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SCIENTIFIC TARGETS FOR THE WORLD'S LARGEST OBSERVATORY POINTED AT THE SOLID EARTH

WORKSHOP REPORT

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WORKSHOP REPORT

SNOWBIRD, UT
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Introduction

Many fundamental aspects of continental structure and dynamics, including those responsible for earthquakes and volcanic eruptions, are not yet well understood. This is, in part, because of the difficulty of piecing together the results of many focused, regional studies carried out by a single investigator or a small team of investigators. Most major Earth processes act, and interact, on much larger and longer time scales than can be resolved by such isolated studies. These processes drive geological events at Earth's surface that affect humankind. To understand how these large-scale systems respond to internal and external forcing requires linking detailed information about surface geology with its underlying crustal structure and extending and linking these observations to interactions between the crust and the underlying mantle.

EarthScope will provide the first detailed, integrated examination of North America's structure and will monitor plate deformation at the continental scale. The seismic and magnetotelluric component of EarthScope (USArray) will map the structure of the continent and underlying mantle at high resolution. EarthScope's geodetic components, the Plate Boundary Observatory (PBO) and Interferometric Synthetic Aperture Radar (InSAR), will measure surface motions at a variety of spatial and temporal scales. Deep drilling across the San Andreas fault by the San Andreas Fault Observatory at Depth (SAFOD) will directly determine stress conditions and rock properties in the seismogenic zone of a major fault. Combining these direct measurements with associated geological, geochronological, geochemical, experimental, and theoretical studies will provide the clearest picture yet of our continent's dynamics. EarthScope's decade-long effort thus offers the potential for unprecedented discovery and a model for a future of truly integrative, multidisciplinary research in the solid Earth sciences.

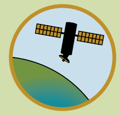
EarthScope is an interdisciplinary experiment of unprecedented resolution that will identify links between the surface geology of North America and the forces at work in Earth's interior.

To further develop ways to fully exploit the measurements provided by EarthScope's observational components, approximately 200 Earth scientists assembled in Snowbird, Utah for the first "pan-EarthScope" workshop. This report summarizes the workshop discussions, divided according to the broad scientific themes around which working groups were formed. These themes blend into a broad-ranging examination of the major issues of continent formation and the factors controlling its current dynamic behavior. This report first lists some of the key scientific questions identified at the workshop as a means of capturing our current understanding of this broad topic. With this background, we then explore the many ways in which EarthScope can contribute to answering these fundamental questions. Working groups also discussed what additional data sets, modeling efforts, and education and outreach are necessary to maximize the scientific return from EarthScope.

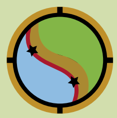
EarthScope offers the first opportunity to measure plate tectonic movements while they are happening, and at the continental

EarthScope's facilities include the following four coupled components:

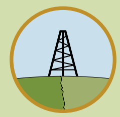
USArray (United States Seismic Array): A combination of permanent, transportable broadband, and flexible seismic arrays will map the structure of the continent and the underlying mantle at high resolution.



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



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



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

spatial scale, so that the cause and effect of these movements finally can be deciphered. The combination of instrument, technique, and computational developments, the existence of a collaborative, multi-institutional, multi-agency infrastructure capable of managing an experiment of this size, and the maturity of the scientific field to which the EarthScope instrument will be directed combine to make this the perfect time to create the EarthScope facility.

The next major advance in our understanding of how the dynamic Earth works, and how humankind can best deal with both the beneficial resources and the dramatic hazards Earth provides, must come by expansion of our observational network to the scale of Earth activity. EarthScope will provide this step for the United States.

Scientific Targets for EarthScope

Fault Properties and the Earthquake Process

Key Questions

Over the last few decades, considerable research into earthquake sources and the hazards they pose have greatly improved our understanding of both. Increases in the quality and quantity of data recorded, combined with the development of new analysis techniques, have resulted in significantly better models of the earthquake rupture process. These in turn have permitted more reliable statistical seismic hazard predictions. Despite this progress, many fundamental questions concerning earthquake rupture and fault processes remain unanswered, and others have been identified as we learn more about them.

At the workshop, five outstanding, fundamental scientific questions were identified that any large-scale initiative in earthquake science needs to address:

1. How does strain accumulate and release at plate boundaries and within the North American plate? Where is slip along a fault aseismic versus seismic? What are the structure and other properties of active fault zones? How do they affect the manner in which faults slip? How can we explain the observed space-time pattern of seismicity? How do earthquakes interact with and trigger one another?

