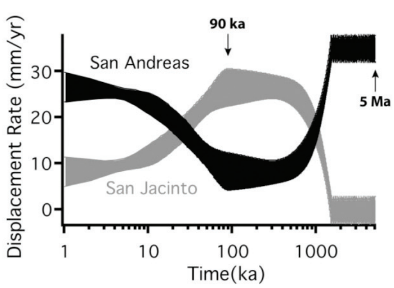
Berger, A.L., J.A. Spotila, J. Chapman, T. Pavlis, E. Enkelmann, N. Ruppert, and J. Buscher, Architecture, kinematics, and exhumation of a convergent orogenic wedge: A thermochronological investigation of tectonic-climatic interactions within the central St. Elias orogen, Alaska, Earth Planet. Sci. Lett., 270, 13–24, doi:10.1016/j.epsl.2008.02.034, 2008.

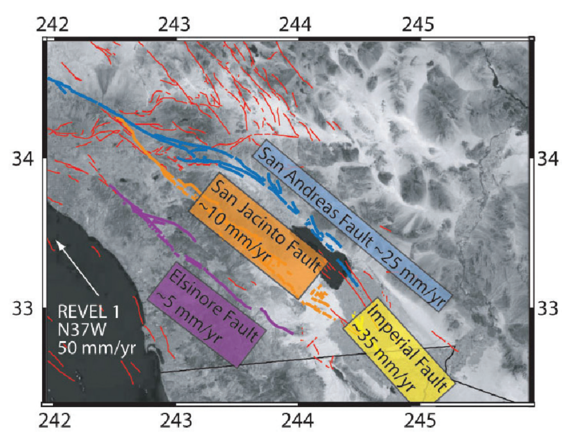
Chapman, J.B., T.L. Pavlis, S. Gulick, A. Berger, L. Lowe, J. Spotila, R. Bruhn, M. Vorkink, P. Koons, A. Barker, C. Picornell, K. Ridgway, B. Hallet, J. Jaeger, and J. McCalpin, Neotectonics of the Yakutat collision: Changes in deformation driven by mass redistribution, in J.T. Freymueller et al., eds, Active Tectonics and Seismic Potential of Alaska, American Geophysical Union, Geophysical Monograph 179, 65–82, 2008.

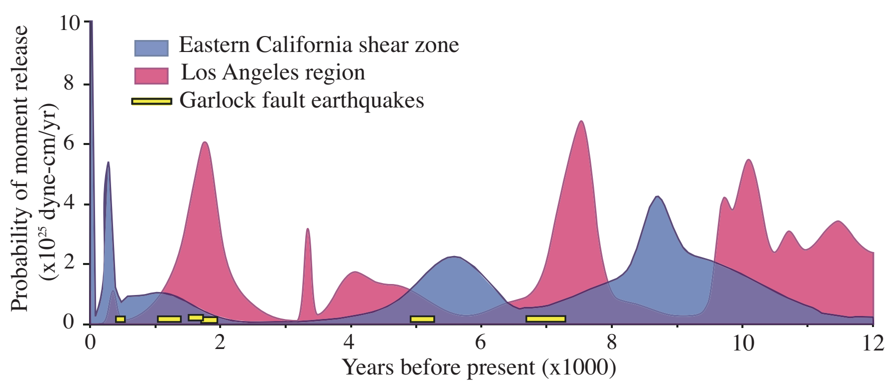
Dolan, J.F., D.D. Bowman, and C.G. Sammis, Long-range and long-term fault interactions in Southern California, Geology, 35:9, 855–858; doi:10.1130/G23789A.1, 2007.

Thatcher, W., GPS constraints on the kinematics of continental deformation, International Geology Review, 45, 191–212, 2003.

Thatcher, W., and F.F. Politz, Temporal evolution of continental lithospheric strength in actively deforming regions, GSA Today, 4/5, 4–11, 2008.

In the Gulf of California and its northern extension, the Salton Trough, divergence is occurring at plate-tectonic velocities and may involve frequent magmatic intrusion. Although EarthScope captures the beginning of the transition from the transform San Andreas system into rifting and seafloor spreading in the Gulf of California, its coverage does not reach the full seafloor spreading that occurs in the southern Gulf of California south of the U.S.-Mexico border. To study the entire transition, EarthScope data acquisition will need to extend into Mexico.

### 3.2.5 INTRAPLATE SEISMIC ZONES

Forty years after the development of plate tectonic theory, the processes responsible for intraplate seismicity remain unclear. As EarthScope continues eastward, one of its major contributions will be to illuminate the causes and consequences of large-magnitude earthquakes in continental interiors. Nearly every state has some record of earthquakes, typically on geological structures that were more active in the geologic past. The New Madrid Seismic Zone, which experienced four large, damaging earthquakes in 1811 and 1812 and continues to be seismically active, is the best-known example. A possible explanation for the New Madrid earthquakes is a stress concentration due to lateral variation in crustal strength and density structure associated with the Proterozoic Reelfoot Rift. Similarly, the devastating Charleston earthquake of 1886 may have occurred within a zone of strong lateral compositional and/or crustal thickness variations originally formed during the early stages of the opening of the Atlantic Ocean. These hypotheses remain to be tested through crustal imaging and geodynamic modeling.

Despite long recurrence intervals, large intraplate seismic events can be disproportionately catastrophic due to high stress drops and the rigidity of surrounding lithosphere, which promotes efficient wave propagation over long distances. EarthScope will help determine what causes these earthquakes, their magnitudes and recurrence intervals, how their waves and damage are affected by shallow subsurface properties, and how they differ from plate boundary earthquakes. Despite the regional seismic hazards posed by these events, local awareness and preparedness is commonly inadequate because of the long recurrence intervals. The upcoming bicentennial of the New Madrid events provides a special opportunity for EarthScope outreach and education.

### RECENT BREAKTHROUGHS

- EarthScope data show that there are ETS events throughout Cascadia and that ETS events preferentially nucleate in specific locations and define distinct segments (*Sidebar 2*).
- EarthScope data have dramatically improved resolution of the patterns and modes of deformation in the contiguous United States and parts of Alaska. These results are now being used to test large-scale dynamic models of plate boundary interactions and deformation within North America (*Sidebars 6 and 7*; *Figure 3.2.1*).
- Recent studies indicate that the entire state of Alaska is part of a broad circum-Pacific zone of deformation, from motion of the Bering plate in the Bering Sea and western Alaska to contraction in the Mackenzie Mountains of the northern Yukon. This realization provides a new framework for designing a data acquisition and interpretation plan for EarthScope in Alaska.
- Estimates of fault motion in eastern California appear to be anticorrelated in time with movement on the San Andreas fault system (*Sidebar 9*), perhaps related to strain hardening controlling alternating periods of activity and quiescence.
- GPS data suggest that the New Madrid fault zone displays very little or no present deformation. Given the recurrence of earthquakes in the geological record, the driving forces for intracratonic earthquakes remain mysterious.

### OUTSTANDING QUESTIONS

- What is the nature of the plate contact in subduction zones? What are the properties that control its potential for large earthquakes and other modes of slip, such as ETS?
- How do subduction interface geometry, composition, physical state, and slip characteristics influence observable forearc deformation?
- What is the 3D rheology of the lithosphere and asthenosphere at active plate boundaries, and how does it relate to earthquake cycle deformation, plate boundary forces, and other stresses that drive large-scale, long-term deformation of the continent?
- What controls the first-order variation from narrowly focused deformation in oceanic plates to broad zones of deformation in continental plates?

- What are the controls and responses to the lengthening of the San Andreas transform fault system, and how are these reflected in the kinematic structures and evolution of faults in the Mendocino Triple Junction region and the Salton Trough/Gulf of California?
- How much elastic vs. permanent strain occurs adjacent to the San Andreas and other strike-slip faults? Does this proportion change along the length of these faults?
- How do fault slip rates change and evolve over time, and over what time scales are fault slip rates constant? How do short-term geodetic measurements match with long-term geological measurements?
- What drives intraplate earthquakes, and how is the cycle of stress buildup and release different from plate boundary earthquakes?
- To what extent is the present deformation of the crust coupled to active deformation in the mantle?

# 3.3 Continental Evolution Through Geologic Time

The first five years of EarthScope activity have provided new insight into the processes that are currently forming and modifying continents. As the TA sweeps across the central and eastern United States and Alaska, a major challenge will be to integrate geological and geophysical data to understand the growth and modification of North America over billion-year time scales. This challenge includes evaluating the degree to which present tectonic processes can explain the geological evolution of the continent. If they cannot, how have the processes themselves changed through time, particularly since the Archean (>2.5 billion years ago)?

North America offers world-class examples of tectonic processes active in the geologic past: continental collision (e.g., the Appalachian-Ouachita Mountains), terrane accretion (e.g., Siletzia in the Cascadia forearc), far-foreland block uplifts associated with the Laramide orogeny in the western United States, Archean granite-greenstone terranes (Great Lakes region), intracratonic uplifts and basins, failed continental rifting (Mid-Continent Rift), and continental rupture. EarthScope can capitalize on recent insights into active tectonic processes by identifying older analogs that are the long-term record of ongoing processes. Similarly, older analogs can help to inform models of active processes by providing views of structures at different crustal levels and by providing time-averaged constraints on rates and boundary conditions. This "space for time" trade-off is not only a useful way to integrate the time dimension from geologic data sets into tectonic models, but will be essential for interpreting the geophysical results.

The core of North America formed from Archean microcontinents that were amalgamated around 2.0–1.8 billion years ago (*Sidebar 10*). A series of orogenic collisional events added large volumes of continental crust to the southern and eastern margins of the continent over the next billion years or so, ending with the Appalachian orogeny (0.5–0.3 billion years ago) whose eroded mountains punctuate the topography of the eastern United States. These continental-growth episodes were interspersed with periods of continental breakup, including the failed Mid-Continent Rift (*Figure 3.3*) and the successful post-Appalachian rifting that produced the Atlantic Ocean and left the eastern United States seaboard as a passive margin (*Sidebar 11*). These coupled collision and rifting events make up the supercontinent cycle.

Much remains to be learned about the architecture of the terranes in the deep crust and mantle, the processes of continental accretion and break-up, how the crust and mantle deform during collision and rifting, the role of magmatism (e.g., *Section 3.6*), and the evolution of surface topography. More broadly, EarthScope science will help to clarify the processes that allowed the thick (>170 km) continental lithosphere found beneath much of cratonic North America to be preserved for billions of years, with a few notable exceptions (e.g., the Wyoming craton; *Sidebar 4*).

Reactivation of earlier structures is a first-order process that influences the long-term evolution of continents and links active tectonics to the deep time aspects of EarthScope. Extreme heterogeneity in the crust (*Figure 3.3*) and mantle lithosphere, resulting from earlier tectonic episodes, ensures that later tectonic events act through a lithosphere that is strongly segmented in terms of its crust and mantle

# SIDEBAR 10. ASSEMBLY OF THE NORTH AMERICAN CONTINENT

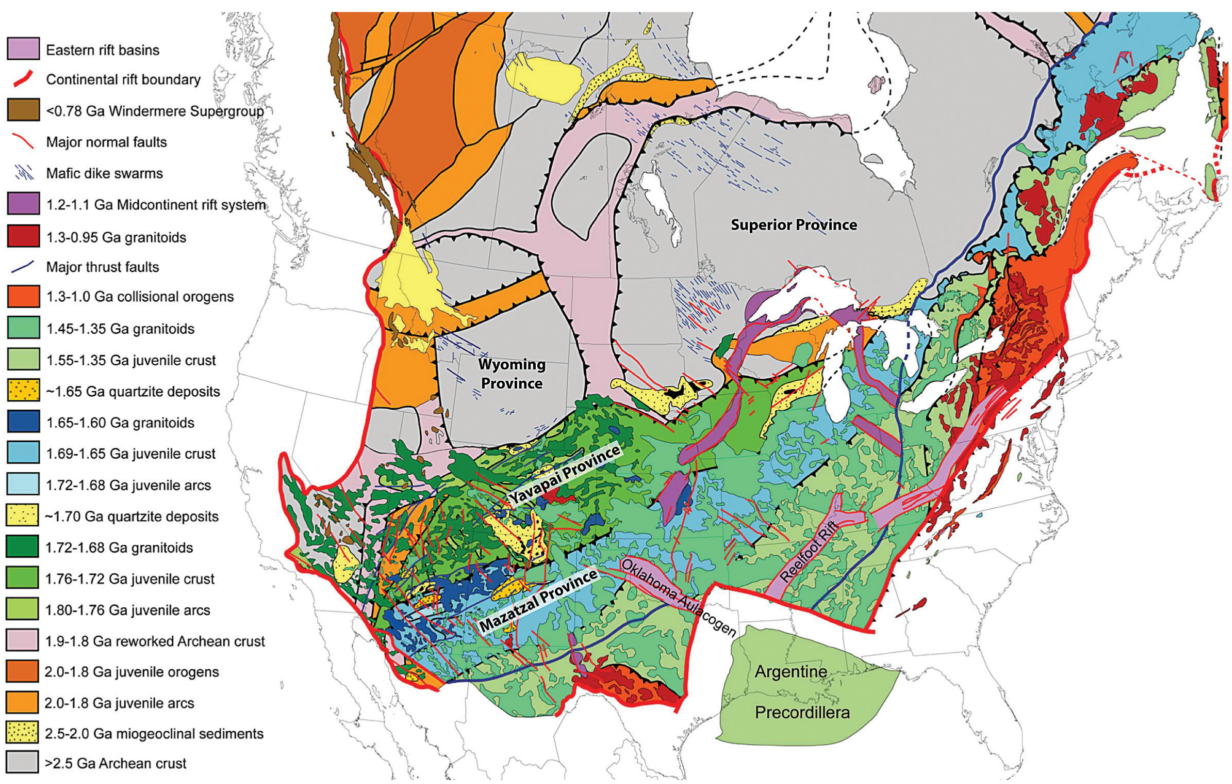
Continents are the long-term recorders of Earth history because they tend to be too buoyant to subduct into the mantle. North America preserves a record of progressive continental assembly in the Precambrian and serves as an important template for reconstructing the global assembly and disassembly of supercontinents.

The mid-continent region of the United States, although covered by a 1–2-km thick veneer of sedimentary rock, preserves the geologic record of some of the earliest events in the growth, stabilization, and evolution of North America. The northern mid-continent records the assembly of Archean microcontinents (the Superior and Wyoming Provinces) that were accreted to form the core of the continent by 1.9 billion years ago (Ga). Large volumes of continental crust were added to the southern part of that proto-continent during orogenic events at 1.8–1.6 Ga to form the Yavapai-Mazatzal Province, which today is oriented ENE-SWS and extends from New England to southern California. Widespread intracratonic magmatism intruded the newly added provinces at 1.4 Ga. Additions and modifications occurred along the eastern and southern margin during the Grenville (1.0 Ga) and Appalachian (0.5–0.3 Ga) orogenies and along the western margin for the past several hundred million years. Each of the mountain-building events involved numerous smaller terranes with a complex accretionary history, similar to western North America over the last 0.65 billion years. Rifting events were interspersed between orogenic events, such as the 1.1 Ga Keweenawan mid-continent rift and the (0.2 Ga) Central Atlantic Magmatic Province, which also modified the continental lithosphere. These coupled collision and rifting events make up the supercontinent cycle and led to the formation of the supercontinents of Rodinia (1.0 Ga) and Pangea (0.3 Ga).

The mid-continent region will be key for investigating issues related to how continents form and how tectonic processes have changed over time. Although the basic geometry of the provinces is known from limited geophysical work, and drill and outcrop data, EarthScope will provide an unprecedented opportunity to define the major accretionary boundaries and especially to investigate mantle structure that may be preserved from accretion and subsequent modification of the continent. A major question concerns the degree to which mantle heterogeneity such as that seen in the western United States will be observed in this apparently "stable" region. In addition, the region will provide insight into the long-term stability of continents and reactivation processes such as mid-continent rifting that have destabilized the continent. Finally, the mid-continent is a classic example of epirogenic uplift and downwarping, a type of tectonism that occurs in the interior of a plate. A challenge for EarthScope mid-continent studies is to clarify the causes and consequences of epirogeny and the links to mantle dynamics.

## Reference


Whitmeyer, S.J., and K.E. Karlstrom, Tectonic model for the Proterozoic growth of North America, *Geosphere*, 3, 220–259, doi:10.1130/GES00055.1, 2007.

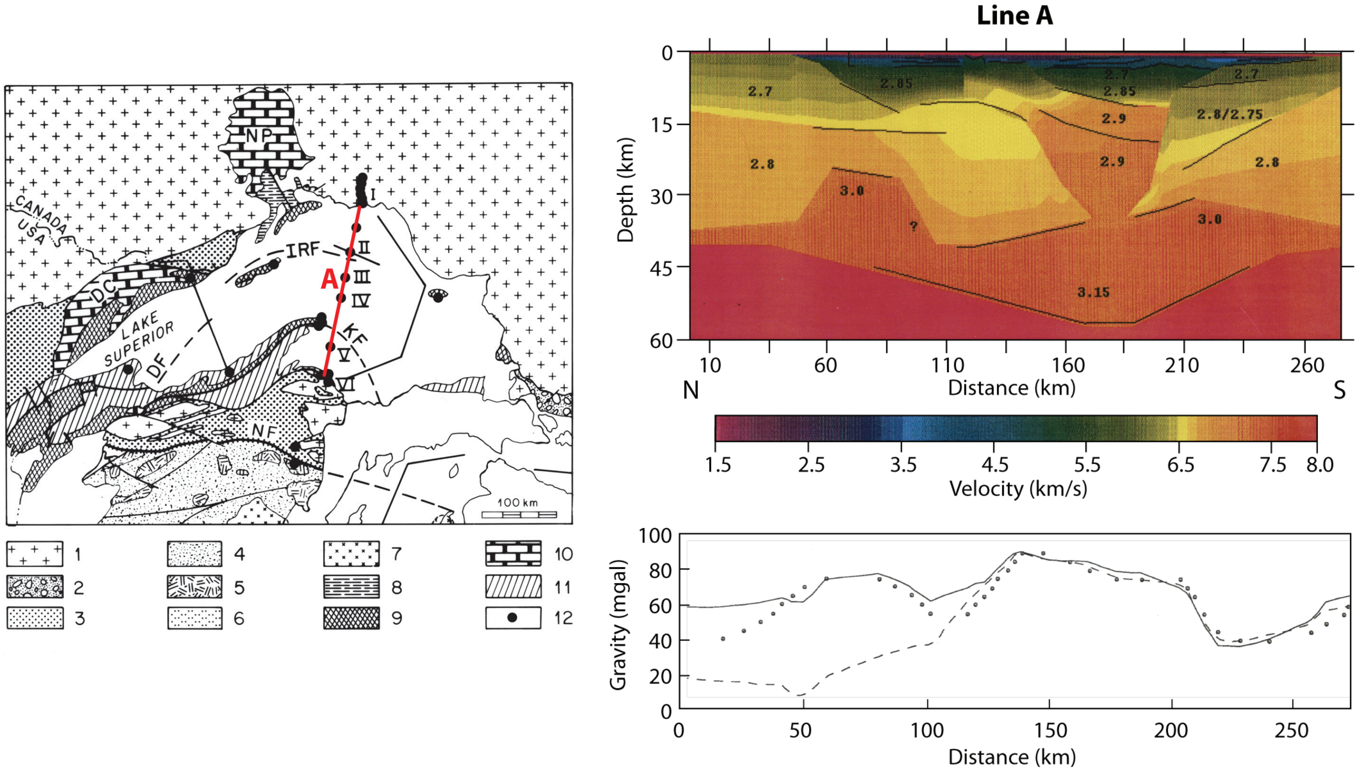



**Figure 3.3.** Crustal velocity model across the Mid-Continent Rift beneath Lake Superior (Tréhu et al., 1991). Data were acquired during the 1986 Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE), funded by the USGS and the Geological Survey of Canada. This program was one of the first onshore/offshore crustal imaging experiments that used ocean/lake-bottom and onshore seismometers to record marine airgun shots. Many others have since been conducted to image the crustal structure of continental margins worldwide. Seismic reflection data reveal a deep basin associated with the rift (Behrendt et al., 1988), and modeling of large-aperture seismic and gravity data indicate that much of the basin fill is dense, mafic rock and that the basin is underlain by a mafic "rift pillow." Strong lateral variations in the density of the crust and uppermost mantle have persisted here for 1.1 Ga. EarthScope data will show whether this event, which produced a volume of melt comparable to that in other Large Igneous Provinces (LIPs) around the world (Hutchinson et al., 1990), also left a signature in the mantle. **(left)** Location map of GLIMPCE seismic reflection profiles in Lake Superior overlain on a simplified geological map. DF – Douglas Fault; DC – Duluth Complex; IRF – Isle Royale Fault; KF – Keweenaw Fault; NF – Niagara Fault; NP – Nipigon plate. A – One of the seismic reflection profiles shot for GLIMPCE in 1986. 1 – Superior Province; 2 – Huron Supergroup; 3 – Marquette Range Supergroup; 4 – Penokean calc-alkaline volcanics; 5 – Penokean plutons; 6 – Baraboo quartzite; 7 – Granite-rhyolite; 8 – MRS lower sediments; 9 – MRS mafic volcanics; 10 – MRS mafic intrusions; 11 – MRS upper sediments; 12 – recording stations collecting refraction/wide angle reflection data during shooting of Profile A. **(right, top)** P-wave velocity model across Lake Superior. Black lines are boundaries from which wide-angle seismic reflections are observed. Numbers are densities used to calculate the gravity anomaly. **(right, bottom)** Gravity anomaly data (circles) and the anomaly predicted by the velocity model with (solid) and without (dashed) a second buried rift at model km 60-85.


*Behrendt, J.C., A.G. Green, W.F. Cannon, D.R. Hutchinson, M.W. Lee, B. Milkereit, W.F. Agena, and C. Spencer, Crustal structure of the Midcontinent rift system: Results from GLIMPCE deep seismic reflection profiles, Geology, 16, 81–85, 1988.*

*Hutchinson, D.R., R.S. White, W.F. Cannon, and K.J. Schulz, Keweenawan hot spot: Geophysical evidence for a 1.1 Ga mantle plume beneath the Midcontinent Rift system, J. Geophys. Res., 95, 10,869–10,844, 1990.*

*Tréhu, A.M., P. Morel-a-l'Huissier, R. Meyer, Z. Hajnal, J. Karl, R. Mereu, J. Sexton, J. Shay, W.-K. Chan, D. Epili, T. Jefferson, X.-R. Shih, S. Wendling, B. Milkereit, A. Green, and D. Hutchinson, Imaging the Midcontinent Rift beneath Lake Superior using large aperture seismic data, Geophys. Res. Let., 18, 625–628, 1991.*

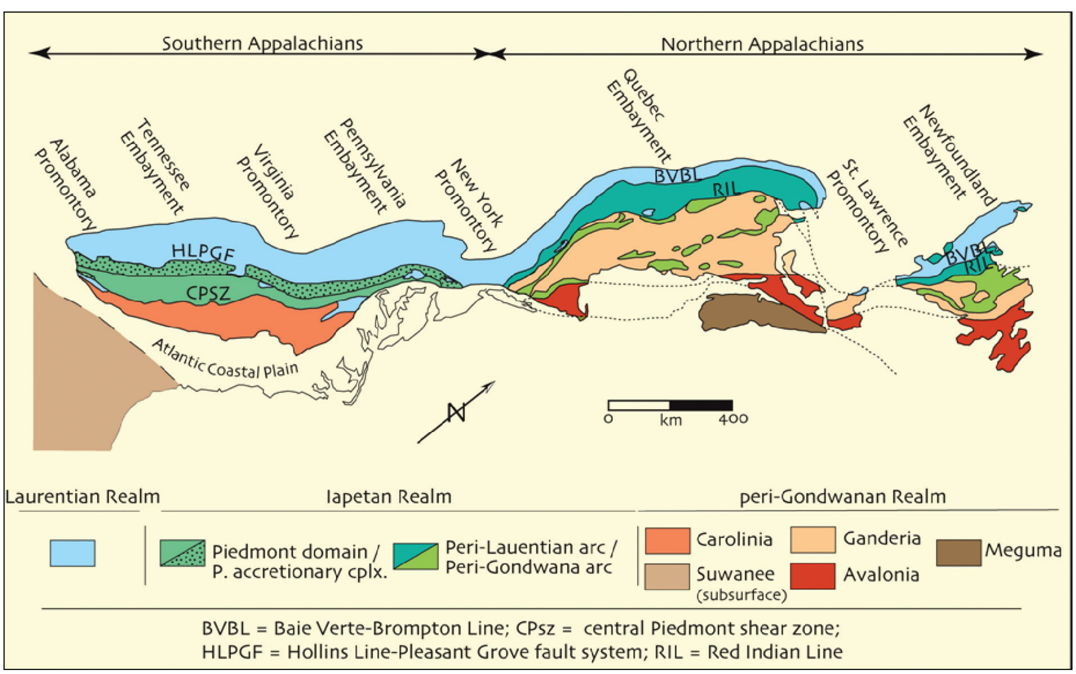

chemical compositions, rock fabric, grain size, and rheology (*Sidebars 10 and 11*). Understanding the effects of this segmentation will involve synergies with USArray, SAFOD, and PBO projects in the western United States, which are providing new insights into the influence of fault zone properties in creating and sustaining weak zones in the lithosphere as well as the impact of lithospheric delamination and "drips" (*Sidebar 5*) on surface deformation. Unraveling the history of the continent will require a strongly multidisciplinary approach that includes geologic mapping to provide the geometry of structures and terranes, geochronology to unravel the timing and overprinting of processes, petrology to constrain the environment of deformation and fingerprint the rock components and tectonic style, high-resolution geophysical images of subsurface structure, geochemical constraints on subsurface pressure and temperature conditions, and geodynamical modeling to integrate these constraints and test specific process hypotheses. Geologic constraints are a critical part of EarthScope, providing the time context that is essential for EarthScope to meet its broadest goals. Because key cratonic provinces cross the U.S.-Canada border and much of the oldest craton lies in Canada, coordinated deployments with Canadian science programs and results from past experiments (i.e., LITHOPROBE) will be important. As TA traverses these longitudes, the planned deployment of seismic stations in Ontario is critical. Additionally, onshore/offshore deployments and coordination with the

## SIDEBAR 11. RECORD OF RIFTING, COLLISION, AND MOUNTAIN-BUILDING EPISODES ALONG THE EASTERN UNITED STATES

The eastern United States, Mississippi Embayment, and Ouachita Mountains contain a record of a complete "Wilson Cycle," including continental collision, several episodes of mountain building during the formation of the supercontinent Pangea, continental rifting, and the establishment of a passive margin. EarthScope will provide a new image of crustal and mantle boundaries and heterogeneities that were established during mountain building and subsequently reactivated during rifting. In addition, worldwide attention has been focused on the causes and consequences of segmentation in continental and oceanic rifts. The eastern United States experienced two major rifting events following the Grenville and Appalachian orogenies. EarthScope will provide new data on preserved rift segmentation and associated transform faults from each of these events and the possible reactivation of rift structure during subsequent orogeny. One of the major outstanding questions concerns the controls on the Appalachian Mountains' present-day topography and the degree to which they reflect ancient tectonic processes or active mantle dynamics. One intriguing hypothesis is that subducted slabs, such as the Farallon slab in the deep mantle, may be contributing to modern uplift and buoyancy in the Appalachian region (*Sidebar 1*). A major challenge and future opportunity for EarthScope will involve integration with NSF-OCE, possibly developing new experiments to characterize the continent-ocean boundary and the preserved structure of continental rifting and the formation of a major ocean basin.

### Reference


Hibbard, J.P., C.R. van Staal, and D.W. Rankin, Comparative analysis of the post-Ordovician geological evolution of the northern and southern Appalachian orogen, in R. Tollo, M. Bartholomew, J. Hibbard, and P. Karabinos, P., eds., From Rodinia to Pangea: the Lithotectonic Record of the Appalachian Region, Geological Society of America Memoir 206, in press.