2. How do earthquakes start, rupture, and stop? Do all earthquakes start from similar beginnings, or does the nucleation process determine the final size of the earthquake? How do fault properties and rupture dynamics combine to control rupture propagation and extent? What causes the rupture to stop?

> EarthScope will help develop predictive models for earthquakes by unraveling the dynamic processes along faults, from stress build-up to catastrophic rock failure.

How are earthquake ruptures on subduction zones different from those on crustal faults? What are the causes of intermediate depth earthquakes (such as the one under Seattle in January 2001), and do they vary with depth?

3. What is the absolute strength of faults and the surrounding lithosphere? Where are plate driving forces carried? Are faults relatively low-strength features? How do faults in different tectonic settings compare?

4. What structural and geological factors give rise to intraplate regions of seismic hazard and seismicity, such as the New Madrid zone?

5. How can we accurately predict earthquake-induced ground motions over a wide frequency range? For example, what is the geometry and response of large sedimentary basins? How nonlinear is site response?

These five questions largely reflect the frustration of the Earth science community in their attempts to solve problems that 25 years ago appeared to be nearly solved. For instance, the Parkfield reach of the San Andreas fault was thought to be sufficiently well understood in terms of earthquake recurrence that a magnitude 6 event was forecast to occur there in January 1988, plus

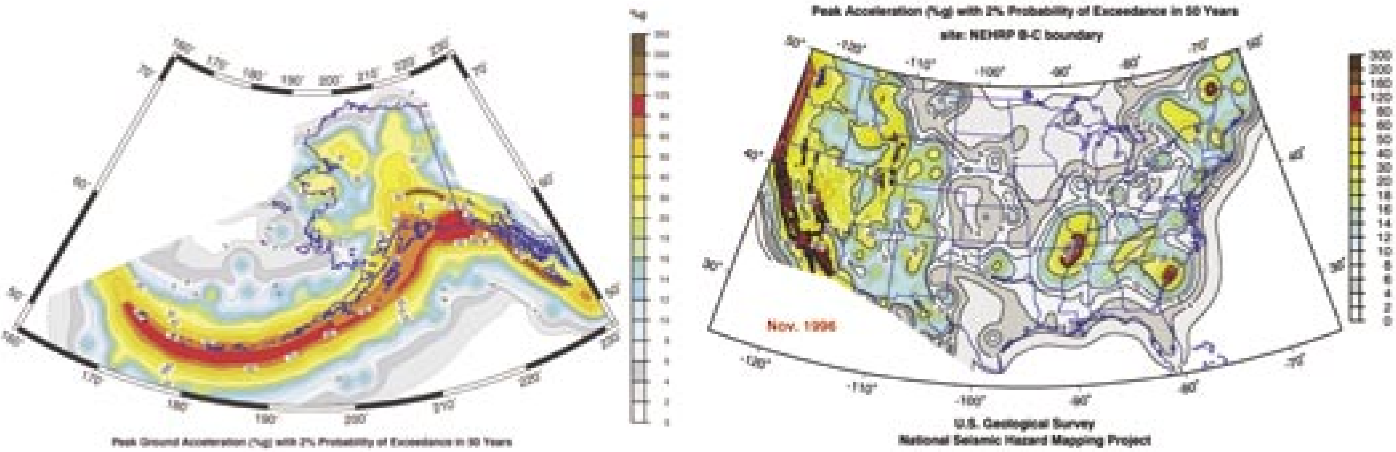


Figure 1. Current seismic hazard maps of the United States demonstrate clearly that California is not the only state to experience or expect large earthquakes. PBO and USArray will greatly improve our understanding of earthquake processes along the Cascadia and Alaskan subduction zones. USArray and InSAR will provide us with unprecedented resolution and information about the eastern half of the United States, where large damaging earthquakes can occur. Figures courtesy of the USGS.

or minus five years, at the 95% confidence level. In 2001, we are much humbler regarding our understanding of the San Andreas fault and, needless to say, are still waiting for the next Parkfield earthquake. Similarly, we do not know, within a factor of three or four, the magnitude of the stresses acting on the San Andreas fault needed to cause slip despite substantial research on this issue beginning in the 1960s. Solving these, and other, fundamental problems of earthquake occurrence and fault dynamics clearly requires a substantially augmented effort to acquire the key, but elusive, data sets that bear on these issues.

To date, most earthquake research has been focused in California, but other parts of the United States also have significant seismic hazards (Figure 1). Earthquakes have been recorded in all but one of the 50 United States, and the country includes a wide range of tectonic environments for studying earthquakes and deformation in many different conditions. EarthScope will improve our resolution of the earthquake rupture process in regions where we currently have the most detailed knowledge, such as California, but will also enable us to study regions that have received relatively little attention to date, such as the subduction zones of Cascadia and Alaska, and the more stable eastern parts of the country where seismicity is rarer, but still significant, and potentially damaging.

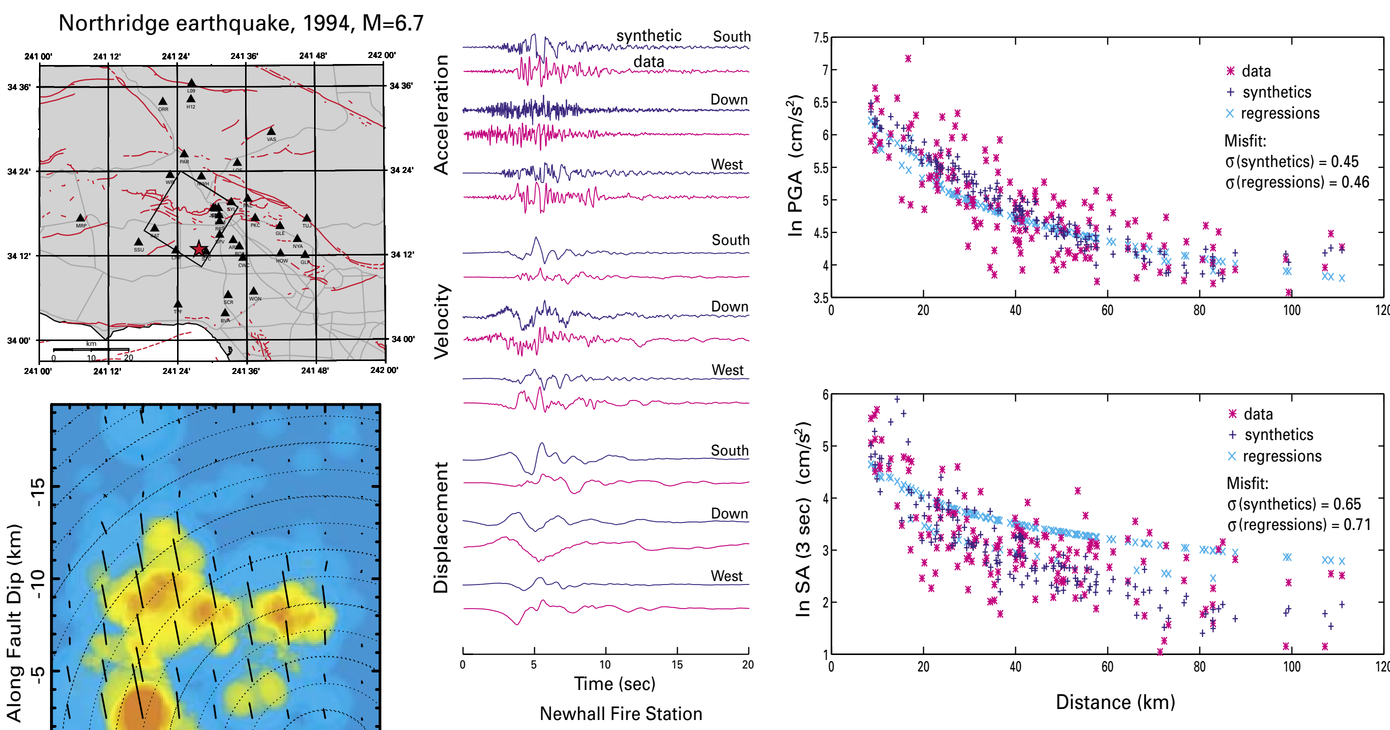
> EarthScope will provide a comprehensive suite of geophysical data sets that are critically needed to advance understanding of earthquake processes and related hazards.