NSF MARGINS program will be necessary to capture the transition from rifted continental lithosphere to oceanic lithosphere in the southern and eastern United States.

### RECENT BREAKTHROUGHS

- Seismic images from EarthScope, the LITHOPROBE program in Canada, and the NSF Continental Dynamics program indicate that ancient continental sutures can preserve geometries and heterogeneities from collision processes, even including remnants of subducted plates. These results suggest that high-resolution imaging, combined with detailed geologic data sets, can reveal detailed records of continental growth processes and that heterogeneities and reactivated structures can indeed play a fundament role in subsequent tectonic processes.
- The science of geochronology has been revolutionized by high-precision dating, high-resolution in situ techniques, and by new methods involving a broad variety of mineral species and isotopic systems. Ancient terranes can now be better dated and correlated, and sedimentary deposits can be linked to source terranes and the evolution of land surfaces.
- The concept that specific zones within the crust or mantle have periods of relative weakness and can flow laterally has had a major impact on tectonic models. This recognition has highlighted questions about coupling and decoupling, heterogeneous flow between distinct layers of the crust and mantle, and the significance of orogenic plateaus through geologic time.
- Understanding the processes that destabilize continental lithosphere has been enhanced by better resolution of lithospheric delamination beneath the Sierra Nevada using data acquired with the FA (*Sidebar 5*).

### OUTSTANDING QUESTIONS

- How can we identify and characterize the geologic evolution of a particular region from subsurface images or geologic maps? To unravel ancient tectonic processes, it is critical to recognize and interpret structures from each stage of each cycle of collision and rifting.
- What are the major steps in the amalgamation and growth of the cratonic core of North America and when was the cratonic lithosphere stabilized?
- Were the processes that formed the early continental crust and mantle different from those acting today?
- How much of today's continental crust formed early in Earth's history or has been recycled from that early crust? How much has grown from younger magmatic and tectonic accretion processes?
- How has the crust-mantle boundary (the Moho) evolved through time?
- What is the composition and thermal structure of the continental mantle lithosphere as a function of age?
- What is the rheological profile of the lithosphere during collision, rifting, and stable periods, and how does this affect coupling as a function of depth?
- How can we recognize and interpret ancient zones of lateral flow in the crust and mantle from seismic images and field geology?
- How do thick roots of cratonic lithosphere survive erosion? Under what conditions are they destroyed?
- Can downwellings (lithospheric delamination or drips) and upwellings (plumes) be recognized in the geologic record and what role do they play in stabilizing or destabilizing the continent?
- What are the controls on along-strike heterogeneity (segmentation) in the Appalachian orogen and how does this heterogeneity persist throughout the super-continent cycle?
- What are the controls on Appalachian topography from the time of orogenesis to the present?

## 3.4 Deep Earth Structure and Dynamics

EarthScope is poised to make major breakthroughs in our understanding of the large- and small-scale patterns of mantle structure, dynamics, and evolution. Sublithospheric mantle processes impact surface tectonics, topography, stresses, and volcanic activity, and determine Earth's thermal and chemical evolution. Earth's large-scale pattern of subduction beneath the Pacific Rim and upwelling beneath the central Pacific and African plates has been identified, but how this system operates and how it is connected with small-scale patterns of mantle flow, with influences that extend through the lithosphere, remain substantially unknown. EarthScope-driven seismic methods are providing a new understanding of these dynamic patterns at spatial scales from tens to thousands of kilometers via the imaging of seismic velocities, anisotropy, attenuation, and mantle reflectors extending to the core-mantle boundary. Through integration of seismological images, geodynamical models, and constraints from petrology, geochemistry, crustal geology, and geodesy, EarthScope scientists are poised to reach a new level of understanding of the processes that connect the deep Earth with Earth's surface.

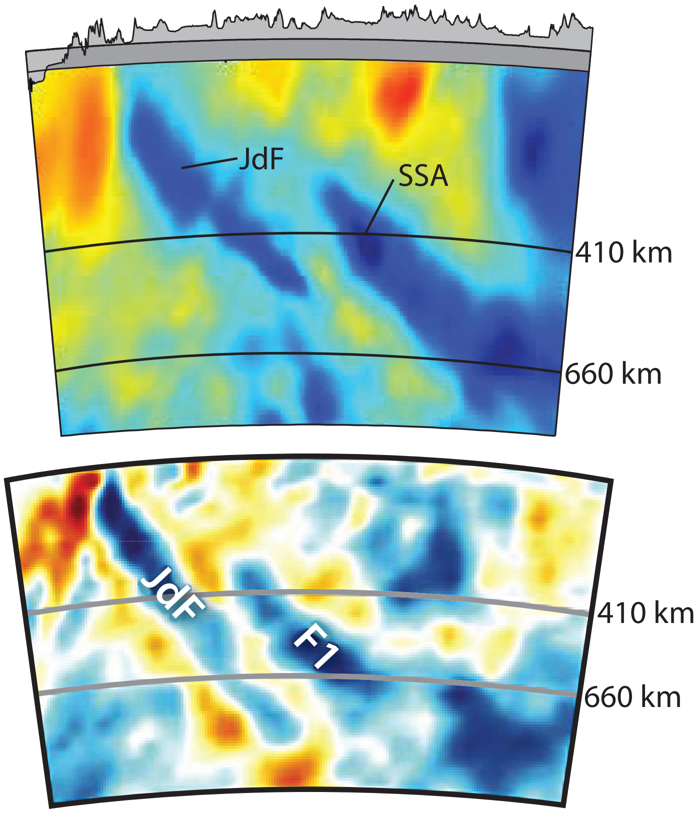



**Figure 3.4.1**. P-wave velocity models obtained by different research groups (upper is from Roth et al., 2008; lower is from Obrebski et al., in review;). As data quality improves, uncertainties decrease, and models derived using different procedures and codes are becoming more similar. Both models extend from the Pacific Ocean to the Colorado Plateau along latitude 41°N and show fast, east-dipping, slab-like anomalies. One anomaly has been interpreted as the subducting Juan de Fuca plate (JdF); the origin of the second slab-like feature (F1/SSA) is debated.

*Obrebski, M., R.M. Allen, M. Xue, and S.-H. Hung, Plume-slab interaction beneath the Pacific Northwest, in review.*

*Roth, J.B.., M. J. Fouch, D. E. James, and R.W. Carlson, Three-dimensional seismic velocity structure of the northwestern United States, Geophys. Res. Lett., 35, L15304, doi:10.1029/2008GL034669, 2008.*

## 3.4.1 SUBDUCTED SLABS AND MANTLE DRIPS

USArray data offer a unique opportunity to image the whole-mantle structure of the lithosphere subducted beneath the western margin of North America, addressing questions about the fate of subducted slabs and the dynamics of subduction. In the western United States, where TA data have already been collected, seismic imaging has revealed new details of the lithosphere as it subducts. For example, in some places the slab appears to buckle or broaden as it nears the 410-km discontinuity, which marks the top of the mantle transition zone (e.g., *Figure 3.4.1*). In addition, results from the western United States indicate that the slab dramatically affects mantle flow, producing flow patterns that curve around the edges of the Juan de Fuca and Gorda plates, the last remaining part of the Farallon plate (*Sidebar 6*). TA data will continue to map out the deepening subducted lithosphere as the array moves eastward, with the potential to add new constraints on the flux of upper mantle material moving into the lower mantle and the dynamics of the deep mantle. TA deployment in Alaska will allow detailed imaging of one of the most complex subduction zones on Earth.

Another exciting result has been the discovery and detailed mapping of active mantle downwellings or "drips" in the western United States (*Sidebar 5*). These downwellings may have been initiated by mantle flow, temperature, and compositional perturbations associated with subduction. A key question with important implications for lithospheric stability is whether apparent downwellings at the base of the lithosphere are ubiquitous across the continent, or whether they are confined to the actively deforming western United States. EarthScope data will answer this question as the TA moves east.

## 3.4.2 UPWELLING MANTLE BENEATH YELLOWSTONE

There are also mantle upwellings beneath North America. EarthScope is beginning to illuminate the structure of the mantle plume beneath the Yellowstone hotspot, which shows significant complexity (*Figure 3.4.2*). The strongest low-velocity anomaly beneath Yellowstone is limited to the upper mantle, but a column of low-velocity material extends as deep as 900 km beneath this region. The significance and implications of the deeper anomaly are currently under vigorous debate, but this feature will be more clearly resolved with

TA data over the next few years. Some of these structural anomalies may be influenced by mantle hydration from the extended history of subduction in the region.

The presence of water has also been suggested to explain a region of upper mantle low velocities beneath the eastern United States, with water possibly rising upward from the transition zone, which is capable of containing up to 2 wt% $H_2O$. The upwelling of water-rich warm plumes has been indicated as a mechanism for the breakup of continents, and resolving this eastern U.S. feature will be an important TA goal as it moves eastward.

## 3.4.3 THE LITHOSPHERE-ASTHENOSPHERE BOUNDARY

Variations in mantle properties that make the mantle lithosphere strong and the underlying asthenosphere weak remain a key question. EarthScope research will reveal much about the location and character of the lithosphere-asthenosphere boundary beneath North America. Colder temperatures at shallow depths undoubtedly play a role in making the lithosphere strong. However, other factors affect strength and viscosity, such as mantle mineral grain size and fabric, bulk chemical composition, water content, and the extent of partial melting. These characteristics are expressed in a variety of geophysical and geological observations, including seismic velocity, heat flow, electrical conductivity, apparent elastic plate thickness, post-glacial rebound, xenolith compositions and ages, and xenolith-derived geotherms. For example, lithosphere-asthenosphere boundary depths have been inferred from TA and permanent station seismic waveforms using a variety of methods (*Figure 3.4.3*). With its broad range of disciplines and high-resolution data sets, the EarthScope community is well poised to integrate these complementary approaches and make a significant contribution to understanding the physical and chemical origins of the lithosphere-asthenosphere boundary.

## 3.4.4 THE 410 AND 660 KM DISCONTINUITIES AND OTHER DEEP MANTLE INTERFACES

EarthScope seismic data will be able to resolve the small-scale topography on the major mantle discontinuities at depths of 410 and 660 km. These mantle interfaces are commonly interpreted as mineral phase transformations, but the degree to which they represent changes that are not purely a function of temperature and pressure, but rather reflect changes in

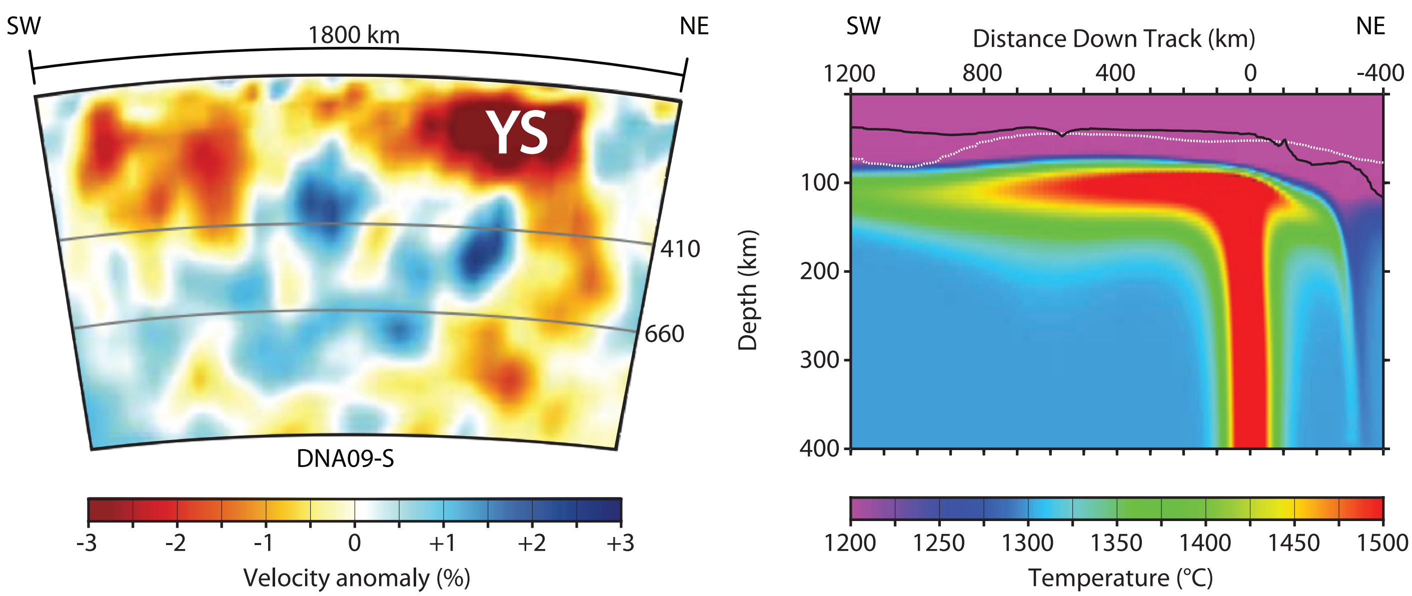



**Figure 3.4.2. (left)** Shear-wave velocity anomalies in a cross section aligned parallel to the track of the Yellowstone hotspot and the absolute velocity of the North American plate (Obrebski et al., in review). The section shows the strong low-velocity anomaly in the upper 300 km beneath the eastern Snake River Plain and a low-velocity conduit extending as deep as can be resolved (1000-km depth) beneath Yellowstone. **(right)** Thermal model for a plume rising beneath Yellowstone showing the effects of the moving lithosphere (Lowry et al., 2000). The imaged low-velocity conduit is more complex in shape than in the simple thermal model, which is likely due to its interaction with other objects in the mantle (not shown).

*Lowry, A.R., N.M. Ribe, and R.B. Smith, Dynamic elevation of the Cordillera, western United States, J. Geophys. Res., 105, 23,371–23,390, 2000.*
*Obrebski, M., R.M. Allen, M. Xue, S.-H. Hung, Plume-slab interaction beneath the Pacific Northwest, in review.*

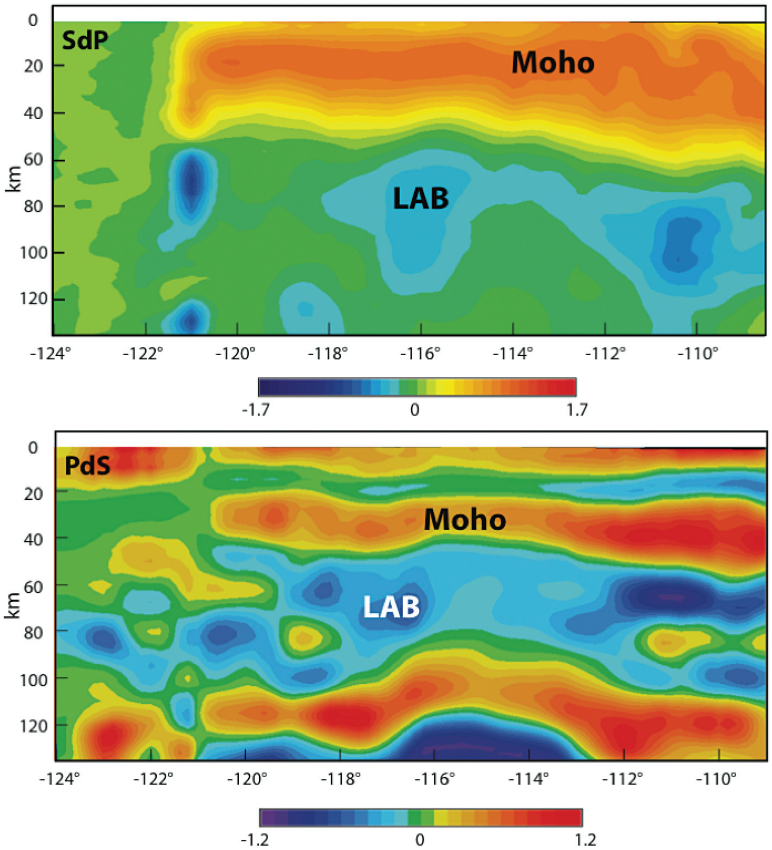



**Figure 3.4.3.** Imaging the lithosphere-asthenosphere boundary (LAB) in the western United States with USArray data. (a) Cross section of Sp receiver functions, Moho, and LAB on a profile from southern California to the Colorado Plateau at 34.8°N. (b) Cross section of Ps receiver functions on the same profile. The positive energy (orange) at 20–40-km depth is interpreted as the Moho, and the negative energy (blue) at 60–100-km depth as the LAB. (from Miller and Levander, in preparation)

chemical constituents, is still an open question. Topography on these boundaries and, in the case of the 410-km discontinuity, the possible presence of partial melt constrain the thermal and hydrous states of the mantle. These features are important indicators of mantle flow patterns. In addition, mid-mantle reflectors have been locally identified. Such features may be remnants of previously subducted oceanic crust that is still foundering in the mantle, and their locations, combined with remnants of erupted lavas, thus provide information about the distribution of ancient subduction zones.

## 3.4.5 MEGAPILES IN THE LOWER MANTLE

The two largest seismic anomalies within Earth's interior are the megapiles beneath the central African and Pacific plates that, in places, appear to extend upward more than 1000 km from the core-mantle boundary. Seismic studies indicate that these features are both high density and seismic low-velocity regions, and therefore may be chemically distinct from other mantle materials at comparable depths. Geodynamic modeling suggests that they are piles of dense mantle dregs that have been swept together by circum-Pacific subduction and entrained upward by mantle upwelling. Many questions about these megapiles remain, such as whether they are single entities or clusters of small-scale plumes. EarthScope data from the large number of western Pacific earthquakes recorded in North America are being used to examine Pacific megapile structure and help complete an understanding of the character of deep-mantle upwelling and therefore whole-mantle circulation.

## 3.4.6 STRUCTURE OF THE CORE AND CORE-MANTLE BOUNDARY REGION

The core-mantle boundary region (CMBR) shows a high degree of complexity and structural diversity. EarthScope data are providing a new level of resolution for this fundamental thermochemical boundary layer, which plays a vital role in Earth's thermal evolution. EarthScope seismic stations in the conterminous United States are well situated to record large numbers of seismic data that interact with the CMBR and reveal a complexity of layering. A major discontinuity above the core-mantle boundary is the result of a phase change from the mineral perovskite to a post-perovskite phase, but recently discovered complex layering has been hypothesized to arise from a combination of folded subducted oceanic crust, multiple phase boundaries, and/or laminar structures of chemically anomalous materials. TA array data also show the CMBR to be highly anisotropic and to contain regions of ultra-low seismic velocities that are likely to be associated with partial melt (*Sidebar 12*).

Though seismic waves are not able to discern velocity heterogeneities within the liquid outer core, the fine resolution of EarthScope TA will help reveal layering in the top and bottom 100 km of the outer core. The presence of distinct layers in these regions is a likely outcome of the unique thermochemical convection that creates Earth's magnetic field, and these regions may have some degree of finite rigidity. The TA will also help to resolve the surprisingly heterogeneous inner core, which shows significant variations in velocity, anisotropy, and attenuation. The strong hemispherical variation of the inner core is especially puzzling in light of observations that it is rotating slightly faster than the mantle. Deployment of the TA in Alaska will be especially important because the seismic paths from South Sandwich Island earthquakes to Alaskan stations, sampling the inner core at directions more parallel to Earth's spin axis than most other paths, have been very important for identifying inner core structure and rotation.

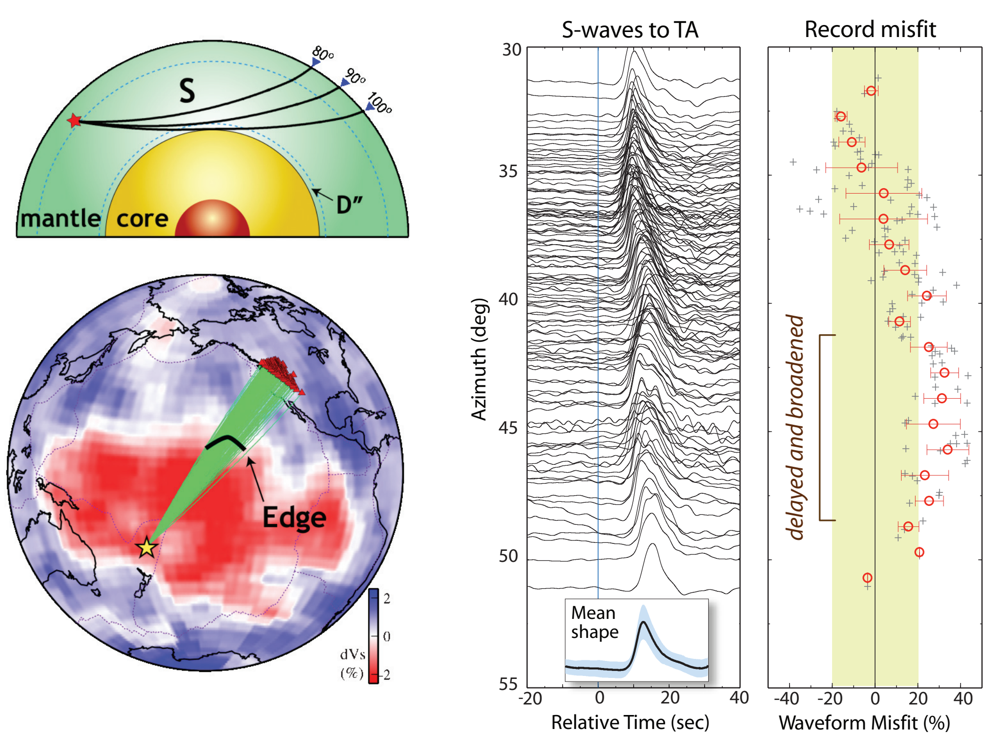
## SIDEBAR 12: HETEROGENEOUS LOWERMOST MANTLE BENEATH THE PACIFIC OCEAN

USArray TA seismic stations record earthquakes from around the globe. Direct P and S waves recorded at ~90°–100° from an earthquake are sensitive to the structure near the core-mantle boundary, where these waves bottom and return to the surface. Recent analyses of seismic waves traveling through the D" region reveal a variety of fine-scale complexities that include isolated and thin ultra-low velocity zones with velocities reduced by ≥10%, directional dependence of seismic wave speed, and discontinuities in velocity consistent with the presence of post-perovskite.

Comparison with global tomography reveals that seismic waves from a 2007 Fiji earthquake that sampled the lowermost mantle beneath the Pacific Ocean propagated near a low-velocity boundary, which is also evident in the broadening of the S waves for azimuths between ~42°–47° due to multipathing. Shown are paths (green) from the earthquake (star) to the TA stations (triangles) on top of lowermost mantle S-wave velocity perturbations (tomography courtesy of Steve Grand, Univ. Texas, Austin), where red and blue represent lower and higher speeds relative to an average model, respectively. The thick black line denotes a sharp velocity boundary deduced from observed waveform and travel time anomalies. Observed SH displacement is plotted relative to predicted arrival time (blue line at time=0) and as a function of direction from the source. The arrival times change systematically. Averaging over several measurements results in robust estimates (red circles) that show significant waveform broadening (circles outside shaded region) corresponding to sharp changes in seismic velocities.

### Reference

Garnero, E., and C. Zhao, Heterogeneous lowermost mantle beneath the Pacific Ocean, EarthScope OnSite Newsletter, fall 2009.



An important limitation of studying the deep mantle and core is uncertainty regarding their chemical and mineralogical natures. However, it is fairly clear now that chemical as well as thermal variations play a role in both mantle and core convection. Not only are surface constraints such as the histories of tectonic motions and crustal evolution required, but also high-pressure mineral physics research is needed to constrain the range of possible chemistries, theoretical geodynamic modeling is needed to define the range of possible convective modes, and geomagnetic research is needed to understand the forces that drive core convection and the growth of the inner core. The integrated, multidisciplinary approach of the EarthScope program is well suited to the collaborative needs of understanding the structure, composition, and history of Earth's deep interior.

## RECENT BREAKTHROUGHS

- Tomographic images have revealed startling complexity in the shape of the subducting Juan de Fuca plate, including an apparent "double" slab. Results from different groups are converging (*Figure 3.4.1*).
- A fast velocity anomaly dips beneath Nevada into the transition zone to depths of 800 km. This feature could represent a cold downwelling, and, based on mantle anisotropy, appears to have significantly disrupted mantle flow patterns (*Sidebar 5*).
- Intense low velocities occur along the track of the Yellowstone hotspot at shallow mantle depths, but this anomaly is underlain by a plume-like column of weaker low velocities that extends as deep as 900 km (*Figure 3.4.2*).
- Shear-wave splitting measurements suggest a tight rotation in mantle flow around the southern edge of the Juan de Fuca/Gorda plates at the Mendocino Triple Junction (*Sidebar 6*).
- USArray is enhancing resolution of the seismic properties of the lithosphere-asthenosphere boundary beneath North America, shedding light on origin of the rheological differences between the lithosphere and asthenosphere (*Figure 3.4.3*).
- USArray data have revealed the 3D shape of the massive Pacific megapile that rises from the core-mantle boundary.
- USArray is being used to map out the complex layering of the CMBR, allowing inferences about the evolution of this thermochemical layer to be made (*Sidebar 12*).

## OUTSTANDING QUESTIONS

- How does the lithosphere subducting beneath North America interact with the transition zone and lower mantle? What does its shape imply about slab and surrounding mantle viscosity and buoyancy? Is the transition zone a temporary resting place for subducting slabs?
- How does the older and deeper subducted lithosphere (the Farallon/Kula slab) connect with the Juan de Fuca and Gorda lithosphere now subducting beneath the Pacific Northwest?
- Is the low-velocity upper-mantle anomaly aligned with the Yellowstone hotspot connected to a plume-like feature at transition-zone depths and deeper? What do the shape and amplitude of this feature imply about mantle flow and temperature?
- To what depth do the Nevada drip and other localized downwellings extend? Do zones of upwelling and melting accompany downwellings?
- What does the pattern of mantle anisotropy imply about flow around the subducting lithosphere or associated with mantle upwellings and downwellings? Where does anisotropy reflect crystallographic fabrics (aligned mineral axes) and where does it reflect melt textures?
- What are the relative contributions of temperature, composition, and asthenospheric melt to creating the rheological difference between the lithosphere and asthenosphere?
- What is the topography on transition zone discontinuities across the continent? What do these topographies imply about mantle temperature, hydration, and flow patterns?
- Is the transition zone the largest reservoir of water within Earth?
- What is the distribution of perovskite and post-perovskite phases in CMBRs densely sampled by EarthScope data?
- Do ultra-low velocity zones represent partial melt and what do they imply about mantle geotherms, solidi, and compositions?
- What are the details of core structure, including inner core anisotropy? What does this structure imply about core dynamics, including inner core rotation?

# 3.5 Earthquakes, Faults, and the Rheology of the Lithosphere

Earthquakes are one of the most dramatic manifestations of lithospheric dynamics. EarthScope's observational wealth and integrated approach are offering new constraints on the basic underlying processes operating within fault zones and the response of the lithosphere to faulting. The combined seismic and geodetic networks have already uncovered a surprising family of slow-slip events and, combined with data from the SAFOD core, the seismological community is starting to fill in the missing links between earthquakes and creep (*Sidebar 2*). The unprecedented seismic coverage combined with LiDAR, geodesy, and direct core samples is constraining the process of earthquake triggering as well as the effects of fault zone structures on ensuing earthquakes. The roots of faults are being imaged by USArray, and PBO is recording the cycle of deformation that includes information on lithospheric rheology and how fault motion is accommodated at depth within the lithosphere. Strategic use of the flexible aspects of the facility during major episodes of slow slip, earthquakes, or volcanic eruptions can further leverage these observational gains. The importance of unanticipated discoveries from exploring the data (e.g., ETS) and from acquiring new types of data (e.g., InSAR and LiDAR) should not be overlooked.