The EarthScope Contribution

Recent work has demonstrated that only an order of magnitude improvement in data quality and quantity will permit us to address the outstanding scientific questions about earthquake processes with any realistic hope of success. The combined EarthScope components will provide much of the data required to significantly increase our understanding of the entire earthquake rupture process. For example, previous work has demonstrated that large earthquakes nucleate as a result of processes acting at a very small scale that currently cannot be resolved. Measurements and observations from SAFOD, USArray, and PBO instrumentation will enable us to resolve earthquake nucleation processes at the smallest scale, but also capture critical information at longer temporal and larger spatial scales.

Adding a time dependence to statistical forecasts of seismic hazard is becoming possible as we begin to understand how one earthquake may affect or trigger another event. Data on earthquake interactions, detailed crustal structure, and the state of stress in the crust exist in too few parts of the country, however, for us to produce reliable forecasts. USArray will provide the needed information about crustal structure and ongoing seismicity that will greatly extend our ability to forecast hazards (Figure 2). The USGS-sponsored Advanced National Seismic System (ANSS) is also important, providing the long-term seismicity coverage needed to address seismic hazard problems. PBO and InSAR will enable us to identify where strain is building up and where it is being released on longer time scales. Detectable earthquakes may not be produced at such locations, but the crustal stress fields may be modified in ways that can accelerate or retard the likelihood of a future earthquake. The proposed paleoseismic component of PBO also is needed to provide an even longer-term perspective on crustal strain build-up and release.

More specifically, each EarthScope component will contribute to answering the five questions posed in the following ways:



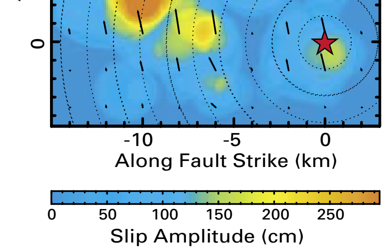


Figure 2: Predicting strong-ground motion over the wide frequency range needed for engineering purposes is becoming possible (as shown in this example from the Northridge, 1994, earthquake), but only where precise information is available on wave propagation, local structure, and site-effects. EarthScope will greatly extend and improve our knowledge of these vital parameters. The figure shows a model of the slip during the Northridge earthquake, comparison of the predicted and observed seismograms recorded at Newhall Fire Station, and the recorded and predicted peak ground acceleration (PGA) and response spectrum (SA) as a function of distance from the earthquake. Courtesy of J. Anderson and Y. Zeng, UNR.

SAFOD will provide direct observations of the structure and properties of an active fault zone at seismogenic depths. Seismic and strain observations over a number of years will provide close-in records of earthquake nucleation, rupture, and termination that are needed to address fundamental questions about the earthquake process. (Questions 1 and 2).

USArray includes the main Bigfoot transportable array, which will provide a significant improvement in our ability to locate earthquakes, and the flexible component, which can be used for higher-resolution studies of more limited areas such as detailed examination of individual faults. Crustal velocity structure and fault orientations are needed to help answer all five questions. USArray's flexible array also will be invaluable for earthquake studies by enabling dense deployment in regions where there is swarm activity or an aftershock sequence, greatly increasing the resolution of the lithosphere structure in those regions. In addition, USArray will permit detailed studies of the nature of earthquake sources in regions far from the plate boundary, and so investigate how different conditions affect the earthquake generation process.

EarthScope will enable us to observe the processes and properties of faults that drive the earthquake machine.

PBO and InSAR will provide much-needed measurements of the integrated strain field, forming the basis for resolving aseismic processes of permanent and transient deformation, as well as seismic strain recharge and release. At the detailed scale of the PBO dense clusters, observations of strain changes before and after earthquakes will be invaluable for understanding how dynamic rupture begins and ends, and what triggers it (e.g., Question 2). The larger scale PBO network and InSAR will enable us to map the distribution of aseismic strain over the continent, which is needed to understand seismicity distributions and larger-scale triggering (Question 1). InSAR and GPS also provide valuable information about the distribution of seismic slip in an earthquake (Question 2).

ANSS will play an important role in addressing these questions. The new stations will provide the long-term monitoring component essential to improve seismic-hazard modeling, as well as adding to the data available to study the earthquake source and crustal structure.

Necessary EarthScope Data Sets

At present, there is a severe lack of reliable high-resolution data on earthquake and fault properties. Thus, workshop attendees spent considerable time discussing the data sets necessary to make headway in answering the five questions mentioned above. Table 1 summarizes the discussion on: (1) which data sets are required to address the five key questions, (2) whether the data sets are currently available, (3) whether EarthScope will provide the required data, and (4) what else is needed to obtain the data.

Table 1: Data Sets Needed for a Better Understanding of the Earthquake Process

Data Set	Relevant to Questions	Available?	Will EarthScope Provide?	What Else?
Instrumental seismicity catalogues	1,2	ANSS	Not enough	Regional networks with local densifications.
Pre-instrumental catalogues	1-5	Partial	No	Additional data (especially at PBO sites). Compile existing data in usable form[1].
3D active fault map (location, strike, dip)	1-5	Partial	Partial (PBO)	Flexible array (P.I. driven).
Internal fault zone architecture in 4D: geometry (e.g., width, depth, continuity), material properties (e.g., seismic velocities, attenuation, anisotropy, viscosity), and geology (e.g., fabrics, microstructures)	1-3,5	A little	SAFOD	Flexible array (P.I. driven). Compile existing data in usable form[1].
Transitions between: (1) fault segments, (2) an entire fault system and surrounding rock, and (3) brittle and ductile depth sections	1-5	A little	SAFOD	Flexible array (P.I. driven). Compile existing data in usable form[1].
Crustal and upper mantle structure in 4D	1-5	Partial	Partial	Flexible array (P.I. driven).
Strain-rate field in 4D	1-4	Partial	PBO and INSAR	Additional geodesy.
Finite strain (geology: total fault slip, pressure solution in bulk)	1,2	Partial	No	Additional geology. Compile existing data in usable form[1].
Heat flow	1,3,4	Partial	SAFOD	At PBO and other sites. Compile existing data in usable form[1].
Electromagnetic/MT	1,2	A little	USArray	Additional measurements. Compile existing data in usable form[1].
Seismic waveforms (broadband with high dynamic range)	1-3,5	Partial	USArray, ANSS, SAFOD	Flexible array (P.I.-driven). Add broadband and strong motion to PBO sites[2].
Site response at all new and temporary sites	2,5	No	Partial	Geotechnical measurements.
Lab data of rheological and geophysical rock properties	1-4	Very little	No	New EarthScope observations will require complementary lab studies to interpret. Compile existing data in usable form[1].
Ground water and other environmental effects	1,3,5	Partial	No	Monitor ground water etc. at PBO sites.

(1) Compilation of existing data in usable form should provide best values and uncertainties for two data sets: raw measurements and interpretation. (2) The current instrumentation plan for the PBO borehole sites does not include broadband and strong ground motion seismometers. This is a major short shortcoming because the PBO sites are close to major faults, and thus are likely to experience moderate and large earthquakes. The sites may also record microearthquake data (e.g., with $M < -1$). Near-fault seismic data over broad magnitude and frequency ranges are critically needed to test different hypotheses on the physics of earthquakes and faults (e.g., existence of strong dynamic variation of normal stress during rupture propagation; scaling of earthquake properties; sources of high-frequency seismic radiation; slip histories). On-scale recording of moderate and large earthquakes over a broad frequency range will require broadband and strong ground motion seismometers at or near the borehole sites. These seismometers should be augmented at selected sites by tight 2D arrays around the fault, or at least by pairs of instruments on the different sides of the fault, to allow imaging of key rupture and fault properties (e.g., symmetry characteristics of particle motion). Detection and recording of microearthquakes may perhaps be done with the geophones currently planed at the borehole sites.

Short Time/Distance Deformation: Crustal Strain Transfer

Key Questions

How the solid Earth responds to deformational forces is a topic of considerable uncertainty. The solid Earth is compositionally heterogeneous, and its ability to carry and transmit stress varies widely with composition, mineralogy, pressure, temperature, deformation history, and the presence or absence of fluids. Variations in these properties determine where the crust will deform broadly and slowly or, alternatively, break locally and rapidly in a damaging earthquake. To understand how the crust will respond to tectonic and/or volcanic forces requires answers to several key questions.