## 3.5.1 STRESS AND FRICTION

Moving from the current empirical understanding of earthquakes to a full physics-based model of earthquake initiation, propagation, and arrest requires knowledge of the stresses on faults, how the stresses change with time, and the influence of pore fluid pressure. Such a model also requires knowledge of how the fault resists slip during an earthquake, how the stresses recover afterward to prepare for the next event, how one earthquake promotes or inhibits another, and how the material properties of a particular fault affect its propensity to fail catastrophically, rather than creep. Resolving these issues depends on the integration of a broad range of data and interpretations.

EarthScope has already made major contributions to fundamental observations of earthquake systems. These include bare-Earth LiDAR imagery of the major active faults of the San Andreas fault system and several other important faults (*Sidebar 13*), borehole strainmeter and continuous GPS recordings of slow slip in the Cascadia subduction zone, regional-scale observations of seismicity from the TA, FA recordings of the non-volcanic tremor wave field, and direct sampling at depth of the rocks, fluids, and gases from the heart of the San Andreas Fault at SAFOD, with accompanying geophysical logs and near-field recordings of microearthquakes (*Sidebar 14* and *Figure 2.3*). InSAR data are being used to measure coseismic and interseismic deformation as well as uplift and subsidence due to volcanic and hydrologic processes (*Sidebar 15*).

These new data sets are being vigorously analyzed by the research community to address the mechanics of earthquakes and the structure, strength, and deformation mechanisms of faults. A major goal of EarthScope science in the coming years will be to incorporate observational data and measurements into physics-based models of dynamic rupture, earthquake interaction, and fault system evolution. The vast range of temporal and spatial scales believed to control fault behavior, however, presents a major challenge.

Progress on characterizing microscopic fault friction is being made with a combination of geological, theoretical, seismological, geodetic, and computational investigations of earthquakes, faults, and fault systems. SAFOD cores are providing samples of microstructures and textures created during earthquakes with important implications for fault processes. Laboratory studies have begun to explore the frictional properties of natural rocks and fault gouge at seismic slip speeds of 1–4 m/s. Theoretical and computational studies critically depend on the field data and laboratory measurements of the rheological properties of fault rocks under crustal conditions. Seismological studies using the high-precision capabilities of the borehole instruments provide measurements of dynamic and static stress changes and are using the earthquake energy budget to constrain dissipation processes. At a slightly larger scale, the non-planar geometry of faults, connections among faults, slip localization, off-fault damage, and deformation all contribute to fault stress and deformational behavior.

## 3.5.2 TOWARD A COMPREHENSIVE THEORY OF FAULTING

A fundamental goal of earthquake science is to develop a theory of faulting that applies across the entire earthquake magnitude spectrum and encompasses other modes of failure, including episodic slip and non-volcanic tremor. Earthquakes with magnitudes of M≤-2 with rupture dimensions of 1 m or less have been detected with the EarthScope instruments at SAFOD. In contrast, the largest earthquakes, M>9, have rupture lengths in excess of 1000 km. Are these greatest earthquakes no more than little ones that ran away, or are there fundamental differences in how large and small earthquakes nucleate and grow? For an earthquake to continue to propagate, the elastic energy flowing into the rupture front must exceed the energy needed to initiate and maintain slip. Laboratory studies suggest that the fault loses its strength

## SIDEBAR 13. MEASURING EARTHQUAKE SLIP FROM HIGH-RESOLUTION TOPOGRAPHY

The great $M_w$7.9 Fort Tejon earthquake of 1857 was the most recent earthquake along the south-central San Andreas Fault (SAF). Surface-slip reconstructions of this and preceding major earthquakes along the 1857 rupture trace have been the cornerstone in the formulation of characteristic and uniform-slip earthquake models, which largely influence current understanding of seismic fault behavior as well as seismic hazard assessment and earthquake forecasts. The 1857 surface slip was reported to have sections with essentially uniform displacement amounts—referred to as segments—and abrupt changes in offset amounts between segments. The largest offset during the 1857 and preceding earthquakes reportedly was 8–10 m along the Carrizo segment. The high-resolution “B4” LiDAR topographic data set covers the 1857 rupture trace. These airborne-acquired data have average shot densities of 3–4 $m^{-2}$, allowing production of digital elevation models with grid sizes as fine as 0.25 m, sufficient for depiction of meter-scale tectonic landforms.

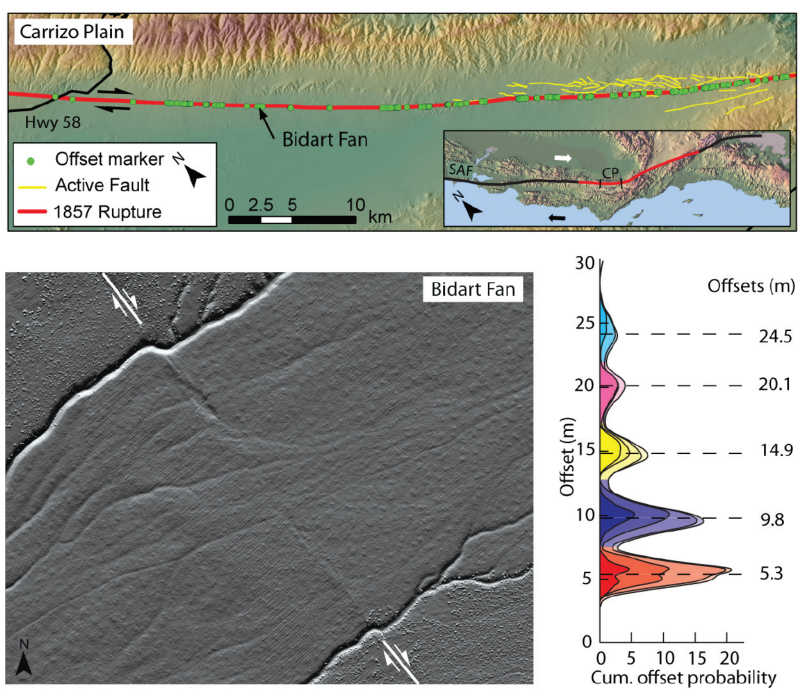
The revised surface-slip distribution based on “B4” data shows that the average slip associated with the 1857 event along the Carrizo section was with 5.3±1.4 m, significantly lower than the previously reported 8–10 m. Surface-slip distribution does not support distinct fault segmentation, eliminating a core assumption for a strong Carrizo segment that dominates fault behavior of the south-central SAF. Earthquake slip along the Carrizo segment may recur in earthquake clusters with cumulative slip of ~5 m.

### References


Ludwig L.G., S.O. Akciz, G.R. Noriega, R. Gabriela, O. Zielke, and JR. Arrowsmith, Climate-modulated channel incision and rupture history of the San Andreas Fault in the Carrizo Plain, Science, doi: 10.1126/science.1182837, 2010.

Zielke, O., J.R. Arrowsmith, L.G. Ludwig, and S.O. Akciz, Slip in the 1857 and Earlier Large Earthquakes Along the Carrizo Segment, San Andreas Fault, Science, doi:10.1126/science.1182781, 2010.

Zielke, O., Dissertation, Tempe, Arizona State University, 315 pp, 2009.


**(top)** Overview of 1857 surface rupture along SAF and distribution of offset measurements in Carrizo Plain. **(bottom left)** LiDAR -based hillshade plot (0.25-m grid size) of Bidart Fan site highlighting spectacular resolution of “B4” data set. **(bottom right)** Cumulative offset probability (COPD) for Carrizo Plain offsets where color intensity is based on quality rating of offsets used in stacking. COPD forms narrow, well-separated peaks.

## SIDEBAR 14. INSIGHTS INTO FAULT MECHANICS AND EARTHQUAKE SOURCE PROCESSES FROM SAFOD

SAFOD provides in situ geophysical and geological sampling of the San Andreas Fault northwest of Parkfield, California, from a depth where earthquakes originate. This is allowing researchers to test hypotheses regarding the composition, structure and processes within fault zones.

Borehole geophysical logs (shown below) document the presence of a 210-m-wide region of low P- and S-wave velocities and low resistivity. At the edges and within the low-velocity zone lie three narrow (1–3 m) zones of very low velocity; two of these are regions of borehole deformation as determined from repeated caliper log measurements. Geochemistry of rocks and gases from this region suggest that fluid-rock interactions play an important role in controlling where the fault is creeping (Wiersberg and Erzinger, 2007; Schleicher et al., 2009). Drill cuttings from the fault zone contained talc, a mineral with unusual physical properties (Moore and Rymer, 2007). Additional work on core samples is underway.

Seismological studies within the SAFOD holes provide insights into rupture and fault zone processes. Ellsworth et al. (2007) captured one of the SAFOD target earthquakes with a borehole instrument 420 m from the source and documented accelerations of up to 200 cm/s$^2$ and a static displacement of a few microns (see *Figure 2.3*).

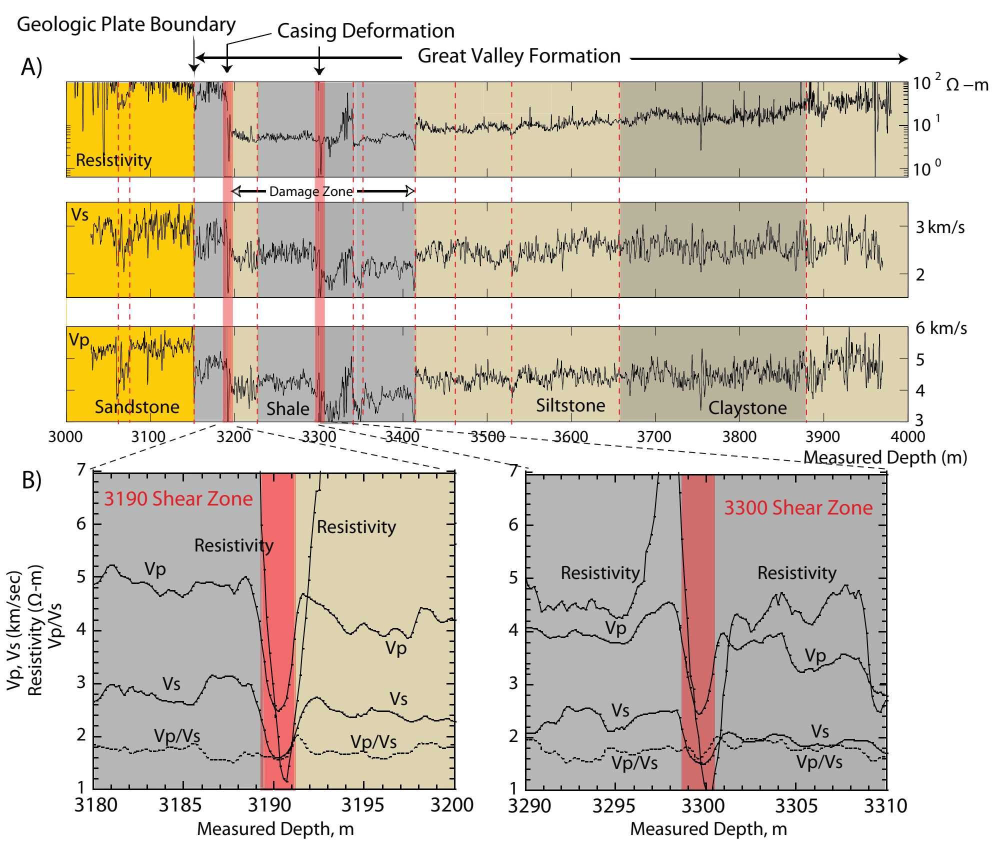
### References


Ellsworth, W., P.E. Malin, K. Imanishi, S.W. Roecker, R. Nadeau, V. Oye, C.H. Thurber, F. Waldhauser, N.N. Boness, S.H. Hickman, and M.D. Zoback, Seismology inside the fault zone: applications to fault-zone properties and rupture dynamics. Scientific Drilling Special Issue, 1, 85–88, 2007.

Moore, D.E., and M. Rymer, Talc-bearing serpentinites and the creeping section of the San Andreas fault, Nature, 448, doi:10.1038/nature06064, 2007.

Schleicher, A. M., S.N. Tourscher, B.A. van der Pluijm and L.N. Warr, Constraints on mineralization, fluid-rock interaction, and mass transfer during faulting at 2-3 km depth from the SAFOD drill hole, J. Geophys. Res., 114, doi:10.1029/2008JB006092, 2009.

Wiersberg, T. and J. Erzinger, Hydrogen anomalies at seismogenic depths of the San Andreas Fault, Abstracts of the 17th annual V. M. Goldschmidt conference: Geochimica et Cosmochimica Acta, 71,15S, A1110, 2007.

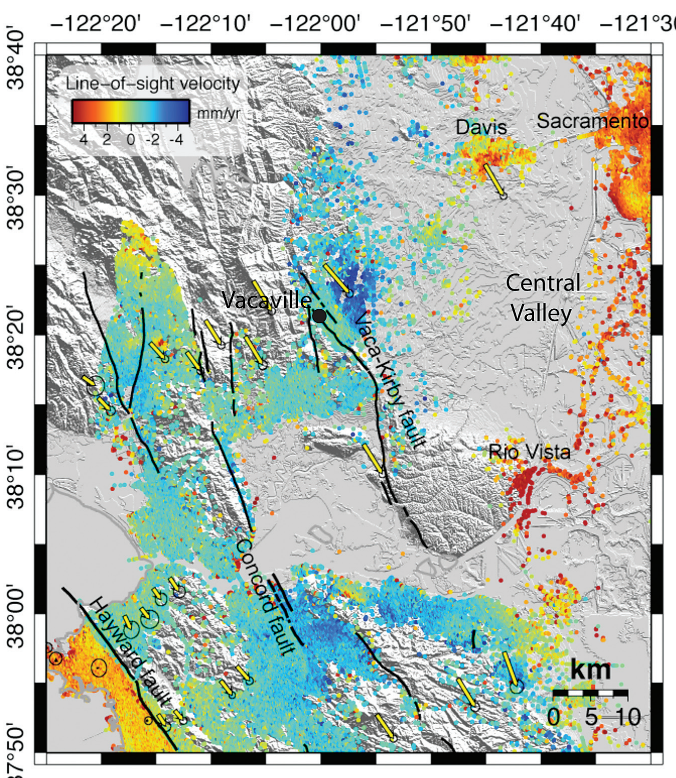




(A) Selected geophysical logs and generalized geology as a function of measured depth along the Phase 2 SAFOD borehole. Dashed red lines indicate faults. Thick red lines indicate deformation of cased borehole by fault creep. (B) The 3190 and 3300 m casing deformation zones correlate with localized zones (red) where physical properties are even more anomalous than in the surrounding fault zone. (courtesy of B. Ellsworth) after a displacement of tens of microns to a few centimeters. As the displacement grows to meters or tens of meters in the largest earthquakes, rocks in the fault zone would be expected to melt unless friction is very low or unless fluids lubricate the fault. Theories of friction, such as the rate-and-state model, need to be tested against direct evidence for how slip occurs at depth, which can only be obtained using near-field borehole observations made during rupture and by rapid-response fault drilling to exhume freshly faulted rock and measure the heat produced during slip.

### 3.5.3 NON-VOLCANIC TREMOR

Episodic slip in subduction zones is often accompanied by non-volcanic tremor, a poorly understood process that radiates feeble, high-frequency (2–10 Hz) seismic waves. Non-volcanic tremor can also be triggered by distant earthquakes and modulated by Earth tides (*Figure 3.5.3*). Transient deformation accompanies the movement of magma within volcanic systems, which may also trigger seismicity in brittle rocks at great distances from the magma. Recent work has shown that the tremor in the episodic slip events appears to result from slip on a fault, probably the interface of the subducting slab (or mega thrust). However, the relationship between the surface area of the fault that slips in ETS events and the area that will slip in a great earthquake remains uncertain. Geodetic models for slow-slip events and steady deformation in Cascadia suggest that there may be a gap between the locked portion of the fault and the region of slow slip, which occurs down-dip of the locked zone in most (but not all) regions. However, comparison of a large slow-slip event in Alaska with the

## SIDEBAR 15. PERMANENT SCATTERER INSAR DATA FROM THE EASTERN COAST RANGES AND GREAT VALLEY




Research using permanent scatterer radar interferometry (PS-InSAR) satellite measurements aims to constrain active tectonic and non-tectonic deformation, fault slip rates, and the distribution of aseismic slip. The measurements obtained provide information on the nature of elastic strain accumulation near seismogenic faults, their locking depth and slip rates, and any 4D variability that may exist.

Note uplift feature (negative line-of-site velocity) near Vacaville and rapidly subsiding areas in the Central Valley. Sharp offsets across the Hayward and Concord faults (black lines) are due to fault creep. Yellow arrows show horizontal GPS velocities from a regional compilation of campaign and continuous GPS measurements relative to a station on the central Bay block (d'Alessio et al., 2005). Figure and data from Bürgmann and Johansen, 2009.

#### References


Bürgmann, R., and I.A. Johansen, Deformation and earthquake potential of the eastern Coast Ranges from PS-InSAR measurements, National Earthquake Hazard Reduction Program, Final technical report, 08-HQGR-0095, http://earthquake.usgs.gov/research/external/reports/08HQGR0095.pdf, 2009.

d'Alessio, M.A., I.A. Johansen, R. Bürgmann, D.A. Schmidt, and M.H. Murray, Slicing up the San Francisco Bay Area: Block kinematics and fault slip rates from GPS-derived surface velocities, J. Geophys. Res., 110, B06403, doi:10.1029/2004JB003496, 2005.

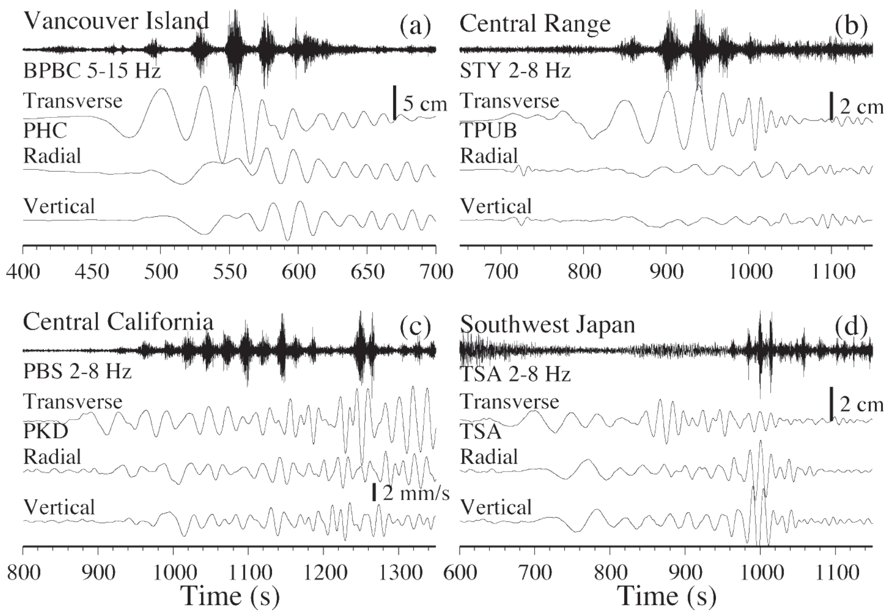



**Figure 3.5.3.** A comparison of surface waves of large teleseismic earthquakes and triggered non-volcanic tremor beneath (a) Vancouver Island in British Columbia (Rubinstein et al., 2007), (b) the Central Range in Taiwan (Peng and Chao, 2008), (c) the San Andreas Fault in Central California (Peng et al., 2008), and (d) the subduction zone is Southwest Japan (Miyazawa et al., 2008). The traces have been time-shifted to reflect the relationship between the surface waves and tremor at the source region.


*Miyazawa, M., E.E. Brodsky, and J. Mori, Learning from dynamic triggering of low-frequency tremor in subduction zones, Earth Planets Space, 60, e17–e20, 2008.*

*Peng, Z., and K. Chao, Non-volcanic tremor beneath the Central Range in Taiwan triggered by the 2001 Mw7.8 Kunlun earthquake, Geophys. J. Int. (Fast track), 825–829, doi:10.1111/j.1365-246X.2008.03886.x, 2008.*

*Peng, Z., J.E. Vidale, K.C. Creager, J.L. Rubinstein, J. Gomberg, and P. Bodin, Strong tremor near Parkfield, CA excited by the 2002 Denali Fault earthquake, Geophys. Res. Lett., 35, L23305, doi:10.1029/2008GL036080, 2008.*

*Rubinstein, J.L., J. E. Vidale, J. Gomberg, P. Bodin, K.C. Creager, and S.D. Malone, Non-volcanic tremor driven by large transient shear stresses, Nature, 448, 579–582, 2007.*


rupture area of the 1964 Alaska earthquake suggests that they are adjacent and may overlap. Although we now know that certain stress changes can trigger tremor, understanding the cause of the strong periodicity of major ETS events in Cascadia (and the apparent absence of strong periodicity elsewhere) is a future goal for EarthScope.

## 3.5.4 ALONG-STRIKE VARIABILITY

Fault properties do not remain constant with depth or along strike. For example, frictional properties may change with depth so as to promote stable creep in the shallowest part, stick-slip behavior at greater depth, and stable creep again below the main seismogenic zone. Along-strike variations are also significant. For example, the central creeping section of the San Andreas Fault appears to creep steadily at all depths, generating frequent small earthquakes but apparently no large ones. Other fault segments of the San Andreas system creep in places, probably only at shallow depth, while others have no shallow creep at all. The Alaska subduction zone shows along-strike segmentation, with some segments having a very wide locked region corresponding to great earthquake rupture zones while others appear to be creeping continuously; the along-strike transitions between these very different segments appear to be abrupt. We do not yet know what controls these variations in fault behavior.

## 3.5.5 LITHOSPHERIC RHEOLOGY AND THE EARTHQUAKE CYCLE

Active deformation of Earth's tectonic plates is unevenly distributed in time and space. EarthScope's PBO provides high spatial and temporal resolution for deformation occurring within the western United States. These data, combined with other experimental and geologic constraints, will provide the basis for more accurate estimates of the rheology of the lithosphere and asthenosphere.

The large and sudden stress changes from large earthquakes result in crustal deformation, which in turn allows estimation of crust and mantle rheology. Studies of postseismic deformation reveal a striking lack of agreement on the relevant rheological properties and the dominant processes. Advancements in our understanding can only come from integrated studies of geodetically determined crustal motion, fault zone processes, deformational mechanics of the lithosphere and asthenosphere, and numerical modeling.

Observed postseismic transient deformation results from a combination of phenomena, including shallow afterslip on the fault, deep afterslip or transient deformation of the lower crustal shear zone beneath the seismogenic fault, viscoelastic relaxation of the upper mantle and perhaps lower crust, and poroelastic relaxation within the upper crust. Unraveling these effects has proven to be difficult. Spatially and temporally dense observations of three-dimensional deformation from a range of time periods before and after the earthquake are needed to address this problem. Data and models that integrate information from earthquakes, large stress changes from load variations (e.g., glacial-isostatic adjustment, load changes from paleo-lakes), and structural information will provide needed rheological constraints to better understand the seismic cycle and associated seismic hazard.

Large earthquakes are often followed by postseismic transient deformation that lasts for decades or even centuries as in the case of subduction zone earthquakes like the great 1964 Alaska earthquake. Postseismic deformation rates during the first few years after the 2002 $M_W$7.9 Denali Fault earthquake were an order of magnitude higher than pre-event rates and are likely to remain elevated for the next decade. Postseismic deformation persists from the 1992 Landers and 1999 Hector Mine earthquakes in southern California, and small but significant transients may remain from historical earthquakes in the Basin and Range province.

The development of reliable physical fault/earthquake models is an important EarthScope goal over the next decade. The simplest earthquake cycle models treat "interseismic" and "coseismic" deformation, but the existence of significant postseismic transients requires a more complex model. EarthScope data will provide sufficient constraints to develop 3D viscoelastic models with non-linear rheologies and/or lateral variations in viscosity. In addition, short-time-scale models must be integrated with deformation models that explain long-term geologic motions and crustal modification over geologic time scales. Such models may or may not be appropriate for regions of mid-plate seismicity, like the New Madrid Seismic Zone, where we fully understand neither the driving stresses nor triggering mechanisms for mid-plate seismicity. Explanation of both the spatial pattern and temporal history of mid-plate seismicity is an important goal of future research.

## RECENT BREAKTHROUGHS

- LiDAR images of the landforms along major active faults are revolutionizing paleoseismology. Results from the Carrizo Plain section of the 1857 Fort Tejon, California, earthquake have overthrown conventional wisdom about the amount and frequency of fault displacements there (*Sidebar 13*).
- The first pristine rock samples of an active fault have been obtained from the San Andreas Fault at SAFOD. Laboratory studies of the foliated, cohesionless, and highly altered fault gouge are showing a series of previously undocumented modes of fault deformation (*Sidebar 14* and *Figure 2.3*).
- Travel times of seismic waves between a seismic source in the SAFOD pilot hole and a receiver in the SAFOD main hole were observed to change prior to nearby microearthquakes on the San Andreas Fault representing a possible precursory signal.
- Changes in the properties of scatterers on the San Andreas Fault suggest that local fault strength is influenced by the passage of seismic waves from large earthquakes and that the largest earthquakes may influence fault strength globally.
- By combining continuous GPS, borehole strainmeter, and dense seismic array observations of ETS in the Cascadia subduction zone, it is now possible to track initiation, growth, propagation, and termination of individual ETS events. The physical connection between geodetically observed slow slip and non-volcanic tremor should become apparent as new data constrain space-time relationships.
- Ordinary earthquakes that radiate high-frequency seismic waves are now understood to be but one process in a spectrum of deformation mechanisms that include ETS, slow slip, creep, and ductile shear (*Sidebar 2*).
- The first comprehensive viscoelastic deformation models for western North America have been developed, which include contributions of viscoelastic relaxation from faulting near the major plate margins and from distributed faulting in the plate interior, as well as lateral variations in depth-averaged rigidity in the elastic lithosphere. Rigidity variations are consistent with a reduced effective elastic plate thickness in a zone a few tens of kilometers wide surrounding the San Andreas fault system.
- Data from the first few years after the 2002 $M_W$7.9 Denali Fault earthquake clearly demonstrate significant impacts from both afterslip and upper mantle viscoelastic relaxation, and require a multicomponent model with viscoelastic structure similar to that inferred from glacial-isostatic adjustment models. Predicted postseismic relaxation from historical earthquakes in the Central Nevada Seismic Belt is consistent with small spatial variations in observed strain, suggesting that effects of even relatively small earthquakes may persist for several decades.

## OUTSTANDING QUESTIONS

- How do earthquakes initiate? What factors trigger earthquakes and how large do they need to be to start rupture? What controls the branching of rupture or the triggering of one fault by rupture of another?
- How do fault geometry, rheology, and history combine to determine the propagation, size, and location of earthquakes?
- What is the friction on a fault at the depths and conditions at which big earthquakes rupture?
- How do earthquakes arrest and what determines the ultimate size of a rupture?
- How do active structures observed at the surface interact to accommodate deformation in the lower crust and upper mantle? What role do fluids play in these interactions?
- What drives earthquakes in areas far from plate boundaries?
- Are post-seismic after-slip, episodic slip, and non-volcanic tremor manifestations of the same physical process or are they distinct processes? What rheological properties control them? Is there a continuum of deformation rates between discrete brittle processes and continuous shear transients?
- What role do fluids play in the generation of non-volcanic tremor? How does non-volcanic tremor differ from volcanic tremor or ordinary earthquakes?
- What is the slip distribution during earthquakes and what can we learn from heterogeneities about fault geometry and fault rheology?
- How localized is the slipping zone during a single earthquake and how does it evolve to form a mature shear zone? How localized is the shear zone beneath the seismogenic zone?
- Is off-fault deformation primarily driven by the need to accommodate slip on non-planar faults or does it result from dynamic stresses at the rupture front?
- Do earthquakes smooth out or roughen stress heterogeneity on a fault? If it roughens the distribution, to what extent is the elastic rebound model an appropriate description of the earthquake cycle?
- Does earthquake complexity scale with magnitude? Do stress drop and radiated energy follow magnitude-invariant scaling or does this scaling break down at some length scale? What causes the large range of stress drops (a factor of 1000 or more) observed for earthquakes with the same magnitudes?
- Does the rheology of the continental crust depend on stress, and if so, what effect does this have on the earthquake cycle?
- What is the 3D variation of rheology across North America, and how does the variation control large-scale deformation?
- What is the stress distribution in the lithosphere, the absolute stress field, and the magnitude of stress heterogeneity? How does stress accumulate, get transferred through the lithosphere, and get released during the earthquake cycle? How much deformation occurs between seismic events, during an event, and shortly after an earthquake?
- Can we develop an integrated model of the earthquake cycle for the major faults in North America, consistent with short-term (tens of years), intermediate-term (hundreds of years), and long-term (>1000 years) deformation?