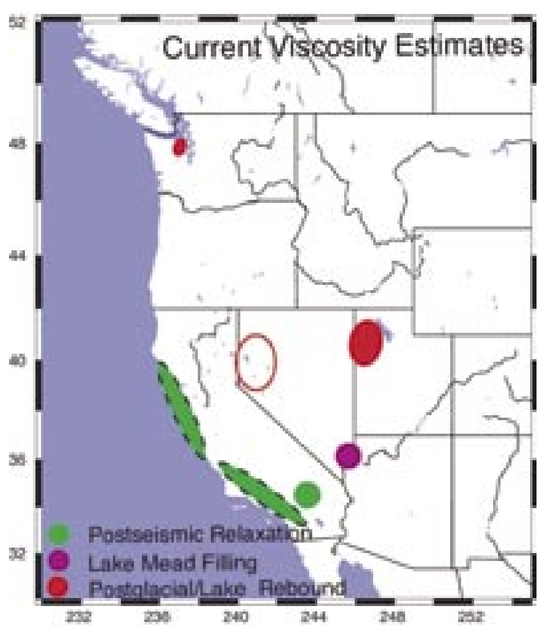


Figure 3. Areas where lithospheric viscosity estimates are available in North America. Figure courtesy of Fred Pollitz.

> Why does North America bend and break, and the ground shift and shake?

1. How does crust and mantle rheology (elastic, viscous, plastic constitutive properties) vary with rock type and with depth? Estimates of the average crustal response to deformation are available for only an extremely small portion of North America (Figure 3). These estimates derive either from the dense GPS and seismic monitoring of crustal movements in response to earthquakes along the various fault systems in California or through such rare opportunities as the crustal subsidence caused by the filling of large reservoirs or crustal rebound following glacial unloading. Of particular importance is how crustal rheology changes with depth. Some models suggest that brittle failure in the upper crust is accommodated by flow in a relatively weak lower crust, but other observations suggest that this stress redistribution is taken up by flow in the upper mantle rather than the lower crust.

2. How does crustal rheology change in the vicinity of the fault zone? What strength changes result from the previous record of fracturing and fluid flow along a fault?

3. What is the distribution of stress in the lithosphere? What is the absolute stress field and the magnitude of stress heterogeneity ? What proportion of stress release is accommodated by creep as opposed to earthquakes? How does stress build up,

move through the lithosphere, and get released during the earthquake cycle? How much deformation occurs between seismic events, during the event, and shortly after an earthquake?

4. What type of transient movements occur in the lithosphere? Recent observations have detected what amount to "slow earthquakes," movement along faults that occurs so slowly that it does not generate seismic waves. What crustal properties allow such slow stress release compared to the violent event of an earthquake?

5. What is the role of non-tectonic processes in creating lithospheric stress? Besides the forces associated with plate movement and gravitational spreading of uplifted crust, how do such events as glacial unloading, lake level variations, and subsurface fluid transport contribute to lithospheric stress? Can these reasonably well-understood sources of stress be used as tests to examine how the lithosphere responds to loading forces?

6. How do faults interact with one another? Movement along one fault can change the stress distribution along nearby faults. Is this stress change transmitted by elastic interaction, transient fault slip, or viscous or poroelastic processes? Earthquake swarms associated with crustal magmatic systems are occasionally triggered by distant earthquakes. How is this triggering accomplished?

7. What effect does tectonic deformation have on water flow in the crust?

The EarthScope Contribution

We seek to gain an improved understanding of stress transfer and the earthquake process through developing conceptual models and modeling frameworks for interpreting data. The basic observations needed for improved understanding of fault interaction will be provided by PBO, for example, GPS and strainmeter time series, consensus GPS velocity models, consensus interferograms, and catalogs of geodetically determined transients. The means and capability to model such data must involve a mechanism for archiving such large quantities of primary data with a high degree of flexibility to permit the development of new ways of interpreting them. The basic observables provided by EarthScope data will enable a new understanding of many commonly invoked, but poorly understood, stress-transfer processes by:

- testing the predictive power of
  - static Coulomb stress change;
  - viscoelastic and poroelastic stress changes;
  - Dieterich rate and state-dependent friction model;
  - critical state hypothesis;
- establishing whether slowly migrating triggered slip is commonplace or an exception (e.g., 1999 Cascadia transient; 1998 Guerrero, Mexico transient);
- extracting more information from aftershock data for
  - stressing rate;
  - background stress;
  - effect of dynamic stress from mainshock;
  - detecting migrating stress pulses.

As an example of where EarthScope data can be instrumental in determining the rheology of the lithosphere, consider the use of InSAR data to measure postseismic surface deformation following the 1999 Hector Mine earthquake (Figure 4). The figure suggests that a model of postseismic upper mantle flow more reasonably predicts postseismic surface deformations compared to an after-slip model.