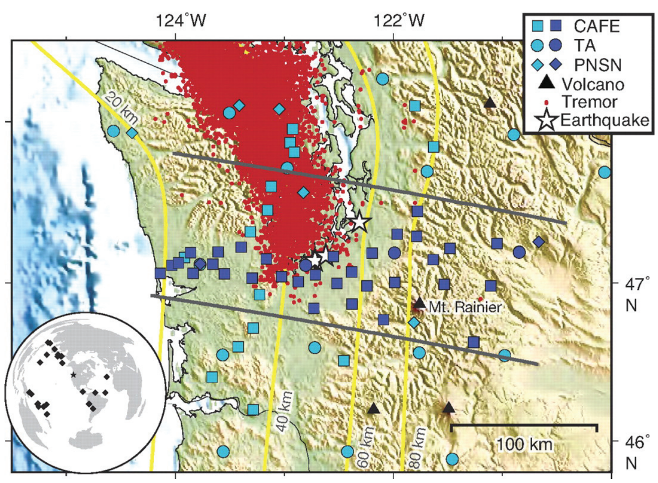
# 3.6 Magmas and Volatiles in the Crust and Mantle

The production and transport of fluids, including magmas, water, and carbon dioxide, fundamentally affect the thermal, compositional, and mechanical evolution of continental and oceanic lithosphere. The rise of melt and its interactions with the uppermost mantle and crust within rifts and subduction zones is the primary mechanism of continent formation. Volatiles (primarily $H_2O$, $CO_2$, and $CH_4$) driven off the top of downgoing slabs at subduction zones control volatile and magma fluxes in the overriding plate, and they moderate the process of fault slip along the plate boundary. The long-term global carbon cycle is controlled by the degree to which such volatiles are recycled into the deeper mantle with the subducted oceanic lithosphere. Magmatic systems regulate Earth's chemical evolution, transferring volatiles from the deep Earth to the atmosphere in both subduction and rift zones, and enriching or depleting volumes of Earth's mantle. With new advances in instrumentation and data coverage achieved by EarthScope, seismic, magnetotelluric, and geodetic methods can provide bounds on the distribution of melt, non-melt fluids, and volatiles dissolved in solid rock, providing some of the first 3D constraints on their generation, transport, and storage within continental regions.

## 3.6.1 SUBDUCTION ZONES

Within subduction zones, volatiles escape from the subducting slab and interact with the overlying wedge of mantle lithosphere, changing it to serpentine in the cold wedge corner, to other hydrous phases (e.g., talc or chlorite) deeper along the plate–wedge interface, and hydrating nominally anhydrous phases such as olivine and orthopyroxene in the deeper mantle wedge. These reactions change the thermal state of the slab-mantle interface at different depths, and probably determine the consequent changes in fault-slip properties with depth along subducting slabs. At still greater depths, these reactions lower the mantle wedge solidus temperatures and lead to partial melting within subduction zones. Magmas then rise to the surface to create subduction zone volcanoes, and thus they may influence rheology in the wedge and at all lithospheric levels, including coupling between plates and the deeper mantle at the lithosphere-asthenosphere boundary.

Transformative science from the first five years of EarthScope documents the importance of fluids and magmas in the lithosphere at a range of time and length scales, and moves us well beyond the traditional viewpoint of magma at discrete volcanoes. EarthScope seismic imaging has revealed the relation among ETS, metamorphic dewatering, and plate structure in Cascadia. The ETS locations indicate that slow slip occurs in a weak zone (e.g., clay-talc-serpentinite layer) at near-lithostatic fluid pressures, whereas intermediate-depth earthquakes nucleate in portions of the downgoing slab undergoing metamorphic dehydration (*Figure 3.6.1*). Newly



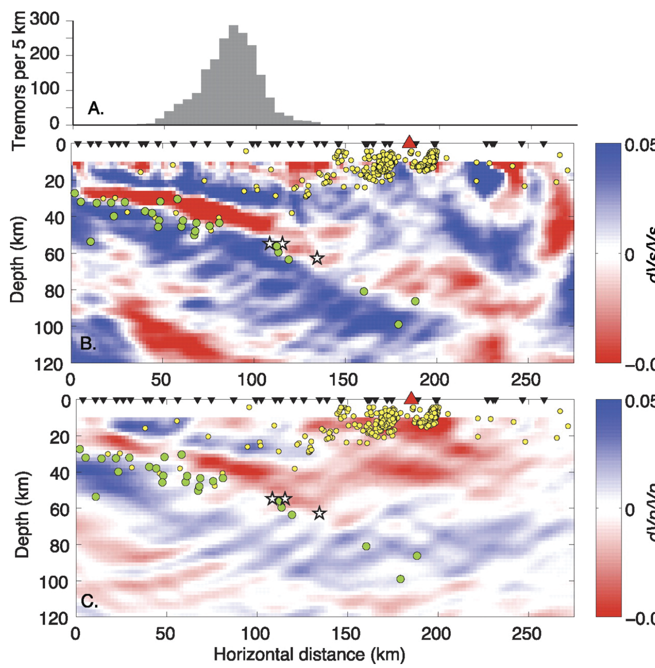




**Figure 3.6.1.** Correlation of earthquakes, seismic tremor, and the structure of the subducting plate in Cascadia (from Abers et al., 2009). **(left)** Tremor events (red dots) from 2004, 2005, 2007, and 2008 sequences located by an automated detection technique (Wech and Creager, 2008). Yellow contours show depth to Juan de Fuca slab at 20-km intervals (McCrory et al., 2004). Dark lines denote cross-section projection region. Stars show epicenters of the three largest (*M*>6.5) recorded intraslab earthquakes, in 1949, 1965, and 2001. Broadband seismic stations are in blue. Symbol shape indicates network (legend): CAFE – Cascadia Arrays for EarthScope; TA – EarthScope Transportable Array; PNSN – Pacific Northwest Seismic Network. Inset, lower left, shows earthquakes used in migration (diamonds). **(right)** Migration images for central Washington, with seismicity and tremor. Stations between the two black lines on the map were used to construct the 2D cross section; horizontal distance of 0 km corresponds to coastline. (A) Histogram of number of tremors shown in upper panel between section lines, in bins 5-km wide. (B) *S*-wave velocity variations from migration. Green circles: earthquakes >20-km deep and between 47°N and 48°N latitude, occurring during CAFE and relocated using same velocity model as migration. Yellow circles: selected events from local catalog (McCrory et al., 2004). Red triangle: Mt. Rainier volcano. Stars: three largest (*M*>6.5) recorded earthquakes at waveform-derived depths. (C) same as (B), but for P-wave velocity variations.

*Abers, G.A., L.S. MacKenzie, S. Rondenay, Z. Zhang, A.G. Wech, and K.C. Creager, Imaging the source region of Cascadia tremor and intermediate-depth earthquakes, Geology 37, 1119–1122, 2009*

*McCrory, P.A., J. L. Blair, D. H. Oppenheimer, and S. R. Walter, Depth to the Juan de Fuca slab beneath the Cascadia subduction margin: A 3-D model for sorting earthquakes, U. S. Geol. Surv. Data Ser., 91, 1–13, 2004.*

*Wech, A.G., and K.C. Creager, Automated detection and location of Cascadia tremor, Geophys. Res. Lett., 35, L20302, doi:10.1029/2009GL035458, 2008.*

developed thermal–petrological models provide a path forward to explore spatial correlations between the predicted locations of dehydration reactions and the observed loci of ETS. Ultimately, a better understanding of slip and coupling at the plate interface will inform assessments of the potential for damaging earthquakes.

Much synergy is also anticipated between EarthScope and MARGINS in the study of subduction zone magmatism and volatile cycling. Such topics have already been the strong focus of multidisciplinary studies at the MARGINS focus sites in the Central America and Izu-Bonin-Marianas subduction zones. Discoveries there have included the seismic evidence for outer-rise hydration/serpentinization of the Cocos plate, the undulating mantle and crustal seismic structure along the Izu volcanic arc, the separate effects of temperature and hydration on seismic attenuation in the mantle wedge, and the direct relationship between the water content of the mantle and the extent to which melting occurs beneath volcanic arcs and back-arcs. Such phenomena have yet to be revealed and modeled in Cascadia and Alaska, where the thermal structure of the subduction zone is at the hot end of the global spectrum (Cascadia) and where convergence rates span from high to low along strike (Alaska-Aleutians), providing an excellent opportunity for EarthScope and MARGINS interaction (see *Section 7.1*).

### 3.6.2 EXTENSIONAL REGIONS

Early and ongoing EarthScope studies, within the context of global studies, demonstrate the importance of magmatism on rifting in both "volcanic" systems as well as those previously identified as "non-volcanic." Ongoing research in the Salton Trough-Gulf of California rift-transform setting (*Figure 3.2.3*) provides fundamental insights into the role of aqueous and magmatic fluids in the evolution of continental rift zones. This research also informs models of geothermal exploration and enables assessment of earthquake and volcanic hazards within continental rifts.

Magma generated within the asthenosphere and/or mantle lithosphere percolates upward and ponds at the base of the crust and within crustal reservoirs. Periodic dike intrusions contribute to the plate opening, and may intrude at lower stresses than are required for fault slip. Dikes transport magma from mantle and crustal reservoirs, and also feed surface eruptions, as seen in the rock record of the Mid-Continent Rift, the U.S. East Coast igneous province associated with a mantle plume, and probably the Gulf of Mexico. Because dikes rarely reach the surface and their passage is marked by relatively small-magnitude earthquakes, their role in rifting remains poorly understood. Repeated episodes of dike intrusions and magma injection over the many millions of years between rift inception and breakup produce crust compositions that are transitional between continental and oceanic, and the magma transfers heat to the lithosphere. Magmatism during rifting, therefore, produces new crust and mantle lithosphere that accrete to the continents, increasing their breadth across passive continental margins and modulating their post-rift subsidence and thermal evolution. When, where, and how this magma transport and ponding occurs within the rift history requires studies of rifts at all stages of evolution, from inception to breakup. Hence, future EarthScope observations gleaned from the successfully rifted Gulf of Mexico and U.S. East Coast passive margins, combined with ongoing studies in the active Salton Trough and Rio Grande Rift, will constrain the volumes of magma and their correlation with fault-controlled segmentation, as well as the degree of mantle depletion from rifting to breakup.

### 3.6.3 CONTINENTAL TRANSFORM FAULTS

Continental transform faults accommodate transitions in tectonic style along plate boundaries and are now known to be associated with devolatilization and possible melting. Characterizing processes by which volatiles and magmas are produced along continental transform faults and the distribution of fluids, water content, and pore pressure are important for understanding geodynamic transitions and fault evolution, fault mechanics, the generation of non-arc volcanism, the influence fluids have on strain localization, and the possible role fluids have on fault strength and the different mechanisms of strain release. An important aspect of these studies is documenting the association between fluids and non-volcanic tremor along the San Andreas Fault and contrasting these findings with non-volcanic tremor within subduction zones.

Recent studies of metamorphic dehydration and modeling of pore pressure development suggest that mantle-derived fluids may play an important role in the strength of the San Andreas Fault in a manner consistent with a wide range of EarthScope-related observations. Isotopic evidence of mantle-derived fluids observed during SAFOD drilling suggests that the San Andreas Fault acts as a flow barrier between the North American and Pacific plates that is characterized by markedly different mantle-helium signatures and pore pressure regimes. In addition, analysis of core material is providing geologic evidence of transient changes in pore pressure and fluid chemistry within the fault zone at depths where earthquakes are being generated. Computations, laboratory studies, and theoretical analyses are unanimous in identifying the critical importance of the effects of pore-fluid chemistry, fluid pressure, and pore-fluid drainage on the mechanics of faults. The existing SAFOD main hole provides a potential opportunity for in situ fluid monitoring. Understanding volatiles and magmas along continental transform faults will ultimately provide greater insight into plate boundary deformation and the mechanics of earthquakes and faulting.

## 3.6.4 VOLCANIC PROCESSES AT CRUSTAL LEVELS

EarthScope is yielding insights into the behavior of magma in the upper crust at intraplate calderas and arc volcanoes. For example, through the link between surface deformation and magmatic plumbing within the crust, EarthScope science is illuminating the deep mantle sources of heat that drive the mid-plate magmatism in the Yellowstone region and the response of the crustal magmatic system (*Figure 3.6.4*). InSAR satellite data reveal 17 cm of uplift over the Yellowstone caldera between 2004 and 2007, prior to an increase in seismic activity at the caldera in late 2008 that is interpreted as recharge of magma to a magma chamber at ~10 km subsurface. Long Valley caldera offers similar opportunities for study.

Deformation from processes associated with active arc volcanoes has been captured by PBO and by GPS instruments installed by the USGS during recent eruptions of Mt. St. Helens (Cascadia) and Augustine, Redoubt, and Okmok volcanoes (Alaska). These data have documented an intriguing variety of pre-, syn-, and post-eruptive deformation. Although the large and very explosive eruption of Okmok in the eastern Aleutians was preceded by a decade of significant magma accumulation at shallow depth (~3 km), accumulation appeared to pause for about three years until just before the eruption. After the eruption, the shallow magma system began to refill almost immediately. In contrast, the other eruptions showed very little pre-eruptive deformation from magma accumulation, implying that most of the erupted material had been in place for many years before the eruption.

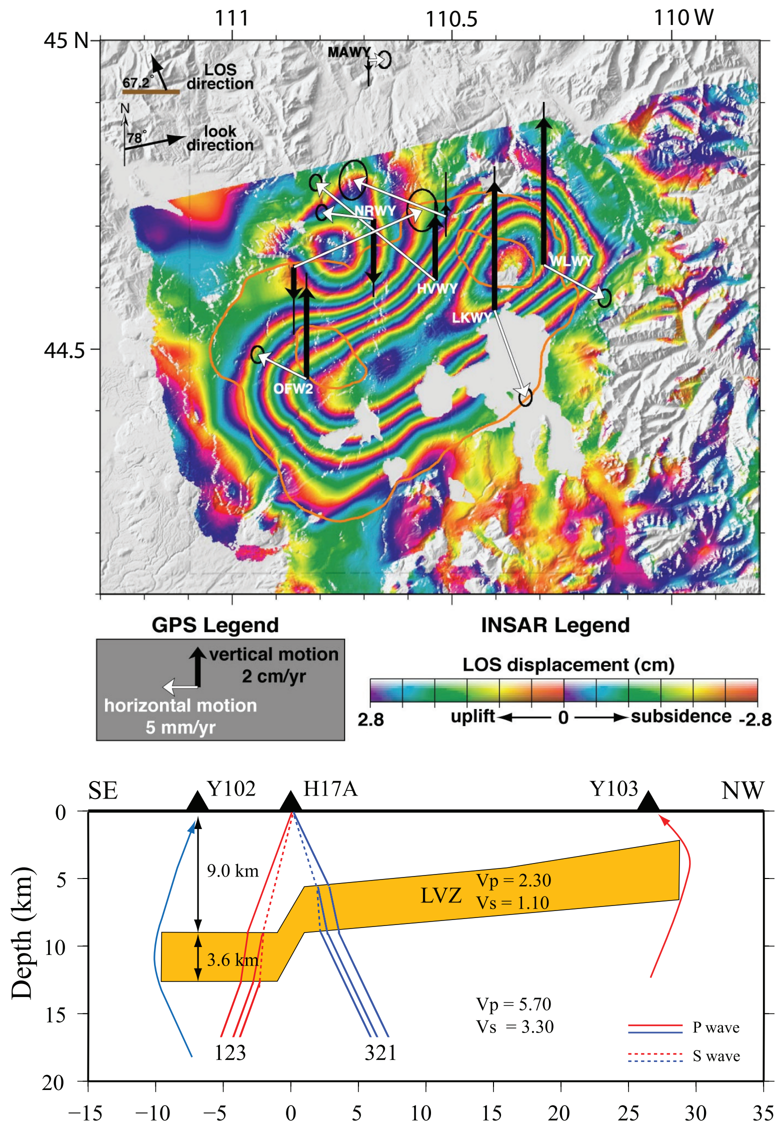



**Figure 3.6.4.** Magma chamber structure and uplift in Yellowstone. Recent GPS and InSAR studies show that the Yellowstone caldera is uplifting at a rate of 7 cm/yr, which is apparently related to a magma recharge (Chang et al., 2007). In receiver functions recorded by EarthScope station H17A from 100 teleseismic earthquakes in 2008, two P-to-SV converted phases exist that are consistent with the top and bottom of a low-velocity layer (LVL) at about 5-km depth beneath the Yellowstone caldera. P- and S-wave velocities suggest at least 32% melt saturated with about 8% water plus $CO_2$ by volume. (from Chu et al., 2010)


*Chang, W.L., R.B. Smith, C. Wicks, J.M. Farrell, and C.M. Puskas, Accelerated uplift and magmatic intrusion of the Yellowstone Caldera, 2004 to 2006, Science, 318, 952–956, 2007.*

*Chu, R., D. V. Helmberger, D. Sun, J. M. Jackson, and L. Zhu, Mushy magma beneath Yellowstone, Geophys. Res. Lett., 37, L01306, doi:10.1029/2009GL041656, 2010.*

"Real-time" geophysical observations of active volcanoes are crucial for a fundamental scientific understanding of volcanic processes. Geophysical signals produced by magma ascent and degassing provide a wealth of information regardless of eruption explosivity, or even visible activity. Studies of deformation at active volcanoes place constraints on the depth of magmatic sources producing inflation and deflation events. Dynamical models through time based on geodetic data provide views into the magmatic system, illuminating periods of magma chamber filling, ascent, and dike injection. In turn, the style and frequency of volcanic eruptions are directly linked to those types of magmatic processes operating at depth. From analysis of volcanic rock samples, petrology and geochemistry contribute important insights into the time scales of pre-eruptive processes and how magmas are stored in the crust. Recent studies show that magma storage depths obtained through experimental petrology methods compare quite well with those derived from geodetic studies, providing strong impetus for continuation of interdisciplinary work. Magma ascent time scales can also be cross-correlated across disciplines, with important implications for eruption predication. For example, 60 to 90 days prior to the onset of the 2006 eruption of Augustine Volcano in Alaska, PBO crustal deformation data revealed magma ascent to shallow levels, a time scale that was corroborated by petrological data.

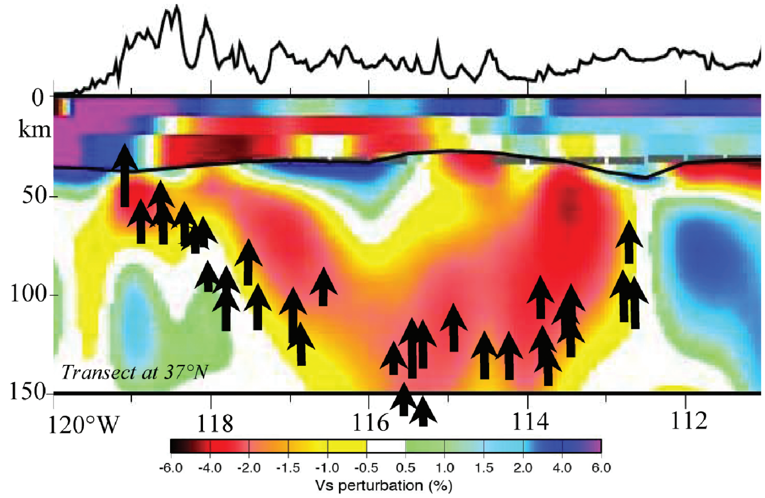



**Figure 3.6.5**. Mantle melting beneath the Basin and Range province in the western United States. Comparison between petrologically inferred mantle melting depths (vertical arrows; Wang et al., 2002) and shear-wave velocity anomalies from ambient noise and earthquake surface wave tomography (Yang et al., 2008). Inferred depths of mantle melting are correlated with low velocities in the asthenosphere.


*Yang, Y., M. H. Ritzwoller, F.-C. Lin, M. P. Moschetti, and N. M. Shapiro, Structure of the crust and uppermost mantle beneath the western United States revealed by ambient noise and earthquake tomography, J. Geophys. Res., 113, B12310, doi:10.1029/2008JB005833, 2008.*

*Wang, K., T. Plank, J. D. Walker, and E. I. Smith, A mantle melting profile across the Basin and Range, SW USA, J. Geophys. Res., 107, B1, doi:10.1029/2001JB000209, 2002.*


The enormous amount of information collected by many researchers over the course of the 2006 Augustine eruption illustrates the potential of an integrated geophysical and petrological/geochemical approach to studying active volcanoes, especially those "caught in the act" of erupting. Future PBO data may clarify the details of magma accumulation and ascent and the onset of eruption at several instrumented volcanoes. Truly integrated studies of these volcanic systems will require FA deployments.

## 3.6.5 SYNTHESIZING PETROLOGICAL, GEOCHEMICAL, AND GEOPHYSICAL OBSERVATIONS

The geochemistry and petrology of a body of magma provide constraints on its source (e.g., lithosphere, MORB-source asthenosphere, or plume-type mantle), and the conditions within the melting region. Complementary geochemical, isotopic, and age data on xenoliths and erupted rocks can constrain the history of magma generation. For example, the sweep of magmatism across the western United States during the Mesozoic provides a fundamental constraint on the interactions of the subducted Farallon slab (*Sidebars 1 and 4*) with the overlying continental lithosphere. New insights into mantle melting conditions are emerging from multidisciplinary studies that combine seismic images of the mantle enabled by TA data with petrological and geochemical data. For example, petrologically inferred depths of mantle melting beneath the Basin and Range show a startlingly good correlation with a pronounced low-velocity zone revealed by surface wave and ambient noise tomography (*Figure 3.6.5*) that likely represents a melt-rich asthenosphere. After application of corrections to the seismic structure to account for the effects of cooling, similar correlations are expected beneath ancient magmatic systems like the Mid-Continent Rift and the Gulf of Mexico and East Coast rifted margins.

## 3.6.6 INTEGRATING ELECTROMAGNETIC AND SEISMIC METHODS FOR DETECTING FLUIDS

Because of the fundamentally different physics of elastic and electromagnetic wave propagation in the presence of fluids, magnetotelluric and magnetovariational methods are more sensitive than seismic methods to the presence of interconnected melt, saline pockets, and hydrated minerals found in subduction zones and along terrane sutures. This sensitivity is illustrated by the results from the first USArray MT deployment in the Pacific Northwest (*Figure 3.6.6*), which revealed extensive areas of high conductivity in the lower crust beneath the Basin and Range province (where it likely results from fluids associated with magmatic underplating) and the Cascade Mountains (where fluids released by the subducting Juan de Fuca slab are present).

Because magnetotelluric and seismic data have different dependencies on crust and mantle properties, sometimes with opposite sign, joint interpretation efforts will yield a greater understanding of how each parameter may be used to constrain the interpretation of the other. As the seismic and magnetotelluric TA deployments migrate across the continental United States, scars of ancient subduction, transform faults, and rift zones within the continental lithosphere are likely to be highlighted in conductivity structure because they serve as either conduits or barriers for the flow of fluids.

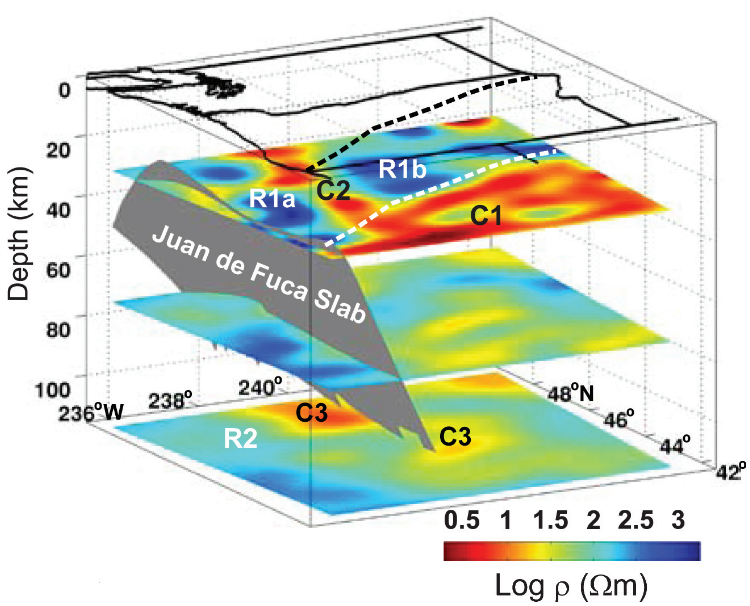



**Figure 3.6.6** Slices from a 3D model of the electrical conductivity of the crust and upper mantle beneath the Pacific Northwest developed from inversion of EarthScope USArray MT data. Regions of relatively high conductivity are labeled C1, C2, C3; more resistive regions are labeled R1 and R2. The dashed line delineates the boundary between a highly resistive region and the more conductive C1. (from Patro and Egbert, 2008)


*Patro, P.K., and G.D. Egbert, Regional conductivity structure of Cascadia: Preliminary results from 3D inversion of USArray transportable array magnetotelluric data, Geophys. Res. Lett., 35, L20311, doi:10.1029/2008GL035326, 2008.*


## 3.6.7 MAGMATIC FLUIDS AND AQUIFERS

Understanding magmatic processes is clearly crucial to volcanic hazard mitigation in arc and rift settings. However, assessments of an even wider range of hazards within both the actively deforming western United States and stable interior require knowledge of the distribution and movement of magmatic fluids, volatiles, and aqueous fluids. High pore-fluid pressures from volcanic degassing, magma-groundwater interactions, and metamorphic reactions can lead to submarine and subaerial landslides along steep slopes. These risks are enhanced in earthquake-prone areas. Mantle degassing and volcanic fluids can also impact groundwater quality. In addition to high $CO_2$ and mantle-derived $^3He$, deeply sourced fluids rising along faults into the groundwater system have been shown to have high total dissolved solids (e.g., salts) and trace metals (e.g., arsenic and uranium) and to affect groundwater quality (*Sidebar 16*).

## RECENT BREAKTHROUGHS

- In the Cascadia subduction zone, the locations of ETS, intermediate-depth earthquakes, metamorphic dewatering, and plate structure are strongly correlated, informing the dynamic properties of the plate interface (*Figure 3.6.1*).
- Seismic data have constrained the potential depth of the recharging Yellowstone magma chamber, matching rapid uplift over Yellowstone caldera between 2004 and 2007 (*Figure 3.6.4*).
- PBO data revealed magma ascent to shallow levels 60 to 90 days prior to the onset of the 2006 eruption of Augustine Volcano in Alaska.
- The relationship of mantle melting to lithospheric structure has been revealed beneath the Basin and Range province, where petrologically inferred melting depths correlate with a low-velocity zone revealed by seismic imaging (*Figure 3.6.5*).
- Strong variations in crustal conductivity in the Pacific Northwest suggest the presence of fluids dehydrated from the Juan de Fuca plate and associated with magmatic underplating (*Figure 3.6.6*).
- Coupled seismic and groundwater chemistry studies indicate that the entire western United States undergoes active mantle degassing at a continental scale (*Sidebar 16*).

## OUTSTANDING QUESTIONS

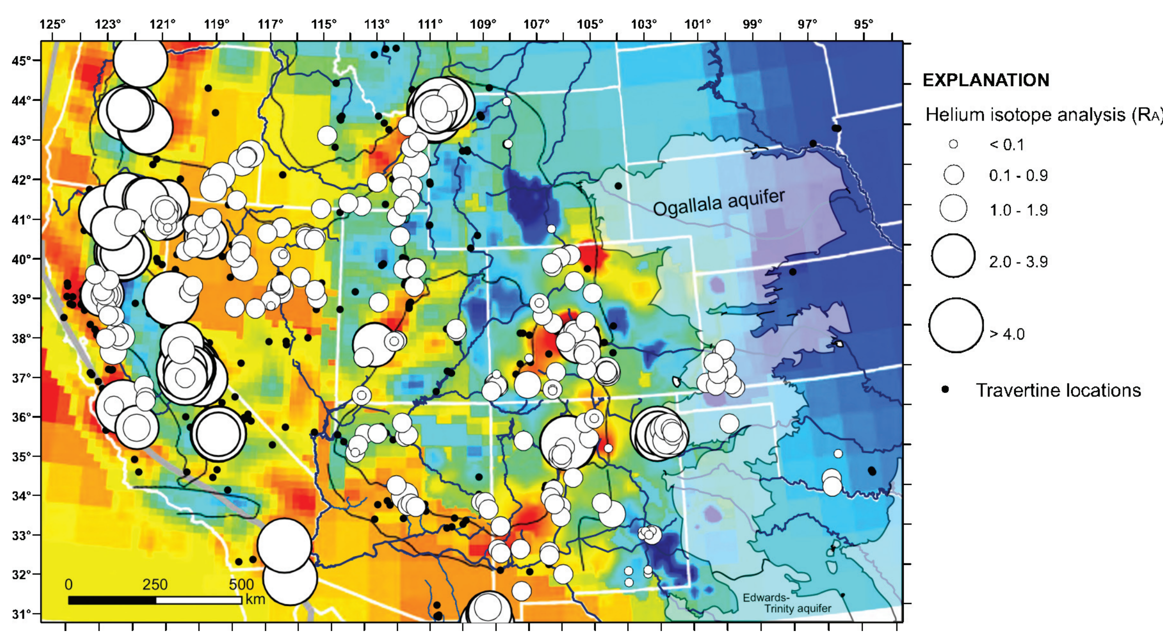
- Geodetic studies of subduction zone and rift volcanoes worldwide show inflation and deflation episodes lasting months to years, yet few constraints exist to differentiate between models of magma influx, volatile degassing, and groundwater interactions. What do volcanic inflation/deflation patterns imply in terms of aqueous fluids, volatiles, and magma replenishment? What are the time and length scales of these transport processes?
- How do the rise of magma and stored volatiles change the state of stress within the plates?
- How do the release or storage of aqueous fluids embrittle or lubricate fault zones in extensional, compressional, and transform settings?
- How do dehydration reactions and fluid transport affect coupling at the plate interface and the potential for great earthquakes in subduction zones?
- How do melt/volatile enrichment and the structure of zones chemically altered by melt extraction vary in 3D along both compressional and extensional margins?
- How does the movement of aqueous and magmatic fluids influence the pore pressure, temperature, composition, and rheology of the crust and mantle? How does fluid influence lithospheric deformation and mantle flow?

## SIDEBAR 16. HELIUM IN "XENOWHIFFS" ACROSS THE WESTERN U.S.

Work on "xenowhiffs" of the western United States has highlighted the importance of mantle to groundwater interconnections (figure courtesy of L.J. Crossey, University of New Mexico). An implication of this work is that the entire western United States has $^3He/^4He$ ratios indicating active mantle degassing at the continental scale, extending east to the Great Plains. Elevated $^3He/^4He$ ratios provide unequivocal evidence for the presence of mantle-derived fluids in hydrologic systems. In addition to high $CO_2$ and mantle-derived $^3He$, deeply sourced fluids rising along faults into groundwater systems have been shown to have high total dissolved solids (e.g., salts) and trace metals (e.g., arsenic, uranium) and to affect groundwater quality (Crossey et al., 2009). These results will be relevant for understanding water quality in several important regional aquifer systems (e.g., Albuquerque basin, Ogallala and Edwards aquifers). This connection between the deep Earth and the surface hydrologic system is a potentially exciting outreach opportunity for EarthScope.

### References


Crossey, L.J., K.E. Karlstrom, A. Springer, D. Newell, D. Hilton, and T. Fischer, Degassing of mantle-derived $CO_2$ and $^3He$ from springs in the southern Colorado Plateau region: Neotectonic connections and implications for groundwater systems, Geol. Soc. Amer. Bull., 121, 1034-1053, 2009.

- How does volatile flux change over time at active volcanoes and through subduction zones, and what are the implications for global climate change?
- How do magmatic fluids modify the continental crust and how does magma generation set the pace for continental growth?
- What controls the position and type of magmatism in the overriding plate of a subduction system?
- What controls the location and type of magmatism as rifting progresses to seafloor spreading?
- How does volcanic degassing impact groundwater quality, both near plate boundaries and in stable cratonic interiors?

# 3.7 Topography and Tectonics: Elucidating Time-Space Patterns of Lithospheric Deformation

Tectonic geomorphology, which provides information at time scales ranging from $10^3$–$10^6$ years, bridges the gap between geodetic and traditional geologic time scales and is poised to make significant contributions to our understanding of lithospheric deformation. Enabled by advances in the digital representation of surface topography, isotopic techniques of dating Earth's surface features, and quantification of the rules that govern the fluxes of mass across Earth's surface, the study of landscape topography has been revolutionized in the past decade. Sedimentology also provides important constraints on surface motions over geologic time scales. EarthScope will provide a wealth of new information with which to explore the coupling among mantle, crust, and surface processes.

## 3.7.1 TEMPORAL VARIATION IN STRAIN RATE

New technologies for the study of active faults have revealed intriguing temporal variations in the pace of deformation across the western United States. High-resolution topography provided by LiDAR acquisitions, coupled with dating of displaced landforms using cosmogenic radionuclides (primarily $^{10}Be$, $^{26}Al$, and $^{36}Cl$) have enabled a rapidly expanding catalog of fault slip rates over $10^4$–$10^5$ yr. In an example described in *Section 3.5*, comparison of these rates with modern strain rates in eastern California reveal significant variability in both space and time, and analysis of geologic slip rates along the plate boundary faults south of Los Angeles suggest coordinated variations in slip along the San Andreas and San Jacinto fault zones (*Sidebar 9*). Such variability challenges traditional notions of steady fault slip driven by far-field plate motions, and may arise from time-dependent variations in the rate and/or location of shear in the lower crust or upper mantle or from fault interactions in the brittle lithosphere. Ultimately, determining the driving mechanisms for non-steady deformation along North American fault systems will lead to a deeper understanding of the processes driving fault slip and generating seismic hazard.

## 3.7.2. TOPOGRAPHIC EVOLUTION ACROSS THE UNITED STATES

The rates and patterns of topographic change can also provide key constraints on long-wavelength deformation of Earth's surface in response to deep-seated processes. In particular, the adjustment of fluvial systems to differential rates of rock uplift allows estimation of the patterns of deformation across broadly deforming regions. Moreover, the transient response of these systems to relative changes in base level leads to relatively predictable patterns of fluvial incision across tectonically active landscapes. Quantitative analysis of the migration of these signals, coupled with measurement of erosion rate (constrained by cosmogenic isotopes and/or low-temperature thermochronology) can reveal the wavelength and patterns of rock uplift. For example, stream profile evolution reveals a systematic pattern of uplift in the Inyo Mountains of California that correlates with uplift rates constrained by detrital $^{10}Be$ analysis (*Figure 3.7.2a*).

Given the continent-wide scale of EarthScope data, the driving forces of regional-scale uplift can be studied in a whole-mantle context. Tomographic images of crust and mantle structure generated with EarthScope data are capable of determining the geometry of buoyancy anomalies whose resulting dynamic topography either pulls down or buoys up the surface. Such anomalies include subducted slabs all the way to the core-mantle boundary (*Sidebar 1*), new forms of lithospheric loss and downwelling (*Sidebar 5*), and buoyant material rising to feed the Yellowstone hotspot (*Figure 3.4.2*).

As the TA migrates east, similar features may be discovered beneath the older parts of the continent, inspiring new questions about the interaction of dynamic topography and tectonic evolution.

Geodynamic modeling suggests that lithosphere subducted beneath the western margin of the continent not only influenced the inundation of the western interior seaway, a major center of sediment deposition in the western United States during the Cretaceous (65 to 145 millions years ago), it may also explain anomalous subsidence along the eastern seaboard during the Cenozoic (65 million years ago to the present) (*Sidebar 1* and *Figure 3.7.2b*). This apparent linkage between the deep mantle and surface raises interesting questions about how mantle flow may have affected development of intra-cratonic basins, subsidence of the North American passive margin, and perhaps even the persistence of ancient Appalachian orogen topography. Elucidating the connections between deep Earth processes and the surface, however, will require close integration of basin analysis with geophysical data as well as studies that link topographic change, erosion, and sediment delivery to offshore regions. Because much data and expertise relevant to questions of basin evolution reside within the oil/gas industry, close collaboration with industry should be encouraged.

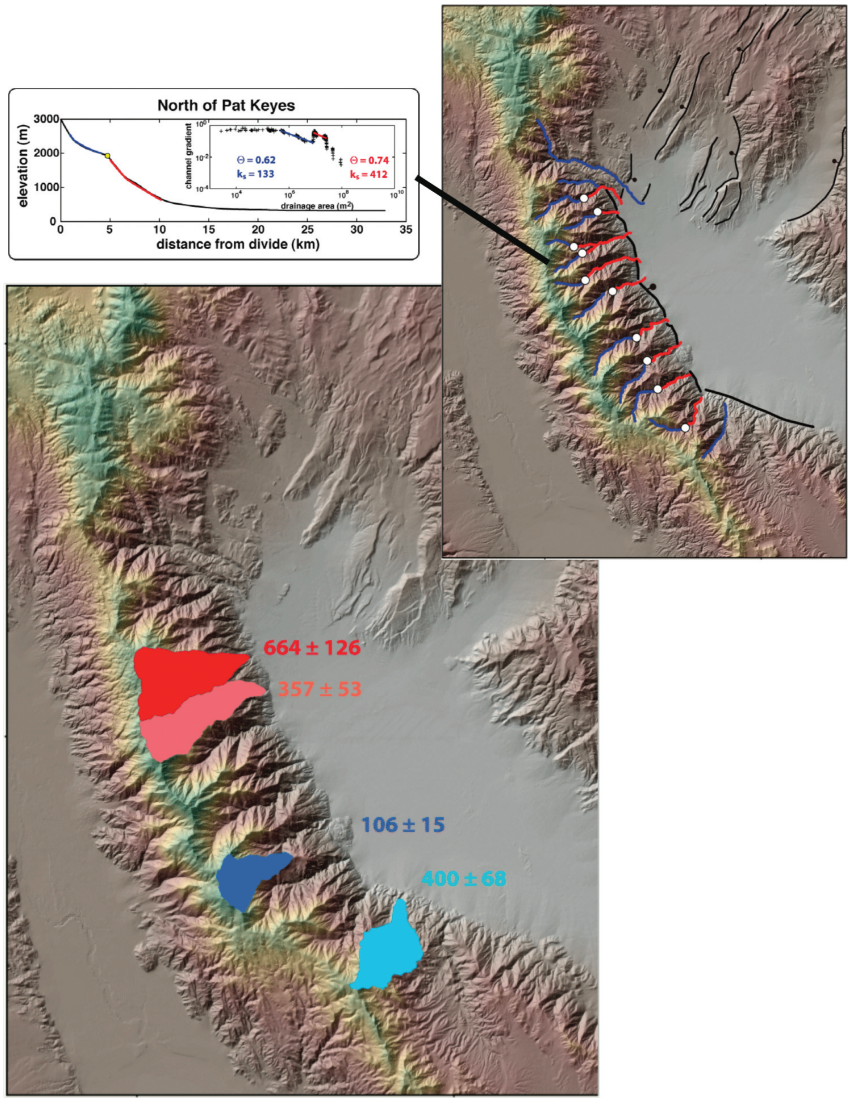



**Figure 3.7.2a.** Example of tectonic geomorphology used to constrain uplift. The Inyo Mountains west of Saline Valley, California, are bound by a right-lateral, oblique-slip normal fault whose activity is part of a system of faults in eastern California. Stream channels draining the eastern flank of the Inyo Range exhibit disequilibrium profiles, characterized by knickpoints that separate lower-gradient reaches from high-gradient reaches near the mountain front. Knickpoints occur at relatively uniform elevations along the range, are not associated with lithologic contacts, and only occur on faults that drain across the range-bounding fault. Systematic differences in channel gradient indices above and below knickpoints are associated with differences in mean erosion rates determined by $^{10}$Be inventories in modern sediment, indicating that steep lower reaches reflect an ongoing adjustment to an increase in base-level fall along the range-front fault. Reconstruction of relict profiles suggests ~800–1000 m of base-level fall has occurred in the past 0.7–1.0 million years. (figure courtesy of E. Kirby, Pennsylvania State University)

## RECENT BREAKTHROUGHS

- Geologic rates of fault motion in California are different from geodetically derived rates, suggesting non-steady-state behavior of faults. Such variability may arise from time-dependent changes in lower crust or upper mantle shear or from fault interactions in the brittle lithosphere, thus challenging traditional notions of steady fault slip driven by far-field plate motions (*Sidebar 9*).

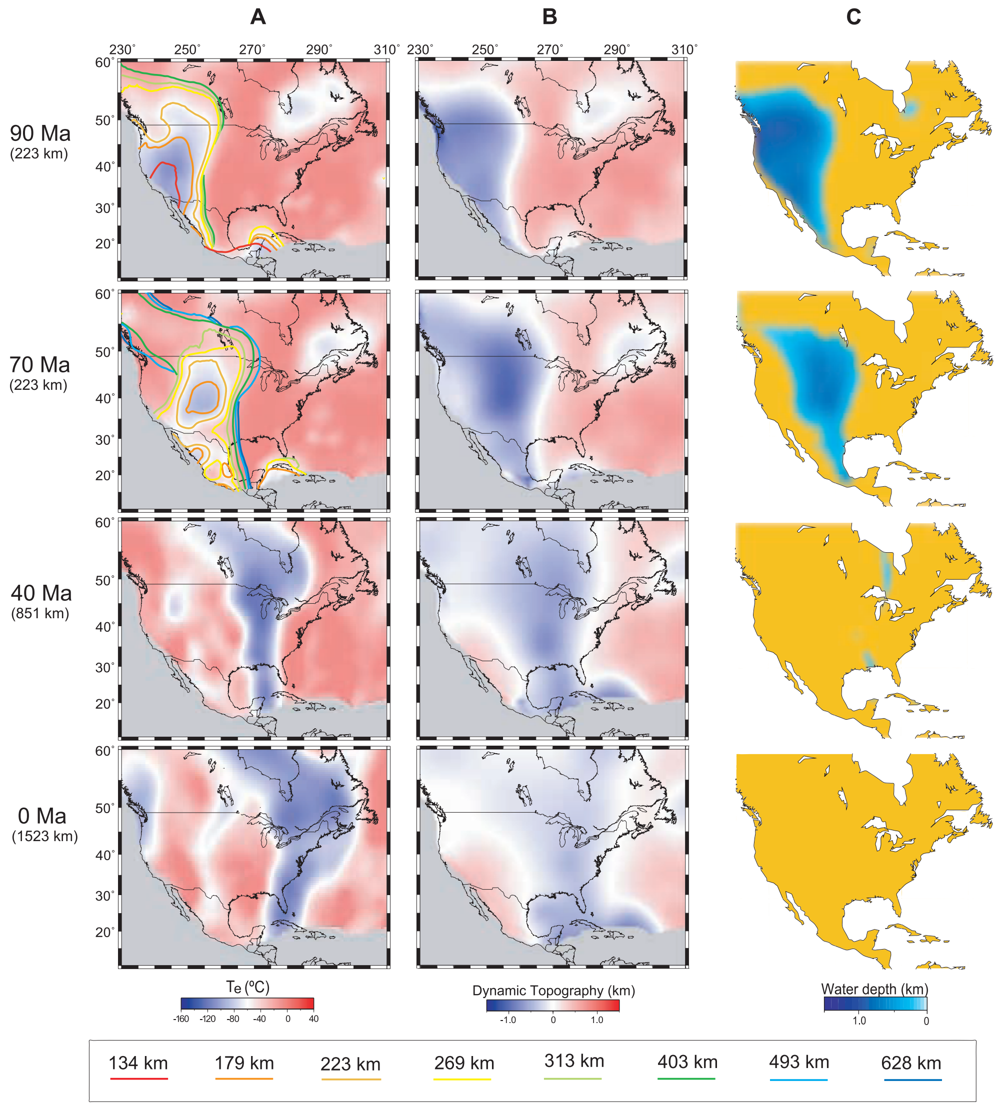



**Figure 3.7.2b.** Evolution of the Farallon plate and North American dynamic topography. (A) Slab geometries at different depths, where the background colors represent the temperature at the depth denoted at the left margin and color contours show boundaries of the slab. (B) Associated surface dynamic topography. (C) Predicted continental flooding at different geological times using initially flat continent at 100 million years ago and Haq and Al-Qahtani (2005) sea level. (from Spasojevic et al., 2009)

*Spasojevic, S., L. Liu, and M. Gurnis, Adjoint models of mantle convection with seismic, plate motion, and stratigraphic constraints: North America since the Late Cretaceous, Geochem. Geophys. Geosyst. 10, 5, doi:10.1029/2008GC002345, 2009.*

- The combination of high-resolution topography and new radiogenic age dating techniques is leading to more precise uplift histories that can, in turn, constrain geodynamic models (*Figure 3.7.2a*).
- Geodynamic models that include coupled deformation, erosion, uplift, and climate are providing new insights into the evolution of complex orogens.
- Sea level estimates on the East Coast (New Jersey and Delaware) show the possible effect of dynamic topography associated with subduction of lithosphere below the western margin of North America (*Sidebar 1* and *Figure 3.7.2b*).

## OUTSTANDING QUESTIONS

- What processes control slip-rate variability along major fault systems, both along a single fault and within a region?
- How do crust and mantle buoyancy and flow influence and support topography in the tectonically active western United States?
- How has lithosphere subducted beneath the western North American plate boundary interacted with the surface evolution of the entire continent through time?
- Why does Appalachian topography still exist?
- To what extent do different types of basins (foreland, forearc/backarc, passive margin, cratonic, or pull-apart) reflect or affect deep crustal and mantle structure?

# 3.8 EarthScope and the Hydrosphere, Cryosphere, and Atmosphere

Water is unique in the Earth system in that it exists in abundance in all three phases (solid, liquid, and vapor). It is responsible for the development of life and serves as the primary way in which Earth balances latitudinal and seasonal differences in incoming solar radiation. The uneven distribution of land and ocean surfaces influences the global distribution of water, creating regions that contain conditions of both severe water abundance and scarcity. As the climate changes, the distribution of water will also change. Observing and monitoring spatial and temporal changes in the water cycle is crucial to our ability to understand and predict a future climate. As an inherently multidisciplinary program with unique facilities, EarthScope has the potential to make strong and significant contributions to questions related to Earth's hydrosphere, cryosphere, and atmosphere. It can provide unique observational capabilities of how water is distributed within Earth (as discussed in *Section 3.6*), on its surface, and up through the atmosphere. The EarthScope community can play a pivotal role in hydrologic, climate, and biosphere studies that are of critical interest to humanity.

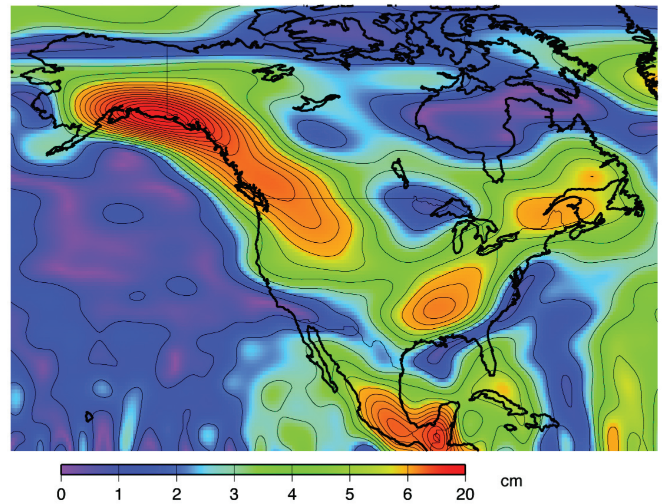



**Figure 3.8.1.** Amplitude of the annual cycle in stored water, in centimeters of water equivalent thickness, as inferred from the GRACE satellite gravity mission between April 2002 and June 2008. Evident in this map is the high-snowfall region running from southern Alaska down the Pacific Northwest coast; the arid regions of southwestern United States, and the high-precipitation regions of Central America, southeastern United States, and Maritime Provinces of Canada. (from J. Wahr, unpublished manuscript)

## 3.8.1 HYDROSPHERE

SUBSURFACE AQUIFERS: The goal of hydrology is to better understand how water is transported and stored on and beneath the land surface. Geodesy has only fairly recently been used for hydrologic research. NASA's Gravity Recovery and Climate Experiment (GRACE)—launched in 2002—has provided heretofore unavailable estimates of seasonal, interannual, and secular changes in water storage at spatial scales of a few hundred kilometers and greater (*Figure 3.8.1*). GRACE senses water by measuring changes in gravity associated with mass change (e.g., because of aquifer pumping and ice sheets melting). GPS and InSAR sense water transport by measuring changes in Earth's surface elevation (e.g., aquifer pumping results in ground subsidence). The effect of loads such as snow can also be resolved by PBO, providing data that are essential for management of the water supply and flood control systems. Because of their differing temporal and spatial sensitivities, GRACE, GPS, and InSAR provide complementary pictures of the water cycle. With the GRACE mission now past its design lifetime, and no follow-on mission set for launch, PBO provides a critical facility for monitoring water usage in the western United States for the next decade. Both the measured surface changes and their loading effects can be used to improve hydrological models, predict drought conditions, and better understand the transfer of water between the land and the atmosphere.

SOIL MOISTURE FROM GPS DATA: Soil moisture is another important part of the water cycle. Soil moisture data are needed to constrain models of evaporation and transpiration at the land-atmosphere boundary. Soil moisture variations also have important implications for surface energy flux. Recently PBO data have been used to measure near-surface soil moisture (*Sidebar 17*). PBO data—available on a daily basis—complement planned NASA satellite missions that have limited temporal sensitivity. GPS soil moisture and GPS vegetation water content data are also valuable for weather prediction and climate models that rely on ground information that is not measured by satellites.

**MONITORING SUBSURFACE FLUIDS:** High-resolution seismic imaging, such as that obtainable with the FA, offers imaging capabilities at the meter-to-kilometer scales needed to define aquifers and fine-scale sedimentary structures. Repeated seismic surveys to detect temporal changes related to fluid migration can be used for the management of hydrocarbon reservoirs, aquifer systems, and proposed $CO_2$ storage facilities, and will be critical to the expected expansion of geothermal energy production.

**SEISMIC "NOISE" FROM OCEAN WAVES:** Ocean wave systems driven by surface winds continuously excite a globally detectable seismic background wave field at periods from several seconds to hundreds of seconds. Nascent studies of these ocean-generated seismic signals using very large broadband seismic arrays, such as the TA, are providing both new insights into Earth's storm processes and gravity/seismic wave interactions with the solid Earth. The microseism is a unique geographic integrator of storm-induced wave energy that complements ocean-based, space-based, and meteorological measurements, and is particularly sensitive to the ocean wave state near coasts (*Sidebar 18*). The integrated microseismic energy levels show significant correlation with El Niño-Southern Oscillation events in the Pacific Ocean, and even show increases over the past 30 years, with very important implications for the increases in ocean warming, storm activity, and global climate change. The ocean-wave-induced microseismic "noise" energy at periods of 4–30 s has been

## SIDEBAR 17. MEASURING SOIL MOISTURE AND SNOW DEPTH WITH GPS

The GPS instruments installed by PBO measure crustal deformation by precisely estimating positions. Given that one of the major corrupting errors in GPS measurements are signals that reflect from the ground, both the GPS receiver and antenna used by PBO were designed to suppress the effect of ground reflections. Despite these efforts, Larson et al. (2008) found that these ground reflections can be quantified and used to study near-surface soil moisture variations (Figure 1). In a follow-up study, Larson et al. (2009) demonstrated that snow depth can also be measured using GPS data (Figure 2). Ground measurements of soil moisture and snow depth such as could be provided by PBO offer important temporal sensitivity unavailable from satellites and illuminate local scale variations. Both are critical for weather forecasting, climate studies, water management, drought prediction, and flood control.

### References:


Larson, K.M., E.E. Small, E. Gutmann, A. Bilich, J. Braun, and V. Zavorotny, Use of GPS receivers as a soil moisture network for water cycle studies, Geophys. Res. Lett., 35, L24405, doi:10.1029/2008GL036013, 2008.

Larson, K.M., E. Gutmann, V. Zavorotny, J. Braun, M. Williams, and F. Nievinski, Can we measure snow depth with GPS receivers?, Geophys. Res. Lett., *36,* L17502, doi:10.1029/2009GL039430, 2009.

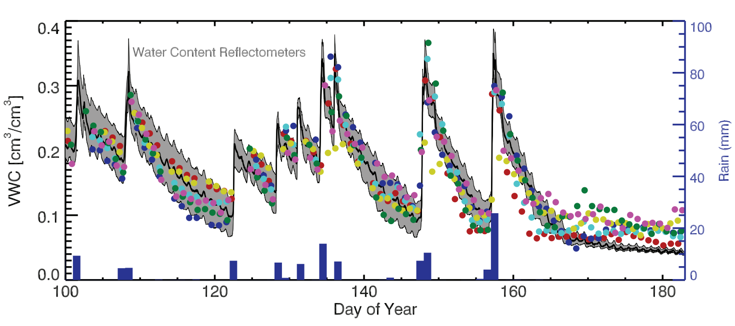




Figure 1. Variation in volumetric water content (VWC) inferred from multiple GPS satellites (colors) and water content reflectometers (WCR) measured at Marshall, Colorado, one of the Plate Boundary Observatory sites. The range of the five WCRs (buried at 2.5-cm depth) is shown in grey and their mean is the black line. Daily precipitation totals are in blue (Larson et al., 2008).

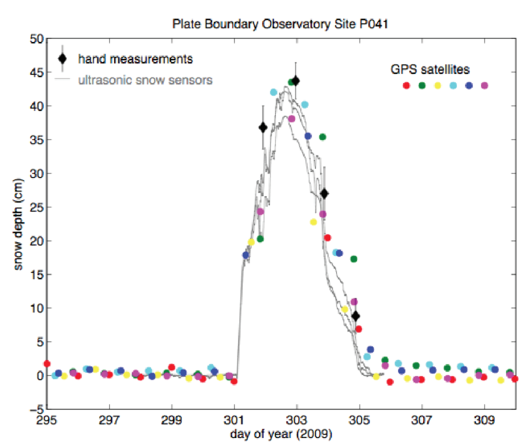



Figure 2. Variation in snow depth over a 50-m transect measured by hand with ultrasonic snow depth sensors compared to data from multiple GPS satellites shown by colors (methodology described in Larson et al., 2009).