Determinations of lithospheric viscosity are critical to understanding the evolution of stress in the crust, and therefore the evolution of fault loading. Consider the influence of the Landers and Hector Mine quakes on the southern San Andreas fault. Models that incorporate postseismic viscous responses predict that Coulomb stress changes resulting from slip associated with earthquakes are magnified in the years following the event (Figure 5).

Activities such as determining the rheology of the lithosphere, then using that information to calculate the evolution of stresses, will benefit from all aspects of EarthScope. All analyses of stress changes require an accurate catalog of seismicity following selected seismic events, for which USArray's flexible array will be indispensable. State-of-the-art viscoelastic

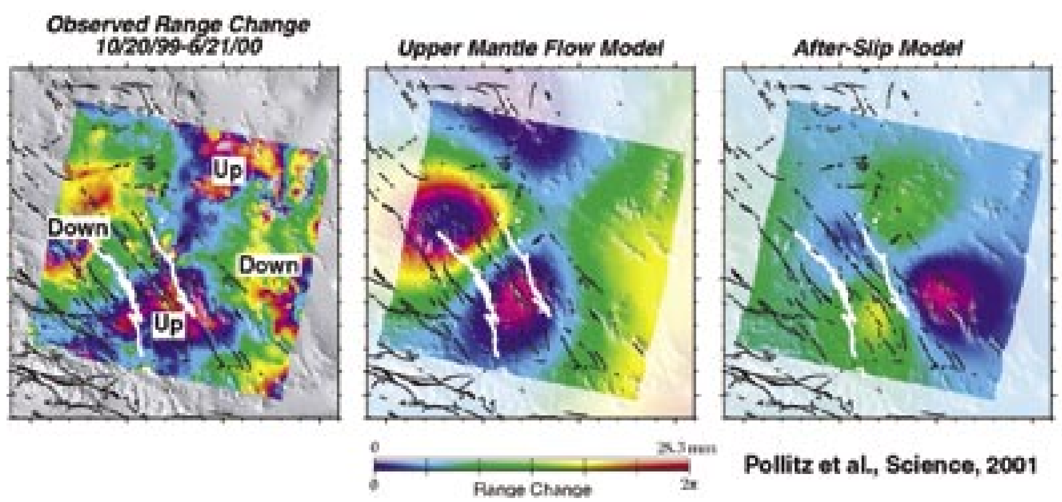


Figure 4. Comparison between InSAR observed surface deformation following the 1999 Hector Mine earthquake and calculated surface deformations based on two candidate postseismic mechanisms. Figure modified from Pollitz, F.F., C. Wicks, W. Thatcher, 2001, Mantle flow beneath a continental strike-slip fault: Postseismic deformation after the 1999 Hector Mine earthquake, *Science*, 293, 1814-1818.

stress-change modeling is showing great promise for general applicability to continental fault interaction provided that the input rheological models are realistic. Adequate constraints on viscoelastic structure will require a combination of postseismic relaxation modeling by PBO and seismic velocity imaging by USArray, which then can provide first-order estimates of the lithosphere's temperature structure and composition. *In situ* sampling of rocks at depth around a real fault zone provided by SAFOD will permit a refined understanding of poroelastic models and the Dieterich rate and state-dependent friction model. PBO and USArray will provide information pertinent to the analyses of stressing rate, the interpretation of heterogeneous background stress, and the effects of dynamic stresses from a mainshock, which all depend on sufficiently accurate models of the seismic source.

The models developed from this improved understanding should be reproducible and, if possible, posted on line to allow others to test the models. There could be a mechanism for feedback of predictions into new data to test current models.