# SIDEBAR 18. MICROSEISMS AND EARTH HUM

A. Power spectral density probability distribution function (McNamara and Buland, 2004; Aster et al., 2008) showing Earth's background seismic spectrum and its three globally predominant principal oceanic components recorded at Global Seismographic Network station TUC in Tucson, Arizona. DF – the "double frequency" microseism excited by standing wave components of the ocean gravity wave field; SF – the "single frequency" microseism excited by waves impacting coasts, and the "hum" signal near 100 s, attributed to very-long-period (infragravity) ocean waves near continental shelves and to be a predominant source of Earth's incessant normal mode excitation (see **C**, below). (after Bromirski, 2009)

B. Seismic array beam-formed image of the near coastal microseism source zone during hurricane Katrina (for August 29, 2005) using 150 broadband stations in southern California, demonstrating the ability to image microseism source zones using the EarthScope TA in combination with other California stations. (1) 14 s vertical component surface (Rayleigh) wave slowness map (0–0.5 s/km horizontal wave slowness radial scale) in decibels. (2) 5.3 s vertical component phase interpreted as a P wave (0–0.15 s/km radial scale). (3) Same as (2), but showing the radial component of the seismic signal. (4) Back-projected source region inferred from (2) (after Gerstoft et al., 2006). At right: (top) GOES-12 NASA digitally processed image of the storm on this day. (bottom) Same-day WAVEWATCH III (Tolman, 2005) wave height hindcast estimated from buoy measurements. Note the preferential microseism excitation to the east of the storm consistent with typical maximum winds at the storm's leading right hand quadrant and associated hindcast wave heights east of the eye.

C. Localization of the hum signal source using seismic array back-projection from data recorded by the EarthScope Transportable Array during its deployment in the western United States, showing episodes in Pacific Mexico/Central America (top), and Atlantic Europe/Northern Africa (bottom), with high-power periods indicated by black dots. R, at right, is a measure of inferred source power localization. (after Bromirski and Gerstoft, 2009)

## References


Aster, R., D. McNamara, P. Bromirski, Multi-decadal climate-induced variability in microseisms, Seis. Res. Letts., 79, doi:10.1785/gssrl.79.2.194, 2008.

Bromirski, P., Earth vibrations, Science, 324, 1026–1027, 2009.

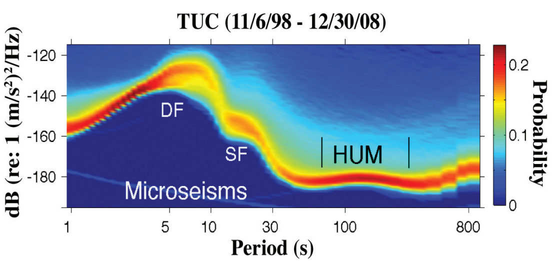
Bromirski, P.D., and P. Gerstoft, Dominant source regions of the Earth's "hum" are coastal, Geophys. Res. Lett., 36, L13303, doi:10.1029/2009GL038903, 2009

Gerstoft, P., M.C. Fehler, and K.G. Sabra, When Katrina hit California, Geophys. Res. Lett., 33, L17308, doi:10.1029/2006GL027270, 2006.

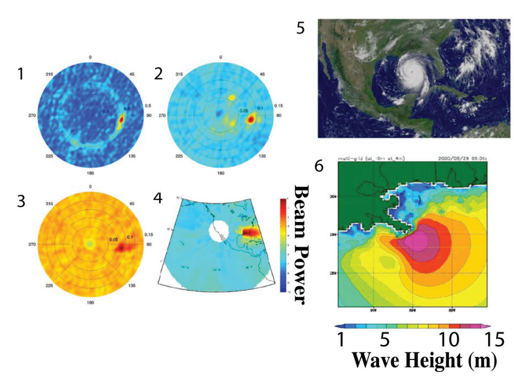
McNamara, D., and R. Buland, Ambient noise levels in the continental United States, Bull. Seis. Soc. Am., 94, 1,517–1,527, 2004.

Tolman, H.L., Manual and Wave User system documentation of WAVEWATCH-III version 2.22, US Department of Commerce. Hindcast files available from http://polar.ncep.noaa.gov, 2005.

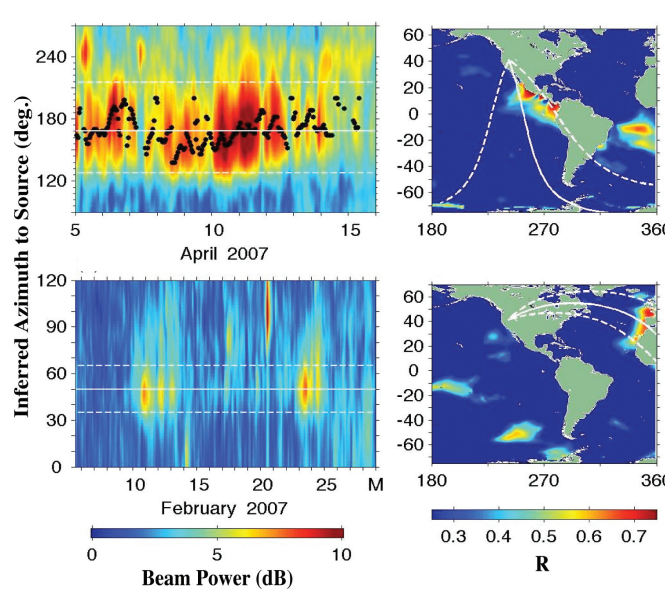

A




B




C



increasingly exploited for crust- to mantle-scale imaging in recent years via revolutionary and still rapidly developing correlation-based methodologies and applications (*Sidebar 18*).

### 3.8.2 CRYOSPHERE

Earth's cryosphere is currently undergoing rapid change, and the application of seismology, InSAR, GPS, and gravity to glacial systems has dramatically increased since EarthScope's inception. Recent NSF development efforts have facilitated the deployment of EarthScope-style portable seismic and GPS instrumentation at new scales and in some of the planet's harshest environments. A fundamental interest in the dynamic processes and stability of smaller glacial systems, such as the rapidly evolving temperate and sub-polar mountain glacial systems of Southeast Alaska and adjacent Canada, has spurred both new scientific studies and increased deployment of geodetic and seismic instrumentation. Southeast Alaska is a globally significant locale for monitoring the rapid retreat of glaciers and examining interactions of glacial loading/unloading, solid Earth viscoelastic isostatic rebound, and hydrospheric loading in a large temperate system. For example, isostatic rebound both influences coastal sea levels and constrains past glaciations. Improved understanding of rebound will require geodetic data collection and modeling of uplift, heat flow, gravity variations, mantle-scale structure via seismic imaging, and storage and deformational effects of the hydrologic system. Detailed modeling and assessment of inundation scenarios can be significantly enhanced through LiDAR mapping coupled with isostatic rebound modeling. Ground-based measurements in such systems can be valuably coupled with NASA Earth-observing missions, such as GRACE (*Sidebar 19*). Anticipated widespread deployment of EarthScope instrumentation in northern Alaska also offers the possibility of new observations of its rapidly changing permafrost system via GPS, LiDAR, or other EarthScope-facilitated data collection and research.

### 3.8.3 ATMOSPHERIC WATER VAPOR

Water vapor is Earth's most abundant greenhouse gas. It has a recycling time in the atmosphere of approximately one week and serves as the primary way in which energy is transported poleward through the atmosphere from the equator. The latent heat that is released when water vapor condenses into its liquid or solid state is a source of energy that fuels the general circulation of the atmosphere and creates storm systems. Improvements in geodetic analysis techniques have led to new observational systems to study the atmosphere, particularly atmospheric pressure and water vapor. GPS can provide accurate observations of total column water vapor, also called precipitable water vapor (PWV), in all weather conditions with high temporal resolution. These data create a potential opportunity for PBO to make a significant contribution to atmospheric science and meteorology.

Historically, there are very few continuous time series of atmospheric water vapor in the western United States. A warming climate will create an atmosphere with increased capacity to hold water vapor. PBO GPS stations provide an infrastructure that can be used to make high-accuracy, continuous measurements of PWV (*Sidebar 20*). Other observing methods, such as satellites, radiosondes, and other types of ground-based remote-sensing techniques, do not have the combined spatial and temporal resolution that the PBO network provides while also being relatively insensitive to other forms of atmospheric water such as clouds, rain, and snow. Accurate measurements of both the spatial and temporal changes in atmospheric water vapor are essential for testing and improving regional and global climate models that can be used to make decisions regarding land use, agricultural production, and population redistribution.

Most of the western United States has an arid climate, with long periods of drought followed by extremes in precipitation. The North American Monsoon (NAM) serves as the primary climatological feature that controls precipitation patterns in the Southwest. The NAM provides the majority of warm season rain that occurs in Arizona, New Mexico, Utah, and Colorado. Exceptionally strong NAM seasons are known to create flash-flood events that impact infrastructure, agriculture, and human safety. Despite its significance, the NAM is poorly understood, with large uncertainties in estimates of its spatial extent and annual variability. A large field project in 2004 called the North American Monsoon Experiment (NAME) showed that GPS PWV estimates are very useful for monitoring the flow of atmospheric water vapor, and an increased capacity to make the GPS-based estimates was recommended by the NAME science team. Data from PBO can greatly increase the number of PWV measurements in the region.

Cold fronts and other baroclinic disturbances are "atmospheric rivers" that move moisture poleward and may be responsible for up to 90% of the moisture moving into the continental mid-latitudes. These rivers replenish aquifers and snow pack along the west coast of the United States, linking the atmosphere to the terrestrial components of the water cycle. The relatively dense distributions of PBO stations in California, Oregon, and Washington may provide an improved understanding of the precipitation events that are created when these moist atmospheric flows are forced across the coastline and across the complex topography of the West Coast.

### 3.8.4 INFRASOUND

The atmosphere is an efficient propagator of low-frequency sound energy (infrasound) at global distances. Under certain conditions, the infrasound field couples strongly and bidirectionally with the solid Earth seismic field, and thus constitutes an extension of solid Earth seismology into the atmosphere. Studies of the infrasonic field allow for novel deep sounding of atmospheric structure (*Sidebar 21*) and facilitate quantitative characterization of volcanic, oceanic, and other infrasonic sources.

### RECENT BREAKTHROUGHS

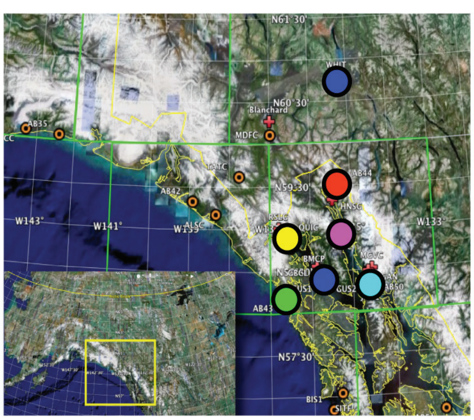
- The high density and high resolution of EarthScope GPS receivers can provide continuous monitoring of soil moisture variations, snow depth, and vegetation water content (*Sidebar 17*).

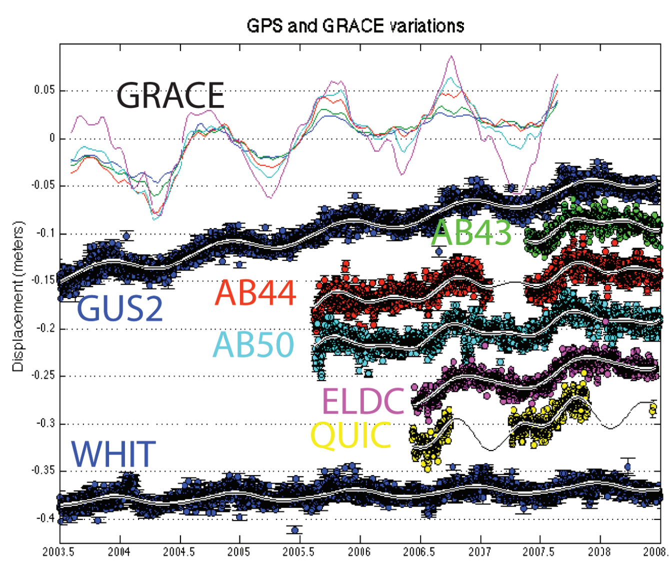
## SIDEBAR 19. MEASURING CHANGES IN GLACIAL MASS WITH GPS AND SATELLITE DATA

Coupled glaciological and solid Earth response to deglaciation and seasonal snow and hydrological loading. GRACE mass concentration (mascon) time series for five glaciated regions in the St. Elias, Glacier Bay, Yakutat, Juneau, and Stikine icefields (left), and daily GPS height estimates with error bars for continuous GPS sites (right) for stations GUS2, AB43, AB44, AB50, ELDC, QUIC, and WHIT (see map at left). For comparison to the GPS time series, GRACE mascon variation values are reversed in sign (because excess mass causes depression of the surface and hence a negative vertical geodetic signal) and arbitrarily rescaled. The GPS measurements show, in general, a larger secular trend than GRACE-inferred mass changes, reflecting post-glacial viscoelastic rebound response to earlier glacial unloading not included in GRACE modeling. Overlain curves on the GPS data show a model consisting of a linear trend plus annual and semiannual sinusoidal terms. Note that the amplitude of the seasonal deformation signal is as large as 20–25 mm (40–50 mm peak-to-peak variations), which are among the largest such variations on Earth. (figure courtesy of J. Freymueller, University of Alaska. GRACE mascon time series from Luthcke et al., 2008)

#### Reference


Luthcke S., A. Arendt, D. Rowlands, J. McCarthy, and C. Larson, Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions, J. Glaciology, 54, 188, 767–777, 2008.

## SIDEBAR 20. ATMOSPHERIC WATER VAPOR AND GPS

In a classic example of one scientist's noise becoming another's signal, the geodetic community improved software analysis strategies in order to improve the accuracy of station position estimates; these improvements were later found to be useful for atmospheric science. When station surface pressure data are available, estimates of atmospheric delay can be transformed into precipitable water vapor (PWV). Water vapor is the most abundant atmospheric greenhouse gas; it is also highly variable and not easily measured. GPS data from PBO provide a useful way to derive PWV in the western United States, where there is a lack of observational instrumentation to make high-resolution temporal and spatial measurements of atmospheric water vapor (Figure 1). Evaluation of errors in the analysis fields used for numerical weather models reveals that PBO data should provide useful information for atmospheric researchers interested in studying the complex climate and weather that evolves over the complex topography that inspired the creation of EarthScope (Figure 2).

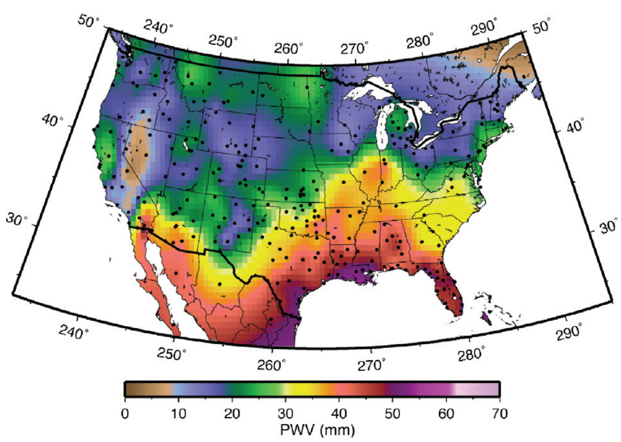



Figure 1: PWV estimates from GPS operations that are analyzed by the COSMIC program at UCAR (http://www.suominet.ucar.edu). These measurements provide valuable information on atmospheric water vapor that is useful for an array of atmospheric science applications including climate and weather.

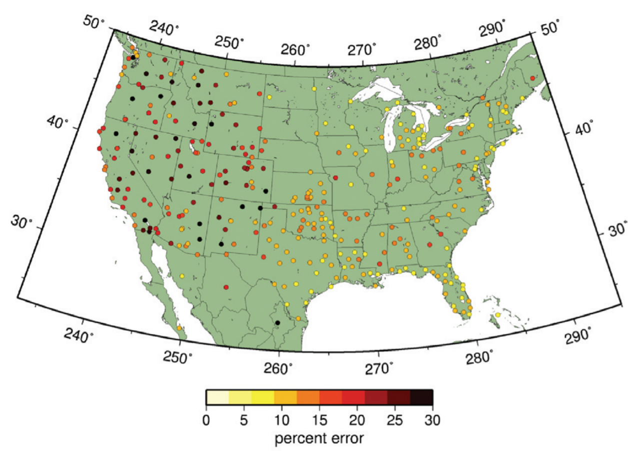


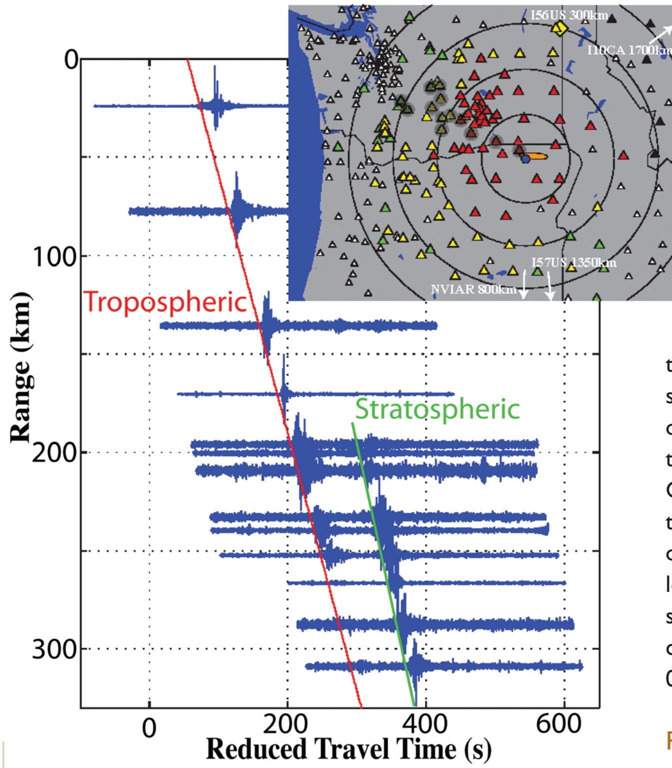

Figure 2: Fractional error in the NOAA Rapid Update Cycle (RUC) analysis fields for PWV. The majority of stations in the western United States are part of PBO.

- Seismic energy recorded by USArray in the microseismic band is being used to infer past and current ocean wave heights, thus helping to monitor climate change (*Sidebar 18*).
- A very-long-period Earth "hum" has recently been detected and is being used to infer Earth's deep structure (*Sidebar 18*).
- Portable seismic stations and GPS are being used to monitor glacial motion.
- GPS, inSAR, and GRACE are providing continuous groundwater monitoring (*Figure 3.8.1* and *Sidebar 16*).
- Atmospheric water vapor can be monitored in near-real time using GPS data; these measurements can be used to improve NOAA forecasts (*Sidebar 20*).
- Migration of USArray TA data at atmospheric acoustic speeds has revealed that detection of atmospheric events by the seismic stations is common. USArray can therefore be used to monitor acoustic noise sources in the atmosphere (e.g., bolides and volcanic explosions) and to derive atmospheric structure (*Sidebar 21*).

## OUTSTANDING QUESTIONS

- Can the EarthScope facilities be used to map water (groundwater, atmospheric water, soil moisture, snowpack, glaciers, and vegetation water content) in time and space in the western United States and Alaska with a resolution that complements other meteorological measurements?
- Can loading/hydrological processes (groundwater, lakes, rivers, glaciers, and dams) be modeled accurately enough to be helpful for hydrologic/atmospheric scientists and water supply managers?
- Can the EarthScope facilities be used to further our understanding of large-scale atmospheric phenomena?

## SIDEBAR 21. INFRASOUND RECORDINGS BY USARRAY




A bolide over Oregon recorded by the USArray TA on February 19, 2008, demonstrates the strong coupling between infrasound and the solid Earth seismic wavefield. In addition to seismographs, the infrasonic airwave was recorded by four infrasound arrays (I10CA, I56US, and I57US of the International Monitoring System, and by the NVIAR array in Nevada [operated by Southern Methodist University]; azimuths and ranges to infrasound arrays are indicated by white arrows and text). The accompanying map shows USArray stations recording the downgoing tropospheric signal in red; green stations recorded the stratospherically channeled signal that becomes visible near a range of 200 km. Black stations recorded a signal associated with this event with an as yet undetermined propagation path. Concentric circles around the epicenter show 100-km distance increments. Recordings from the shaded stations west of the bolide shown in the record section display the gradual loss of tropospheric signal and the emergence of the stratospherically ducted signal near a range of 200 km. The vertical-component records have been band-pass filtered between 0.8 and 3.0 Hz and time has been reduced at 450 m/s.

### Reference

Hedlin, M., C. de Groot-Hedlin, D. Drob, K. Walker, A. Le Pichon, and M. Zumberge, Studies of atmospheric sources and propagation using the USArray, Eos Trans. AGU, Fall Meet. Suppl., 2008.

- Can the EarthScope facilities be used to characterize atmospheric propagation paths and can this information improve our understanding of atmospheric dynamics?
- How are the ice mass, permafrost, and Arctic freeze-thaw cycles changing?
- What other routine “data products” can be developed from EarthScope data to serve the hydrologic, cryospheric, and atmospheric communities?

# 4. EARTHSCOPE CONTRIBUTIONS TO UNDERSTANDING EARTHQUAKE, TSUNAMI, VOLCANO, AND LANDSLIDE HAZARDS

Understanding natural hazards such as earthquakes, volcanic eruptions, tsunamis, and landslides is of fundamental societal as well as scientific value. Achieving many of EarthScope's scientific goals will lead to a better understanding of the underlying processes causing these catastrophic events that affect the United States and other countries. As the USArray TA completes its journey across the continent and into Alaska, it will be detecting seismicity in areas where presently no comparable networks exist. Precise measurements of active deformation from GPS, InSAR, and strainmeters can pinpoint where faults are accumulating elastic strain or where volcanoes are inflating. LiDAR mapping of topography offset by faulting can reveal the surface slip in past earthquakes (*Sidebar 13*), giving us insights into how the faults might rupture in the future. Records of past earthquakes, volcanoes, and landslides are crucial for helping us understand the potential for future natural hazards and making accurate hazard maps.

## 4.1 EarthScope Contributions to Community Response

EarthScope is well positioned to speed the scientific community's response to hazardous events by rapidly providing data on the extent of damage and the magnitude of subsequent hazards, for example, aftershocks from earthquakes, volcanic eruptions and resulting lahars, and mudslides and secondary landslides. In the immediate aftermath of a destructive event, a rapid response is important so that the scientific community can obtain the ephemeral, time-critical data required to better understand the fault structures or magmatic systems. The same data types can be equally important for ongoing hazard assessment. Rapid assessments of damaged regions using LiDAR, UAVSAR, or InSAR images, especially in remote regions, can help direct emergency response and recovery efforts. Real-time displacements of GPS stations and high-resolution locations of post-event seismicity along a fault zone can be used to rapidly determine the location and extent of rupture in a large earthquake. Volcanoes almost always exhibit precursory deformation and seismicity before an eruption. A pre-eruptive response can capture unique data for both hazard evaluation and understanding magmatic processes. Post-event experiments, including rapid-response drilling, can give information about the immediate post-seismic and post-eruption processes, which is essential for understanding the physical processes controlling the system.

## 4.2 Identifying and Assessing Hazard

Through real-time continuous GPS measurements, improved records of seismicity, and high-resolution airborne and satellite images of temporal changes in the land surface, EarthScope can make key contributions to our understanding of where faults, volcanoes, and landslide structures are active and what hazards they pose. For example, InSAR measurements of the Three Sisters volcanic system in the Cascades of central Oregon revealed active inflation beneath what was thought to be a dormant volcano. As described in *Section 3.6.4*, PBO also captured crustal deformation related to magma ascent prior to the onset of the 2006 eruption of Augustine Volcano in Alaska. Other studies are focusing on volcanoes elsewhere in the Cascade arc and in the Aleutians, Long Valley, Yellowstone, the Rio Grande Rift, and the Basin and Range. GPS and InSAR data can constrain fault slip rates and determine the depth of the locked/creeping transition on active faults; the product of these two quantities is proportional to the long-term earthquake moment rate, which drives hazard calculations.

TA data have been used in western states to augment permanent seismic networks, aiding in the location and assessment of seismic sources. In regions that have relatively sparse seismic networks, use of TA data may improve detection thresholds and location accuracy, features of the TA that will become increasingly important as the TA moves eastward and to Alaska. The TA will also better define the crust's attenuation structure, which is critical for predicting the propagation of damaging seismic waves and the resulting strong ground motions that destroy the bridges, roads, and buildings in which we live and work.

Earthquake prediction is an elusive and controversial goal of seismology. Recent work has made significant progress on short-term, probabilistic forecasts. Aftershock warnings are now routinely issued based on the usual statistics of sequences. The TA's broad spatial extent will permit improvement of these forecasts by measuring statistical behaviors in regions and under conditions that have been previously unsampled. The combined instrumentation will also allow testing of new ideas and methods to identify the immediate triggers of earthquakes.

## 4.3 Suggested Actions

The ability to better forecast and respond to hazards and mitigate the associated risks remains an important goal for EarthScope. The following actions are important for an increased EarthScope contribution to natural hazard assessment over the next five to 10 years:

- Provide InSAR deformation products (interferograms and tools to facilitate time series analysis) for improved spatial resolution of the strain field.
- Convert as many PBO sites as possible to real-time, high-sample-rate data acquisition to provide good spatial resolution of real-time deformation data.
- Contribute data for improving routine earthquake locations using 3D velocity models and EarthScope seismic data resources.
- Coordinate with NASA to enable rapid UAVSAR (Uninhabited Aerial Vehicle Synthetic Aperture Radar) response to events.
- Coordinate with USGS to ensure that telemetered seismic and deformation data are immediately available for monitoring faults and volcanoes.
- Develop a response plan for high-probability destructive events.

# 5. EXPANDING EARTHSCOPE'S REACH

The EarthScope community includes not only the researchers, postdoctoral associates, students, and technicians working with the data or developing models to explain observations derived from the data, but the broader community of scientists, teachers, students, and members of the public who are interested in the natural processes occurring around them (*Sidebar 22*).

## 5.1 The EarthScope Research Community Today

The EarthScope Program at NSF has funded more than 120 independent researchers since it was established in 2004. This number, however, underestimates the impact of the program because the data produced by EarthScope facilities have enabled research projects and outreach efforts that extend well beyond funded projects. The large, and growing, number of EarthScope-related presentations at national meetings reflects this impact. For example, there were 175 abstracts with EarthScope, PBO, SAFOD, or USArray in the title or text at the fall 2008 meeting of the American Geophysical Union; this number had increased to 219 for the fall 2009 meeting. In each year, these abstracts involved ~600 different co-authors. The number of publications acknowledging EarthScope also continues to grow rapidly.

In 2007, NSF established a rotating, university-based EarthScope National Office (ESNO) to facilitate communication among NSF, the facilities, the research community, and the public. This office will move every three to four years. The office is awarded based on a competitive, peer-reviewed process. The first ESNO (2007–2010) was located at Oregon State University (OSU) and took responsibility for managing the newsletter and web content, as well as organizing the speaker series, the National Meeting, and other workshops. The OSU ESNO also expanded EarthScope's Education and Outreach efforts from the K–12 classroom to informal education venues by organizing a series of regional workshops to train park and museum staff to incorporate EarthScope observations and science results into their interpretive programs and exhibits.

## 5.2 Expanding and Strengthening the EarthScope Research Community

A major objective for EarthScope in the next decade is to further enlarge and diversify the EarthScope community in order to maximize integrative and multidisciplinary research. Some of these links are obvious. For example, collaboration between geophysicists and geologists has been recognized as essential from EarthScope's inception. Recent funding of ambitious, integrated, and interdisciplinary proposals that include high-resolution geophysical studies as a bridge between geologic observations and large-scale subsurface images will involve a large cross section of the geoscience community (e.g., *Figure 3.2.3*).

## SIDEBAR 22. THE EARTHSCOPE EDUCATION AND OUTREACH PYRAMID

Any particular EarthScope science project commonly involves interactions among a handful to scores of scientists, including PIs, students, postdocs, and their collaborators. The results are disseminated to scientists working on related Earth science research via scientific journals and presentations at AGU, GSA, SSA, and other professional meetings. These results can reach a broader spectrum of the Earth and other scientists when presented at colleges and universities. One example is the ongoing EarthScope Speaker Series (http://www.earthscope.org/speakers), whereby EarthScope scientists present their findings in seminars that reach faculty and students in geology, geophysics, and physics departments across the country. Other examples are web sites established by individual PIs and mini-courses that provide training for using various types of EarthScope data or data processing tools (e.g., strainmeters, massive seismic data sets).

A large audience for EarthScope data and results is K–12 teachers and students. Much EarthScope science is directly related to Earth science topics (e.g., the "Big Ideas" of the NSF-funded Earth Science Literacy Principles: http://www.earthscienceliteracy.org). Because these topics are directly correlated with state and national science standards, schools are eager recipients of these materials. EarthScope can increase its impact through the inclusion of EarthScope information in mainstream textbooks. For example, a feature on the EarthScope TA appears in the new Pearson Education middle school textbook program, which will reach tens of millions of students.

IRIS and UNAVCO have ongoing programs to reach students at all levels by training K–12 and college teachers:

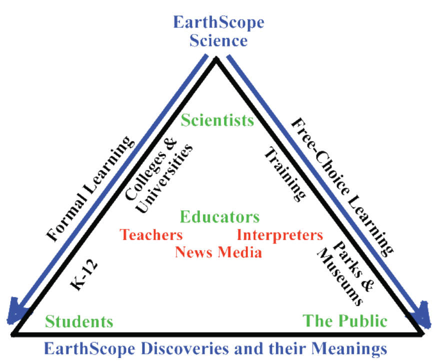
- http://www.iris.edu/hq/programs/education_and_outreach/professional_development
- http://www.unavco.org/edu_outreach/workshops.html

Examples of PI-driven projects to train K–12 teachers include:

- Bob Butler's "Teachers on the Leading Edge" project in the Pacific Northwest. http://orgs.up.edu/totle
- Sally McGill in the San Andreas region. http://gsa.confex.com/gsa/2009AM/finalprogram/abstract_166921.htm
- Skip Nelson in the Midwest. http://gsa.confex.com/gsa/2009AM/finalprogram/abstract_163015.htm.

A number of efforts engage informal educators ("interpreters") in parks, museums, libraries, and other settings where visitors are by their own choice rather than as part of a required learning activity. An example is the series of workshops for interpretive professionals in parks and museums initiated by Bob Lille and the EarthScope National Office (http://www.earthscope.org/eno/parks).

One aspect of Education and Outreach that is not currently very well developed is technical outreach to science and engineering practitioners and policymakers. Development of this branch of EarthScope outreach programs should be encouraged.




**Scientists**
- EarthScope Researchers
- Other Earth Scientists
- Scientists From Other Disciplines

**Educators**
- College/University Faculty
- K–12 Teachers
- Park/Museum Interpreters
- News Media

**Students**
- College/University
- K–12
- Lifelong Learners

**The Public**
- Planning/Policymakers
- Science/Engineering Practitioners
- Land Owners
- Park/Museum Visitors

Workshops and training courses have an important role to play in expanding the pool of scientists who can use the diverse range of EarthScope data. One mechanism to foster communication across disciplines is the periodic convening of EarthScope Institutes, which bring large groups of scientists together to address major, cross-cutting themes that require observational, theoretical, and laboratory approaches. Such Institutes not only serve as incubators for novel ideas and proposals, but also create an intellectual framework to attack the broad science goals of EarthScope. In order to facilitate future multidisciplinary collaboration, additional mechanisms suggested at the 2009 Snowbird workshop included pilot money for small-group planning meetings. It is important to note that multidisciplinary investigations with multiple investigators complement, but do not replace, traditional single investigator and/or disciplinary investigations.

As illustrated by *Sidebars 17–21*, a major attraction of the EarthScope facility is its ability to promote discovery-based science in a variety of new and unexpected directions. This activity is leading to new collaborations among scientists from disciplines that were not explicitly considered when planning the facility, including atmospheric scientists, oceanographers, hydrologists, and geomorphologists.

Educating and involving the next generation of EarthScope scientists is a key priority of the program. Young investigators are represented across the range of EarthScope projects, and they have been active participants in EarthScope meetings. To sustain this trend, young investigators should continue to be encouraged to join and lead workshops and collaborative proposals. EarthScope policies regarding instrument use and data release should be considered in light of the tenure deadlines faced by junior faculty. In addition, an EarthScope postdoctoral fellowship program should be pursued. Classes to train investigators—from graduate students to senior scientists—in the special techniques required to take full advantage of the massive data sets or new data types provided by EarthScope are also needed.

## 5.3 Beyond the Research Community

Efforts to convey EarthScope observations, scientific results, and their broader meanings to audiences beyond technical journals and research meetings can have great impact. EarthScope provides a unique opportunity to bring geophysics and the study of Earth to citizens across the United States. It is an unfortunate artifact of our educational system that Earth science is generally taught only in middle school, if at all, and that only 7% of Americans get any Earth science education in high school. Earth science therefore relies greatly upon informal education as a primary means of capturing the interest and imagination of American citizens. The public readily appreciates many of the Earth science topics that are directly related to EarthScope, such as earthquakes and volcanoes. These topics are commonly the biggest draws in exhibits at science museums and in popular science television programs. The ideas involved with probing into the San Andreas Fault, watching as the western United States wrinkles or stretches, and having a giant upside-down stethoscope that moves across the continent, listening to the heartbeat of our planet, are ideas that can captivate most citizens. It is imperative, therefore, that the Earth science community continue to use the opportunity that EarthScope provides to increase America's awareness and appreciation of geoscience. As EarthScope moves from its successful facilities installation stage to achieving rapid advances in the understanding of the structure and dynamics of the North American continent, efforts must be made to ensure that these exciting discoveries reach the public's attention. EarthScope also provides a great opportunity to improve science literacy by showcasing research into Earth that can be incorporated into the formal education system at all levels.

Permanent geodetic, seismic, and magnetotelluric stations have been installed across the United States. Seismic stations are being reinstalled in Cascadia, and more than half of the U.S. states have yet to be reached by the EarthScope TA. Thus, great opportunities remain for the ongoing engagement of a range of audiences throughout the United States as well as targeted regional audiences. Prior to arrival in a region, USArray and UNAVCO have outreach programs dedicated to station siting. The TA program, which involves large numbers of faculty and students making contact with landowners of potential sites, is particularly noteworthy (*Appendix 9.1.1*). In addition, opportunities to reach the general public should be increasingly encouraged. The permanent seismic, magnetotelluric, and geodetic backbone stations can also be used to excite and maintain interest.

The ultimate goal of EarthScope Education and Outreach (E&O) is to broaden the community of contributors and users of EarthScope resources. The 2002 and 2007 EarthScope Education and Outreach Implementation Plans outlined a variety of ways in which scientific and lay audiences can learn about and benefit from EarthScope observations and discoveries. Five specific goals for EarthScope E&O that are highlighted in the plans are to:

- Create a high-profile public identity for EarthScope that emphasizes the integrated nature of the scientific discoveries and the importance of EarthScope research initiatives.
- Establish a sense of ownership among scientific, professional, and educational communities as well as the public so that a diverse group of individuals and organizations can and will make contributions to EarthScope.
- Promote science literacy and understanding of EarthScope among all audiences through informal education venues.
- Advance formal Earth science education by promoting inquiry-based classroom investigations that focus on understanding Earth and the interdisciplinary nature of EarthScope.
- Foster use of EarthScope data, discoveries, and new technologies in resolving challenging problems and improving our quality of life.

Achieving these goals requires that EarthScope data and discoveries, and their implications, reach a broad spectrum of audiences that includes scientists, educators, students, landowners, policymakers, and the general public (*Sidebar 22*). The EarthScope research community will need to efficiently take advantage of outreach infrastructures that already exist. The EarthScope National Office can be a facilitator in this effort by compiling training materials for local scientists who are interested in informing their communities about EarthScope. Ideas include:

- Preparing a web-based public relations packet, with information, maps, images, videos, and names of local scientists willing to be interviewed by local newspaper and radio/TV reporters; reporters are eager to get information about local stories with national impact.
- Coordinating EarthScope E&O activities to ensure that the highest E&O priorities are being met. Possible actions include tracking activities across the program, recruiting individuals to develop specific activities, and establishing E&O networks to increase visibility.
- Working with the EarthScope facilities and other groups involved in Earth science education and outreach to make available succinct and attractive K–12 and undergraduate lesson plans that are tailored to the local geology and incorporate national and state science standards, which is necessary for school adoptions.
- Creating and maintaining a complete registry of EarthScope E&O products.
- Continuing to develop regional *Active Earth* kiosk modules to be installed in informal education venues nationwide. IRIS designed the original *Active Earth* kiosk, which focuses on general information about seismology. Regional modules, which cover broader aspects of the geology and natural hazards in Cascadia, the Basin and Range, and the San Andreas fault zone, have been developed through collaborations among the EarthScope National Office, IRIS, and UNAVCO. These modules have been connected with workshops for informal educators in parks and museums in order to introduce the geologic interpreters to the kiosks and their content.

EarthScope, through the National Office, facilities, and individual researchers, should provide a variety of educational products and training venues to reach a wide variety of audiences. If vigorously pursued, this is a win-win situation: audiences of all types get access to exciting new discoveries and increased public support for science enhances recruitment of the next generation of scientists (including minorities and underrepresented groups). EarthScope E&O can play an essential role in realizing NSF's overall mission by leveraging current investments in "people, ideas, and tools," facilitating integration of research and education, and developing the workforce for the twenty-first century.

# 6. EARTHSCOPE DATA IN THE SERVICE OF EARTHSCOPE SCIENCE

The primary goal of EarthScope is to facilitate synoptic science aimed at addressing questions associated with the structure, dynamics, and evolution of the North American continent. EarthScope facilities are a foundation for this work by providing seismic, magnetotelluric, GPS geodesy, strainmeter, LiDAR, InSAR, borehole, and cognate data sets, with open data access, and providing open-source software for the benefit of the whole community. This open-access paradigm is serving as a model for other science efforts worldwide. From its inception, however, EarthScope has recognized that answering the questions highlighted in *Section 3* requires many types of geological and geophysical data as well as geodynamic models to tie the different types of data together.

## 6.1 Current Access to EarthScope Data and Data Products

As EarthScope science becomes more mature and interdisciplinary, it is important to broaden the definition of "data" and establish a classification system for different types of "data products." The following classification was established when EarthScope was initially defined.

- Data (raw and quality-controlled geophysical data from EarthScope instruments and rock samples from SAFOD core and drill cuttings)
- First-order data products (first level of data reduction, such as GPS coordinates, earthquake locations, and magnetotelluric response functions)
- Higher-order data products (e.g., strain rate maps, seismic tomograms, electrical conductivity models, and mantle flow models)
- Interpretive products (e.g., volcanic hazard assessments and earthquake probability maps)

Data and some first-order data products are currently being provided by the facilities (see *Appendix 9.1.3*), and discussions are underway both within the EarthScope advisory structure (the EarthScope Cyberinfrastructure Subcommittee) and through the main facility data centers to begin providing higher-level data products. For example, a subcommittee of the IRIS Data Management System Standing Committee is charged with designing a framework for the implementation of tools to visualize and compare different 3D velocity models. Although it is widely recognized that development of higher-level data products is needed, it is important to maintain a dynamic balance between standardization of such products and continuing research into better data analysis methods. Good coordination of efforts between the facilities and the EarthScope advisory and research community is also essential.

Successful integration across its many data types is critical for achieving many of the EarthScope science objectives. A unified portal (EarthScope Data Portal; http://www.earthscope.org/data) provides unrestricted access to raw data and derived data products from the EarthScope facilities. Currently, higher-order and interpretive products developed and maintained by individual investigators (e.g., a shear wave splitting database, P- and S-wave tomography databases, seismic surface wave group and phase velocity maps derived from ambient seismic noise, earthquake ground motion animations, regional moment tensors, receiver function reference models, continuous deformation maps of the western United States and Hawaii, and time-dependent strain maps) as well as complementary geophysical and geological databases, are compiled by the EarthScope National Office and can be accessed from a single web page (http://www.earthscope.org/science).

# 6.2 Steps Toward an Integrated Cyberinfrastructure System for EarthScope

EarthScope's continued success depends on having a cyberinfrastructure framework that facilitates the processing, distribution, and analysis of core data sets, as well as the modeling and integration of a variety of data. Having an effective framework would significantly democratize the process of using EarthScope data. Although there has been notable progress in developing an infrastructure to turn raw and quality-controlled data into first-order derived products, perhaps the single greatest challenge remaining is to address the lack of software for the analysis, interpretation, and integration of those products. Analysis software is produced both by academic and commercial groups (some of which has been made available at low cost to academic groups for student training), but this software can require specialist knowledge or licensing to use, require computing power and maintenance that can be prohibitive for small groups, or be so specialized that it is not flexible enough to accommodate a wide range of research needs. Examples include 3D/4D commercial seismic and electromagnetic imaging software products that could be suited to licensing on TerraGrid, SDSC, and other national research computer systems.

Additional improvements are desirable in the area of routine EarthScope data processing. The current structure is for individual investigators to maintain their own mix of individually assembled data processing components, often optimized for pre-EarthScope data volumes. Greater capability, efficiency, and "buy-in" from a wider community would be expected if routine data processing software were organized on a community-wide basis, and if derived data products were made available in an agreed-upon form (e.g., having InSAR interferograms available in addition to raw SAR images). At present, too much effort is spent developing data processing codes that already exist but are not discoverable or documented. It would also be helpful to establish standards for use of SAR and its integration with other data products. EarthScope provides a unique framework for setting format standards and benchmarks that should be exploited to further the integration of disparate data sets and for developing community software according to accepted interface standards.

Another challenge is the integration of data with very different characteristics. Data integration often begins with the "simple" task of overlaying map layers displaying different information at the same scale and projection. This task is often more difficult than it sounds because the metadata that provide information about the data (e.g., the geodetic datum used to establish latitude, longitude, and elevation) may not be readily available or may be missing altogether. There is a general need for a catalog of GIS data resources through the EarthScope data portal, with links to GEON as well as to widely used commercial environments such as Google Earth. By providing incentives for researchers to register GIS layers that may be of use to others, the integration and synthesis goals of EarthScope can be advanced. An expanded EarthScope data portal could incorporate synoptic continent-wide data sets (e.g., gravity, magnetic, seismicity, heat flow, and the USGS national atlas) in a common format, tying in state and regional GIS data (e.g., geologic maps, faults, and drilling data).

At the highest level of integration and synthesis, interface standards are needed to promote sharing of model products (e.g., tomographic and electrical conductivity models). There is a strong desire by the EarthScope community to share models, which can be facilitated by separating interface standards from the internal and external formats of the models. Metadata standards for models are also needed so that information on spatial resolution and related parameters can make results understandable to non-specialists. By establishing interface standards, metadata requirements and, where appropriate, format standards, EarthScope can be proactive in ensuring that EarthScope data and data products are compiled, archived, and released in ways that are as straightforward and seamless as possible.

Additional activities that EarthScope should nurture and encourage include:

- Incorporation of appropriate pre- and syn-EarthScope data sets obtained outside of the EarthScope program, with the goal of integrating these other sources into EarthScope databases for enhanced analyses and interpretations. Examples might include tighter integration with USGS activities and compilation of seismic, magnetotelluric, and other geophysical transect data obtained prior to or outside of EarthScope.
- Greater incentives for potential EarthScope data product users to make use of data discovery tools. Additional developments are required to provide data products in simpler formats that are more familiar to end user communities (such as EDI, ASCII, Excel, and MATLAB formats), and to provide greater ease of access for the general public.
- A standard set of tutorials and exercises to familiarize students across multiple disciplines with EarthScope tools. Education and outreach efforts can further the development of tutorials for cross-disciplinary education as well as for student training in the use of discipline-specific data management and modeling tools.
- Use of national high-performance computing resources and development of new algorithms to derive processing kernels that can take advantage of modern multi-core desktop class computers, including emerging GPU-based architectures that can incorporate hundreds to thousands of desktop processing cores. There may be increasing synergies with GEON and other community cyberinfrastructure initiatives.
- Virtual institutes (e.g., OpenEM.org) to provide community services such as forums, webinars, open source software repositories, and data portals that could be built on the foundations of the current EarthScope.org web services. These services also need to include providing collaborative workgroup resources that enable EarthScope researchers to share workspaces.

# 7. LINKS TO OTHER PROGRAMS

EarthScope's ultimate goal is to produce and disseminate high-quality scientific results. In pursuit of this goal, it will be productive and efficient for EarthScope to pursue explicit links with other NSF and non-NSF programs in support of research, education, and outreach.

## 7.1 NSF MARGINS Program

The science goals of EarthScope and the NSF MARGINS program intertwine, yet the programs remain distinct. EarthScope makes use of revolutionary on-land geophysical facilities and focuses on North America; these traits are complemented by the onshore-offshore nature of MARGINS studies and MARGINS' emphasis on global comparisons. As previously mentioned, EarthScope is collaborating with the MARGINS program to support projects in regions of mutual interest, including the Cascadia subduction zone and the Salton Trough/Gulf of California. In 2009, both programs put out a joint call for proposals to support facility-related investments in the form of ocean bottom seismographs (OBSs) to support onshore/offshore studies of the Cascadia margin. MARGINS is also in the process of creating a new science plan, and integrated EarthScope-MARGINS studies are expected to be increasingly important in the future. For example, as the TA moves to the rifted margins of eastern North America and the Alaska-Aleutian subduction zone, many more natural partnerships will emerge. The next decade should see the initiation of EarthScope Virtual Institutes, similar to the MARGINS Theoretical and Experimental Institutes, to bring investigators together from different disciplines and different communities to compare results and find solutions in an informal and collegial atmosphere.

## 7.2 Other NSF Programs

Other NSF programs that can potentially collaborate with the EarthScope program, either by co-funding projects or supporting projects that use EarthScope data, include the following:

- Geophysics, Continental Dynamics, Petrology, Geochemistry, Sedimentology and Tectonics programs in EAR
- OCE programs such as IODP (International Ocean Drilling Program), Marine Geology and Geophysics
- Ocean Observing Initiative (OOI)
- Office of Polar Programs
- Atmospheric and Geospace Sciences (AGS)
- Office of International Science and Engineering
- George E. Brown Network for Earthquake Engineering Simulation (NEES)

The IODP has a strong record of integrated science and is the standard for core repositories; it will be involved in any drilling on the continental margin for future EarthScope/MARGINS collaborations. The ICDP (International Continental Drilling Program) will be involved in any onshore drilling. The Marine Geology and Geophysics Program portfolio includes offshore seismic, electromagnetic, and geodetic research, as well as management of the Ocean Bottom Seismic Instrument Pool (OBSIP). The Office of Polar Programs has potentially significant overlap with respect to studies in Alaska. If possible, the EarthScope/Polar Programs relationship should be clarified prior to the movement of USArray to Alaska. The Office of International Science and Engineering has overlap with USArray efforts in Canada as well as possible future collaborations with Mexico.

# 7.3 Related NSF-Funded, Community-Based Initiatives

There are several NSF-funded, community-based initiatives that complement EarthScope.

- SCEC (Southern California Earthquake Center) is an independent center funded primarily by NSF and the USGS. Collaboration between EarthScope and SCEC has already yielded significant results. The broad geographic extent of EarthScope's PBO, as well as the detailed fault mechanism studies of SAFOD, have assisted SCEC in developing a comprehensive understanding of earthquakes in Southern California. SCEC is also well versed in the potential and pitfalls of developing community models, which provide a mechanism for compiling integrated data sets and evaluating their implications; lessons learned by SCEC about nurturing interactions between different communities and integrating different types of data may be transferable to EarthScope.
- CIG (Computational Infrastructure for Geodynamics) is an organization that develops and maintains software for computational geophysics and tectonics. At the 2009 Snowbird meeting it became clear that geodynamic modeling is a key mechanism for integrating different data sets.
- GEON is a collaborative project to develop cyberinfrastructure for integration of three- and four-dimensional Earth Science data. Because geophysical data are a core focus of the GEON Project, communication between the two programs is essential.
- COMPRES (Consortium for Materials Properties Research in Earth Science) can be informed by the detailed studies of the deep Earth provided by USArray, and vice versa.
- CIDER (Cooperative Institute for Dynamic Earth Research) shares interests in deep Earth structure, composition, and dynamics and can help in collaborative research and student training using EarthScope data.
- CUAHSI (Consortium of Universities for Advancement of Hydrologic Science) can help identify new uses for EarthScope data (see Section 3.8).

# 7.4 WInSAR and the European Space Agency

Continued close collaboration between WInSAR and EarthScope will ensure dense SAR data coverage, supporting the "fourth leg" of EarthScope and enabling significant advances in the measurement and modeling of spatially variable geophysical processes. WInSAR is both a committee under UNAVCO and a group recognized by foreign space agencies for the distribution of data to U.S. scientists. Close collaboration with the European Space Agency (ESA) can provide dense SAR data coverage for the EarthScope area and partly make up for the missing InSAR satellite (EarthScope's fourth, but unfunded, leg). GeoEarthScope obtained excellent SAR coverage for 2005–2008. It is important that similar imagery be acquired in the future through WInSAR. It is particularly important that the forthcoming Sentinel satellite (to be launched in 2011) include North America in its routine observation plan. SAR imaging of the North American continent should be seen by all parties as a European contribution to EarthScope.

# 7.5 The Private Sector

The hydrocarbon industry has great potential for interaction with EarthScope. For example, industry has access to a large number of reflection profiles and is currently defining and using the cutting-edge of technology with respect to active source seismology. The EarthScope science community would welcome access to some of these data and to data acquisition and processing techniques pioneered by industry. Closer interaction also benefits the industry because a significant percentage of the students working on EarthScope-related projects and using EarthScope-produced data will eventually find employment in the hydrocarbon industry, either for exploration or for monitoring of reservoirs, and there are significant concerns within the industry about the size and quality of the pipeline for training future employees. It is likely that seismologists will be increasingly needed in the hydrocarbon industry and by hydrologic consulting companies for reservoir delineation and monitoring. Applications include $CO_2$ sequestration and monitoring of water resources as well as the traditional areas of hydrocarbon exploration and extraction.

## 7.6 International Universities and Geological Surveys

International collaboration with EarthScope is also critical. Although the Canadian LITHOPROBE program has ceased, it provided an initial impetus for the EarthScope program. Looking forward, interaction with Canadian geophysicists and geologists is essential for achieving the EarthScope goal of understanding the evolution of the continent. This is particularly evident in the Great Lakes region of North America, where the boundaries of tectonic terranes do not correlate well with the location of the lakes or the international border. The adjacent areas of Mexico must, in similar fashion, be studied to reconstruct the geological evolution of the southwestern United States. Northern Mexico is poorly known from both a seismological and geological point of view, and thus data from this area would be particularly valuable.

## 7.7 Other Earth Science Education and Outreach Programs

EarthScope can leverage its education and outreach efforts by collaborating with other initiatives. For example, EarthScope and the E&O components of IRIS and UNAVCO have been working to varying degrees with the National Association of Geoscience Teachers (NAGT), National Science Teachers Association (NSTA), Digital Library for Earth System Education (DLESE), Global Learning and Observations to Benefit the Environment (GLOBE), Research Experience in Solid Earth Science for Students (RESESS), SCEC, NEES, Science Education Resource Center (SERC), Significant Opportunities in Atmospheric Research and Science (SOARS), and Teachers on the Leading Edge (TOTLE). Not only do EarthScope audiences (*Sidebar 22*) stand to benefit, increased E&O collaborations will also greatly contribute to Earth science literacy principles identified as critical to an educated and informed public by NSF and other agencies.

# 8. CONCLUSIONS AND RECOMMENDATIONS

The EarthScope program offers an unprecedented opportunity within the Earth sciences. The EarthScope facility, described in the initial (2002) EarthScope Science Plan and implemented with funding from the NSF Major Research Equipment and Facilities Construction program, has provided the tools for a decade of exploration of the North American continent. The next decade of EarthScope science will undoubtedly be very exciting and will likely result in many new and unanticipated discoveries as well as answers to many of the questions posed in this Science Plan. To maximize these results, the following recommendations should be followed.

## 1. MAINTAIN AND ENHANCE THE EARTHSCOPE NATIONAL OFFICE

The EarthScope National Office has helped to communicate EarthScope progress, data, and research opportunities and has expanded education and outreach efforts to include informal as well as formal education. Details of the role of the office will certainly evolve along with the program. Efforts to improve communication and integration within the research community through support of workshops, informative newsletters, and other means should be encouraged.

## 2. FACILITATE INTEGRATIVE AND MULTIDISCIPLINARY RESEARCH

It is essential to broaden the EarthScope community with the goal of encouraging integrative and multidisciplinary research. This emphasis applies to scientific communities that were not closely involved with EarthScope a decade ago (e.g., hydrologists, atmospheric scientists) as well as the more naturally related scientific communities (e.g., geologists, geochemists, petrologists, structural geologists, geodynamicists). Mechanisms to facilitate submission of multidisciplinary or exploratory proposals that integrate disparate fields and to expand access to higher-order data products are essential.

## 3. ENCOURAGE EXPLORATION

Many of the most interesting scientific results of EarthScope have been unexpected. EarthScope science should take advantage of this "discovery" aspect, and use its flexibility to build on serendipitous findings. Possible means of facilitating research includes allowing rapid response to earthquakes and/or volcanic events, supporting unconventional deployments of geophysical instrumentation, and supporting work in areas of interest even if they fall outside of the onshore portions of the United States.

## 4. ENHANCE OUTREACH EFFORTS

It is critical to create a high-profile public identity for EarthScope. This will involve better coordination of EarthScope E&O activities and materials and an overall assessment of the roles of the many stakeholders in these activities. Although the EarthScope National Office, facilities, and individual investigators have been active in promoting a wide variety of outreach efforts, there are many opportunities and new communities that need to be involved in these activities.

## 5. DEVELOP EFFECTIVE CYBERINFRASTRUCTURE

EarthScope will increasingly depend on its cyberinfrastructure framework to facilitate scientific findings, particularly for multidisciplinary projects. Immediate needs include:

- Cataloging of and access to data products, derived products, and interpretive products
- Establishing of data and metadata standards
- Encouraging and coordinating efforts by IRIS and UNAVCO to develop software tools to process and analyze large volumes of data and establish databases of higher-order data products
- Creating greater incentives for potential EarthScope data product developers to make their products available to the community
- Creating greater incentives for potential EarthScope data product users to make use of data discovery tools
- Developing a framework for implementing the above recommendations

## 6. LINK TO OTHER PROGRAMS

This includes:

- Encouraging international cooperation around the edges of the EarthScope footprint
- Co-funding of projects by multiple NSF programs and other agencies whose objectives overlap, including facilitation of onshore/offshore experiments
- Collaborating with industry on cyberinfrastructure and on acquisition and processing of active source data
- Improving integration of EarthScope data into databases used for locating and cataloging earthquakes, monitoring volcano inflation and deflation, and other programs led by agencies such as USGS and NOAA that are charged with responding to a variety of geological and environmental hazards

## 7. SUPPORT INSAR (SPACEBORNE RADAR) DEVELOPMENT AND DATA ACQUISITION

Radar measurements of fine-resolution, spatially continuous crustal deformation are critical to many of the EarthScope science goals, as they reach inaccessible areas with frequent revisit times. A U.S. radar satellite mission is needed to provide these essential data to EarthScope investigators. Collaborations with other agencies, primarily NASA, should be pursued to realize this critical data set within the decade. In the short term, EarthScope should encourage high-level government agreements and systems to facilitate the use of data from international satellite platforms.

## 8. ENHANCE THE EARTHSCOPE FACILITIES

The community should be proactive in proposing projects that involve funding for extending or enhancing the EarthScope facilities in response to evolving science needs. Key aspects of EarthScope facility enhancement could include:

- Reinstalling the SAFOD borehole observatory and expansion of its capabilities to include additional measurements (e.g., pore pressure)
- Acquiring new SAFOD cores
- Upgrading additional GPS stations to high-rate, real-time recording
- Acquiring new USArray seismic and magnetotelluric stations for onshore/offshore deployments
- Augmenting EarthScope stations with other instruments that provide new capabilities

# 9. APPENDICES

## 9.1 More on the EarthScope Facilities

### 9.1.1 USARRAY

TRANSPORTABLE ARRAY (TA): The TA is an array of broadband seismic stations deployed on a roughly 70-km grid. All TA stations have real-time data telemetry. At any given time, there are approximately 400 stations in operation. Each station is operated for two years and then is moved to the eastern edge of the active array. The TA has now occupied over 850 sites in the western United States and is midway through its multiyear migration toward the Atlantic coast. Cumulative data return from the TA has exceeded 97%, and was 99.3% during 2009. See *Figure 2.1* for a map of past, present, and future TA locations.

FLEXIBLE ARRAY (FA): The FA consists of 326 broadband, 120 short-period, and 1700 short-period/short-deployment instruments that are available for PI-driven experiments that address EarthScope program scientific goals. FA equipment also includes solar panels, enclosures, cables, communications gear, and field computers; PIs must only provide batteries and personnel to deploy and maintain the stations. Funding for FA experiments comes from a variety of sources in addition to the EarthScope program. *Figure 2.1* also shows the locations of experiments that have used FA equipment as of January 2010.

REFERENCE NETWORK (RN): The RN (*Figures 2.1 and 2.2*) consists of 106 stations located at ~300-km spacing across the contiguous United States, plus nine stations in Alaska. These stations serve as fixed reference points for tying together observations made by the "rolling" TA. Most RN stations are operated by the USGS as part of the Advanced National Seismic System (ANSS) network, or by IRIS (referred to as the USArray Permanent Array during the construction phase of USArray). All RN data flow both to the IRIS Data Management Center (DMC) and to the USGS National Earthquake Information Center (NEIC), where RN data are used in real time for earthquake monitoring applications. Twelve of the RN stations are equipped with GPS sensors, which provide baseline data for the PBO/UNAVCO data archive.

MAGNETOTELLURIC ARRAY (MT): The MT component of USArray (*Figure 2.1*) has established seven backbone stations distributed across the United States. In an ongoing campaign of MT transportable array installations, 20 portable MT instruments have been deployed and relocated thus far during campaigns in the summers of 2006–2009, collecting data from 221 temporary sites in the northwestern United States. A field operations depot and data quality control group have been established at Oregon State University, providing operations and maintenance support for all MT activities.

SITING OUTREACH: The Siting Outreach component of USArray has conducted a broad spectrum of activities, including actively working with numerous state and local organizations to encourage the use and understanding of USArray. Several outreach workshops have been held to encourage participation in and awareness of EarthScope. Universities have been recruited to provide summer student hires to conduct site reconnaissance for TA stations. To date, more than 100 students from 25 universities have performed reconnaissance for nearly 1000 sites. Students from nearly a dozen universities have also formed the core of magnetotelluric transportable and backbone array field crews since 2008, providing practical field experience in the MT method.

AS-1 seismometers and *Active Earth* interactive Earth science kiosks have been acquired and distributed to museums and other locations to enhance the impact of USArray. The quarterly EarthScope newsletter, *onSite*, was originated by USArray to provide an overview of EarthScope facility science and status and is distributed to 700 USArray landowners. In 2007, the EarthScope National Office took over the lead editorial role for *onSite* and expanded the audience by 1200 to include geoscience departments and the offices of state geologists. In 2010, the newsletter designed for the broad science community was renamed *inSights—the EarthScope Newsletter,* and *onSite* returned to its roots as an outreach newsletter for TA landowners edited by IRIS.

## 9.1.2 PLATE BOUNDARY OBSERVATORY (PBO)

GLOBAL POSITIONING SYSTEM (GPS): The PBO network consists of 1100 permanently installed GPS stations located throughout the United States with a majority of the stations installed along the Pacific-North American plate boundary in the western United States and Alaska (*Figure 2.2*). PBO also maintains a pool of 100 portable (campaign) GPS receivers for temporary deployment and rapid response activities, allowing individual PIs to densify GPS observations within the PBO network. The PBO network instrumentation operates at over 95% uptime and has 98% network-wide data return.

BOREHOLE STRAINMETERS AND SEISMOMETERS: PBO includes 74 borehole strainmeters (BSM) and 78 borehole seismometers (*Figure 2.2*). The strainmeters are designed to detect deformation on a time scale of minutes to a month and thus provide a bridge between the seismometers and GPS instrumentation, allowing scientists to characterize a continuum of time scales for active tectonic deformation from earthquakes to aseismic creep. PBO has developed training sessions to introduce the scientific community to the uses of strainmeter data. Short-period seismometers are included at each site to provide collocated, high-frequency seismic data for event detection and location and to confirm aseismic slip.

BOREHOLE TILTMETERS: Measurement of deformation in the vertical field is essential to constrain fault models and provide insight into magma body location and rise. Because the precision of GPS in the vertical is still at the millimeter level, tiltmeters can provide measurements in periods ranging from days to years, adding to the temporal spectrum of deformation not covered by GPS. PBO includes 26 borehole tiltmeters collocated with GPS and BSM stations on active volcanoes. These tiltmeters are primarily used to study the volcano shape prior to and during eruptions.

LONG-BASELINE STRAINMETERS (LSM): PBO maintains six LSMs. LSMs use a laser to measure the change in the relative position of end monuments hundreds of meters apart. These very stable high-precision instruments measure strain change over months to decades and are an important tool for cross-validating long-term GPS measurements and monitoring stored energy near major faults.

INSAR AND LIDAR IMAGERY AND GEOCHRONOLOGY: The PBO GeoEarthScope initiative included the acquisition of airborne LiDAR imagery for the detailed mapping of Earth's surface, satellite InSAR imagery for the precise mapping of surface change during deformation events (until September 2008), and geochronology data to provide age constraints on prehistoric earthquakes and long-term fault offsets. Combined, these techniques allow the measurement of strain rates over very broad time scales.

## 9.1.3 DATA MANAGEMENT

All data can be accessed via the EarthScope portal (http://www.earthscope.org/data). Data can also be accessed via IRIS, UNAVCO, and other groups that are contracted by the EarthScope program to maintain the databases and provide software tools to facilitate access. Details are given below.

SEISMIC: All EarthScope seismic data are made freely available via the IRIS Data Management Center (http://www.iris.edu/dms/). Data are transmitted to the IRIS DMC from all components of USArray, as well as from the PBO seismometers and strainmeters and the SAFOD seismometers, tiltmeters, and strainmeters. Over 20 terabytes of EarthScope data have been archived by the DMC to date. Data may be obtained via a variety of data request tools. TA data are available in near-real time via various streaming data protocols.

MAGNETOTELLURIC: All EarthScope backbone and transportable array magnetotelluric data and derived data products are made freely available with no proprietary hold via the IRIS DMC. Data from the MT transportable array are retrieved by field crews during site visits and transmitted to the Oregon State University MT data quality control group, where they are processed and uploaded to the IRIS DMC. Approximately 1.25 gigabytes of post-quality-control 1-Hz MT time series have been archived by the DMC to date. Magnetotelluric response functions (impedances and magnetic transfer functions) are also archived at the DMC, typically within weeks of receipt of raw data by the quality control group. Real-time telemetry of MT backbone data to Oregon State University is being implemented, and a similar data flow to the IRIS DMC for MT backbone and transportable array data is being developed.

**GPS AND TILTMETER:** GPS and tiltmeter data are made available via the UNAVCO PBO (http://facility.unavco.org/data/dai2/app/dai2.html#), which manages distribution of 4 terabytes of raw PBO GPS data and derived data products. Secondary archives are maintained off site to assure redundancy.

**STRAINMETER:** PBO strainmeter data are available through the Northern California Earthquake Data Center (http://www.ncedc.org/pbo/).

**LIDAR:** The "OpenTopography Portal" (http://www.opentopography.org), developed and maintained by the San Diego Supercomputer Facility and Arizona State University, provides access to high-resolution topographic data, including LiDAR data acquired by GeoEarthScope. Data can be downloaded as DEMs, point clouds, and KML files. Data processing and visualization tools and a user discussion forum are also available.

**INSAR:** Data are supported directly by EarthScope through the WInSAR consortium, and can be found at http://geoes-insar.unavco.org/main.php. Investigators must be associated with a U.S. academic or government institution for data access. Registration of new institutions is straightforward but requires completing UNAVCO's WInSAR web forms.

**ROCK SAMPLES:** SAFOD core samples are requested via a web-based tool that can also be used to view the cores (http://www.earthscope.org/data/safod_core_viewer). Because the amount of core material is very limited, not all requests can be filled. Distribution of samples is decided by a committee of scientists through a protocol designed to optimize use of the core and minimize conflict of interest.

## 9.2 Workshop Agenda

The Workshop for an EarthScope Science Plan (WESP) was held in Snowbird UT on October 7-9, 2009 with the following agenda. Presentations from the workshop can be found at http://www.earthscope.org/meetings/science_planning_workshop.

### WEDNESDAY, OCTOBER 7

Speakers are listed with general topics; specific titles will be provided soon. Co-chairs of breakout groups are also listed.

**7:00 A.M. – 10:00 A.M.** **REGISTRATION**
Ballroom 3 Lobby

**7:00 A.M. – 8:00 A.M.** **BREAKFAST/MEETING WITH WRITING TEAM, ESSC, AND DISCUSSION (BREAKOUT) LEADERS**
Peruvian A

**7:00 A.M. – 8:00 A.M.** **GENERAL ATTENDEE BREAKFAST**
Magpie Room

**8:00 A.M.– 8:55 A.M.** **OPENING SESSION**
Ballroom 3

*Welcome & Agenda – From Snowbird 2001 into the next 10 years* (10 min)
Mike Williams

*NSF Perspectives on the Science Plan* (10 min)
Greg Anderson, Goran Ekstrom

*Tribute to Paul Silver and his contributions to EarthScope* (10 min)
Lucy Flesch, Fenglin Niu, Maureen Long

*Facility Highlights – Brief updates on facilities progress* (25 min)
Bob Woodward, Mike Jackson

**8:55 A.M. – 9:45 A.M.** Ballroom 3

**PLENARY ONE – BUILDING ON BREAKTHROUGHS – THE NEXT MILESTONE FOR EARTHSCOPE** (4 talks, 20 min each plus 5 min of questions)

*Fault properties and slip processes*
Chris Marone

*Plate boundary deformation and 4-D Stress*
David Sandwell

**9:45 A.M. – 10:00 A.M.** **BREAK**
Ballroom 3 Lobby

**10:00 A.M. – 10:50 A.M.** *Making, shaping and breaking a continent: Structure and evolution of North America*
Richard Allen

*Deep Earth structure and dynamics*
Jun Korenaga

**10:50 A.M. – 11:00 A.M.** **PLENARY – BREAKOUT GROUP INTRODUCTIONS**
Ballroom 3

**11:00 A.M. – 12:20 P.M.** **BREAKOUT SESSION I – BUILDING ON BREAKTHROUGHS**

| Peruvian A | Peruvian B | Alpine B | Alpine C |
|---|---|---|---|
| *Fault properties and slip processes*<br>Jim Evans, Joan Gomberg | *Plate boundary deformation and dynamics*<br>Joann Stock, Brad Hager | *The structure and evolution of the North American lithosphere and asthenosphere*<br>David Foster, Gary Egbert | *Deep Earth structure and dynamics*<br>Ed Garnero, Bill Holt |

**12:20 P.M. – 1:30 P.M.** **LUNCH**
Golden Cliff/Eagles Nest

**1:30 P.M. – 2:30 P.M.** Ballroom 3

**PLENARY IIA – PANEL AND DISCUSSION – MAKING INTERDISCIPLINARY COLLABORATIONS WORK**

Each group will provide a 5-minute introduction to their project and the highlights and challenges of interdisciplinary work, to be followed by open discussion.

Maureen Long, Randy Keller – High Lava Plains
Ken Creager, Tim Melbourne, Brad Hacker – Cascadia
John Hole, Joann Stock – Salton Trough
Terry Plank – Basin and Range

**2:30 P.M. – 3:20 P.M.** Ballroom 3

**PLENARY IIB – NEW RESEARCH DIRECTIONS** (4 talks, 20 min each plus 5 min of questions)

*Geomorphology and landscape evolution: Contributions to EarthScope*
Eric Kirby

*Structure of the Lithosphere and the Sedimentary Record: Where do they Meet?*
Michelle Kominz

**3:20 P.M. – 3:35 P.M.** **BREAK**
Ballroom 3 Lobby

**3:35 P.M. – 4:25 P.M.** *Linking EarthScope to the hydrosphere and cryosphere*
James Famiglietti

*Linking EarthScope to the atmosphere*
John Braun

**4:25 P.M. – 4:30 P.M.** **BREAK**

**4:30 P.M. – 5:50 P.M.** **BREAKOUT SESSION II – INTERDISCIPLINARY COLLABORATIONS AND NEW RESEARCH DIRECTIONS**

| Peruvian A | Peruvian B | Alpine B | Alpine C |
|---|---|---|---|
| *Integrating geological and geophysical constraints to study crust and mantle processes*<br>Walter Mooney, Jeff Vervoort | *Integrating geological and geophysical constraints to study Earth surface processes (including the hydrosphere, cryosphere and atmosphere)*<br>Kristine Larson, Jeanne Sauber | *New opportunities in education and outreach*<br>Jim Davis, Dave Mogk | *EarthScope contributions to understanding earthquake, volcano and landslide hazards*<br>Tom Heaton, Steve McNutt |

**6:00 P.M. – 7:30 P.M.** **DINNER**
Golden Cliff/Eagles Nest

**7:30 P.M. – 10:00 P.M.** **POSTERS (WITH NO-HOST BAR) – "EXCITING DISCOVERIES AND NEW OPPORTUNITIES"**
Ballrooms 2 & 3
Jazz band as a tribute to Paul Silver: Ed Garnero, Mike Wysession, and others…

## THURSDAY, OCTOBER 8, 2009

**7:00 A.M. – 8:00 A.M.** **BREAKFAST**
Peruvian A
Early career scientist discussion led by Lara Wagner and Kate Huntington

**7:00 A.M. – 8:00 A.M.** **GENERAL ATTENDEE BREAKFAST**
Ballroom 3 Lobby

**8:00 A.M. – 9:50 A.M.** **PLENARY III – NEW REGIONS TO EXPLORE** (4 talks, 20 min plus 5 min of questions)
Ballroom 3

*Linking mantle structures to surface deformation through time across the U.S.*
Mike Gurnis

*Appalachian geology: Key questions for EarthScope*
Jim Hibbard

*Continental rifting and passive margin development*
Cindy Ebinger

*Alaskan geology: Key questions for EarthScope*
Terry Pavlis

**9:50 A.M. – 10:05 A.M.** **BREAK**
Ballroom 3 Lobby

**10:05 A.M. – 11:25 A.M.** **BREAKOUT SESSION III – NEW REGIONS TO EXPLORE**

| Peruvian A | Peruvian B | Alpine C | Summit Room |
|---|---|---|---|
| *Cyberinfrastructure and EarthScope: challenges and opportunities*<br>Gary Pavlis, Vince Cronin | *The Appalachians, the passive margin the Gulf Coast and Mississippi embayment*<br>Jay Pulliam, Dennis Harry, Chuck Bailey | *The craton and continental interior*<br>Dan Holm, Ernest Hauser | *Alaska*<br>Sarah Roeske, Sean Gulick |

**11:25 A.M. – 12:15 P.M.** **FREE TIME** (view posters in breakout rooms, take a walk, share ideas…)
(Break-out leaders meet to synthesize reports into 5 min presentations)

**12:15 P.M. – 1:30 P.M.** **LUNCH**
Golden Cliff/Eagles Nest

**1:30 P.M. – 2:40 P.M.** **PLENARY SESSION – THE SCIENCE PLAN – REPORTS FROM BREAKOUTS AND EARLY CAREER CAUCUS**
Ballroom 3
(Full breakout reports will be made available on web.)
Report from Breakout Session I (20 min report plus 10 min of discussion)
Report from Breakout Session II (20 min report plus 10 min of discussion)
Report from early career scientists (5 min report plus 5 min of discussion)

**2:40 P.M. – 3:00 P.M.** **BREAK**
Ballroom 3 Lobby

**3:00 P.M. – 3:30 P.M.** **REPORT FROM BREAKOUT SESSION III** (20 min report plus 10 min of discussion)

**3:30 P.M. – 4:30 P.M.** **MODERATED OVERVIEW DISCUSSION**
Ballroom 3

**4:30 A.M. – 5:30 P.M.** **INFORMAL MEETINGS BETWEEN WRITING GROUP AND OTHER PARTICIPANTS**
Ballroom 3 & Any Breakout Rooms

**5:45 P.M. – 7:00 P.M.** **DINNER**
Peruvian A

**7:00P.M. – 8:30 P.M.** **WRITING GROUP MEETS**
Ballroom 3

### FRIDAY, OCTOBER 9, 2009 (WRITING GROUP ONLY)

**7:30 A.M. – 8:30 A.M.** **BREAKFAST**
Peruvian A

**8:30 A.M. – 12:00 P.M.** **WRITING GROUP MEETS**
Peruvian A

## 9.3 Workshop Participants

| FIRST NAME | LAST NAME | INSTITUTION | POSITION |
|---|---|---|---|
| Duncan | Agnew | Scripps/University of California, San Diego | Professor |
| Richard | Allen | University of California, Berkeley | Associate Professor |
| Marcos | Alvarez | IRIS | Deputy Program Manager |
| Falk | Amelung | University of Miami | Associate Professor |
| Greg | Anderson | National Science Foundation | EarthScope Program Director |
| Richard | Aster | New Mexico Tech | Professor of Geophysics |
| Don | Atwood | Alaska Satellite Facility (ASF) | ASF Chief Scientist |
| Charles | Bailey | William & Mary | Professor |
| Chaitan | Baru | San Diego Supercomputer Center, University of California, San Diego | Director, SDSC Science R&D |
| Gerald | Bawden | U.S. Geological Survey | Researcher |
| Margaret | Benoit | The College of New Jersey | Assistant Professor |
| Frederick | Blume | UNAVCO | Senior Project Manager |
| Adrian | Borsa | UNAVCO | PBO Data Products Manager |

| FIRST NAME | LAST NAME | INSTITUTION | POSITION |
|---|---|---|---|
| John | Braun | COSMIC/UCAR | Project Scientist |
| Jochen | Braunmiller | Oregon State University | Research Associate |
| Robert | Busby | IRIS | TA Manager |
| Peter | Cervelli | U.S. Geological Survey Volcano Science Center Menlo Park | Research Geophysicist |
| David | Chapman | University of Utah | Professor of Geophysics |
| Ken | Creager | University of Washington | Professor |
| Vince | Cronin | Baylor University | Professor and Director of Center for Spatial Research |
| Chris | Crosby | San Diego Supercomputer Center, University of California, San Diego | Project Manager |
| Laura | Crossey | University of New Mexico | Professor |
| James | Davis | Harvard-Smithsonian Center for Astrophysics | Senior Geodesist |
| Robert | Detrick | National Science Foundation | NSF Division Director, Earth Sciences |
| Herb | Dragert | Geological Survey of Canada | Research Scientist |
| Cynthia | Ebinger | University of Rochester | Professor of Geophysics |
| Gary | Egbert | Oregon State University | Professor |
| Goran | Ekstrom | Columbia University | Professor |
| William | Ellsworth | U. S. Geological Survey | Research Geophysicist |
| Susan | Eriksson | UNAVCO | Director of Education and Outreach |
| James | Evans | Utah State University | Professor |
| James | Famiglietti | University of California, Irvine | Professor |
| Karl | Feaux | UNAVCO | PBO GPS Operations Manager |
| Karen | Fischer | Brown University | Professor |
| Lucy | Flesch | Purdue University | Assistant Professor |
| Sean | Ford | Lawrence Livermore National Laboratory | Researcher |
| James | Foster | University of Hawaii | Researcher |
| David | Foster | University of Florida | Professor |
| Jeff | Freymueller | University of Alaska Fairbanks | Professor |
| Gary | Fuis | U.S. Geological Survey | Geophysicist |
| Patrick | Fulton | Oregon State University | Post-doctoral Researcher |
| Ed | Garnero | Arizona State University | Professor |
| Joan | Gomberg | U.S. Geological Survey | Research |
| Sean | Gulick | University of Texas at Austin | Research Scientist/Lecturer |
| Michael | Gurnis | California Institute of Technology | Professor |
| Bradley | Hacker | University of California, Santa Barbara | Professor |
| Bradford | Hager | Massachusetts Institute of Technology | Professor |
| Bill | Hammond | University of Nevada, Reno | Research Professor |
| Barry | Hanan | San Diego State University | Professor |
| Roger | Hansen | University of Alaska | State Seismologist for Alaska, Professor |
| Dennis | Harry | Colorado State University | Professor |
| Ernest | Hauser | Wright State University | Associate Professor |
| Tom | Hearn | New Mexico State University | Professor |
| Thomas | Heaton | California Institute of Technology | Professor of Engineering |
| Don | Helmberger | California Institute of Technology | Professor |
| James | Hibbard | North Carolina State University | Professor |
| Kathleen | Hodgkinson | UNAVCO | PBO Strainmeter Data Manager |
| John | Hole | Virginia Tech | Faculty |
| Daniel | Holm | Kent State University | Professor and Chair |
| William | Holt | Stony Brook University | Professor |
| Kate | Huntington | University of Washington | Assistant Professor |
| Michael | Jackson | UNAVCO/PBO | Plate Boundary Observatory Director |
| Angela | Jayko | U.S. Geological Survey | Research Geologist |
| Karl | Karlstrom | University New Mexico | Professor |
| Randy | Keller | University of Oklahoma | Professor |
| Graham | Kent | University of Nevada | Director, Nevada Seismological Lab |
| Eric | Kirby | Penn State University | Associate Professor |
| Michelle | Kominz | Western Michigan University | Professor |
| Yev | Kontar | Illinois State Geological Survey | Geophysics Section Head |

| FIRST NAME | LAST NAME | INSTITUTION | POSITION |
|---|---|---|---|
| Jun | Korenaga | Yale University | Professor |
| Kristine | Larson | University of Colorado | Professor |
| Vadim | Levin | Rutgers University | Associate Professor |
| Robert J. | Lillie | Oregon State University | Professor of Geology |
| Maureen | Long | Yale University | Assistant Professor |
| John | Louie | University of Nevada, Reno | Professor |
| Anthony R. | Lowry | Utah State University | Assistant Professor of Geophysics |
| Ian | MacGregor | Smithsonian Institution | Science consultant |
| Maria Beatrice | Magnani | CERI - University of Memphis | Assistant Professor |
| Chris | Marone | Pennsylvania State University | Prof. of Geophysics |
| Stephen | Marshak | University of Illinois | Professor and Director School of Earth Society & Environment |
| Stephen | McNutt | Geophysical Inst. University of Fairbanks, Alaska | Research Professor |
| Charles | Meertens | UNAVCO | Facility Director |
| Timothy | Melbourne | Central Washington University | Professor |
| David | Mencin | UNAVCO/PBO | Senior Engineer/BSM Operations Manager |
| M Meghan | Miller | UNAVCO | President |
| David | Mogk | Montana State University | Professor of Geology |
| Mark | Murray | New Mexico Tech | Research Professor |
| Jessica | Murray-Moraleda | U.S. Geological Survey | Research Geophysicist |
| Susan | Owen | Jet Propulsion Lab | Research Geophysicist |
| Gary | Pavlis | Indiana University | Professor |
| Terry | Pavlis | University of Texas at El Paso | Professor |
| James | Pechmann | University of Utah | Research Associate Professor |
| Zhigang | Peng | Georgia Institute of Technology | Assistant Professor |
| David | Phillips | UNAVCO | Project Manager Geodetic Imaging |
| Terry | Plank | Lamont-Doherty Earth Observatory | Professor |
| Fred | Pollitz | U.S. Geological Survey Menlo Park | Research Geophysicist |
| Jay | Pulliam | Baylor University | Professor |
| Christine | Puskas | University of Utah | Postdoctoral Fellow |
| Sarah | Roeske | Geology Dept. University of California Davis | Research Geologist |
| David | Sandwell | Scripps Institute of Oceanography | Professor |
| Jeanne | Sauber | NASA Goddard Space Flight Center | Staff Geophysicists |
| Adam | Schultz | Oregon State University | Professor |
| Giovanni | Sella | NOAA-NGS | CORS Program Manager |
| John | Shervais | Utah State University | Professor |
| David | Simpson | IRIS | President |
| Ramesh | Singh | Chapman University | Professor |
| Joann | Stock | California Institute of Technology | Professor of Geology & Geophysics |
| Wayne | Thatcher | U.S. Geological Survey | Research Geophysicist |
| Basil | Tikoff | University of Wisconsin - Madison | Professor |
| Chad | Trabant | IRIS Data Management System | Director of Projects |
| Anne | Trehu | Oregon State University | Professor & ESNO Director |
| Aaron | Velasco | University of Texas at El Paso | Professor and Chair |
| Frank | Vernon | University of California, San Diego | Research Geophysicist |
| Jeff | Vervoort | Washington State University | Associate Professor |
| Lara | Wagner | University of North Carolina-Chapel Hill | Assistant Professor |
| Gregory | Waite | Michigan Tech | Assistant Professor |
| Guoquan | Wang | University of Puerto Rico at Mayaguez | Assistant Professor |
| Linda | Warren | National Science Foundation | EarthScope Associate Program Director |
| Jim | Whitcomb | National Science Foundation | Section Head Deep Earth Processes |
| Michael | Williams | University of Massachusetts | Professor |
| Paul | Winberry | Central Washington University | Researcher |
| Bob | Woodward | IRIS | Director USArray |
| Michael | Wysession | Washington University | Associate Professor |
| Yingjie | Yang | University of Colorado | Senior Research Associate |
| Peter | Zeitler | EES Dept. Lehigh Univ. | Professor |

# 9.4 Credits

### WORKSHOP PLANNING COMMITTEE

Michael Williams (University of Massachusetts Amherst) – co-chair
Karen Fischer (Brown University) – co-chair
Jeff Freymueller (University of Alaska Fairbanks)
Basil Tikoff (University of Wisconsin at Madison)
Anne Tréhu (Oregon State University and EarthScope National Office)

The workshop planning committee also served as the editorial committee for this report.

### WRITING TEAM

Rick Aster (New Mexico Tech)
Cindy Ebinger (University of Rochester)
Bill Ellsworth (U.S. Geological Survey)
John Hole (Virginia Tech)
Susan Owen (Jet Propulsion Lab)
Terry Pavlis (University of Texas, El Paso)
Adam Schultz (Oregon State University)
Mike Wysession (Washington University)

### SPECIAL THANKS

The following members of the EarthScope community volunteered detailed and constructive reviews of the draft plan:

| | | |
|---|---|---|
| Geoff Abers | Goran Ekstrom | Paul Mueller |
| Falk Amelung | Gary Fuis | Terry Plank |
| Bruce Applegate | Charlotte Goddard | Evelyn Roeloffs |
| Jay Bass | Jim Hibbard | David Sandwell |
| John Braun | Andrea Jayko | David Simpson |
| Jochen Braunmiller | Kristine Larson | Suzan van der Lee |
| Tom Brocher | Chris LeBoeuf | Phillip Wannamaker |
| Emily Brodsky | Robert Lillie | Howard Zebker |
| Vincent Cronin | David Mogk | |

*Selected presentations from the workshop and summaries of breakout group discussions, as well as contributed research summaries that provided additional background for the report, can be found at http://www.earthscope.org/meetings/science_planning_workshop.*

*Support for the Workshop for an EarthScope Science Plan was provided by the National Science Foundation under award EAR-0954294 and by the USGS under award G09PG00244. Additional support for development of the plan was provided by NSF through award EAR-0719204 to the EarthScope National Office.*

*Editing and design by Geo Prose.*

earth
scope

www.earthscope.org

NASA NSF USGS science for a changing world