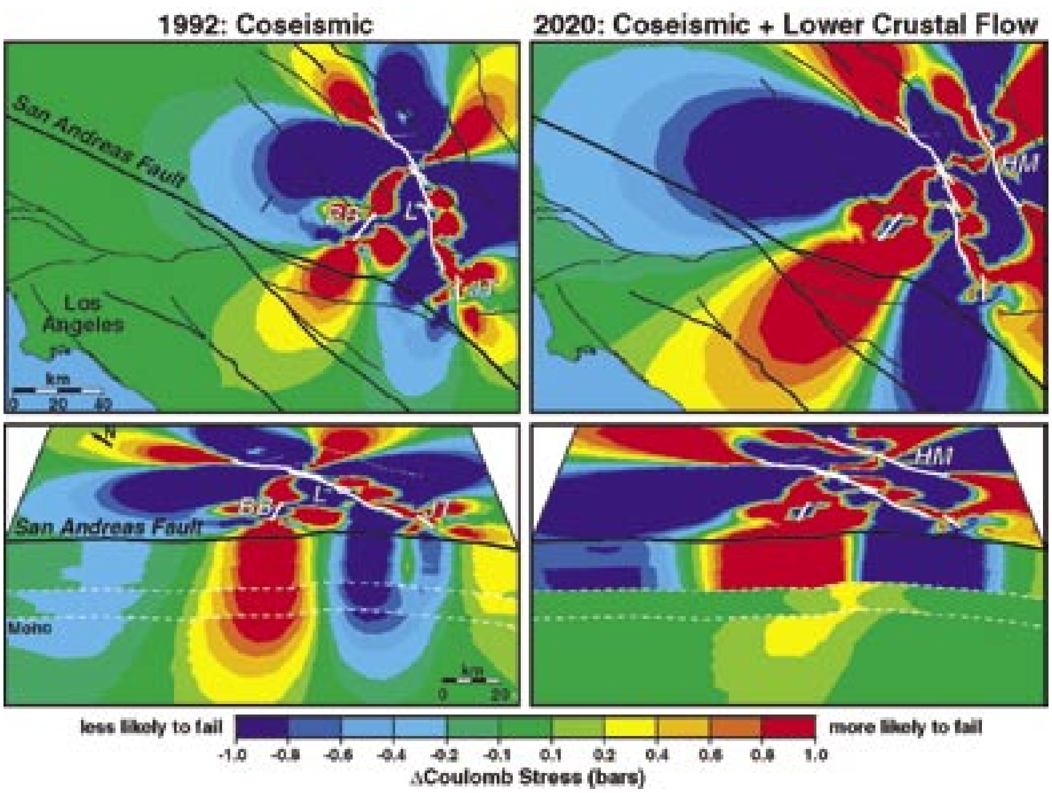


Figure 5. Upper left: Calculated coseismic Coulomb stress changes caused by fault slips associated with the 1992 Joshua Tree (JT), Landers (L), and Big Bear (BB) quakes. Lower right: same as above but stresses are shown for the top surface and a cut plane along the San Andreas Fault. Upper right: calculated combined stress changes associated with the 1992 quakes, the 1999 Hector Mine quake, and postseismic relaxation of a viscous lower crust layer from 1992 through 2020. Bottom right: same as above but stresses are shown for the top surface and a cut plane along the San Andreas Fault. Figure from: Freed, A. M. and J. Lin, 2002, Accelerated stress buildup on the southern San Andreas fault and surrounding regions caused by Mojave Desert earthquakes, *Geology*, in press.

Fluids and Magmas in the Crust and Upper Mantle

Key Questions

EarthScope provides a unique opportunity to examine the entire magmatic "life cycle," from magma genesis in the mantle melting region, to magma transport through the plumbing system in the crust, to final emplacement through intrusion or eruption. This system challenges traditional modes of study because it operates over a vast range of time scales, from the hours preceding volcanic eruption, to the days and years of magma ascent, to the millions of years over which magmato-tectonic systems evolve. An integrated view of the complete magmatic system can only be obtained through combining data collected by EarthScope components with data from petrology, geochemistry, geochronology, and other fields.

> Understanding the physics of active volcanic systems

1. Magma Genesis. Although the basic modes of melt production in the mantle are known (adiabatic decompression and water-fluxing) very little is known about the volumes and rates of magma produced anywhere except mid-ocean ridges. An understanding of magma production is essential to understanding continental growth. There is abundant evidence that magma production rates vary in space and time by a large amount, although these rates remain poorly quantified.

Critical questions relating to the process of magma genesis include:

- How do tectonic rates (e.g., convergence rate, extension rate, or mantle upwelling rate) affect magma production rates? Few reliable estimates of magma production exist to test these tectonic controls.
- Where exactly in the mantle does the melting occur, and what path does the melt take through the upper mantle and into the lower crust?
- Can we use seismic tomography to constrain the volume of mantle melting regions? What combination of seismic parameters can resolve mantle temperature, melt, and fluid heterogeneities? Can we develop forward models for the volume and rate of magma production in the mantle, given tomographic images of the melting region and the age, volume, and composition of magmas erupted at the surface?
- What volume of the North American continent was created by recent (since when?) magmatism? During the Cenozoic? At various time intervals in the past? What is the pulse of continental growth?

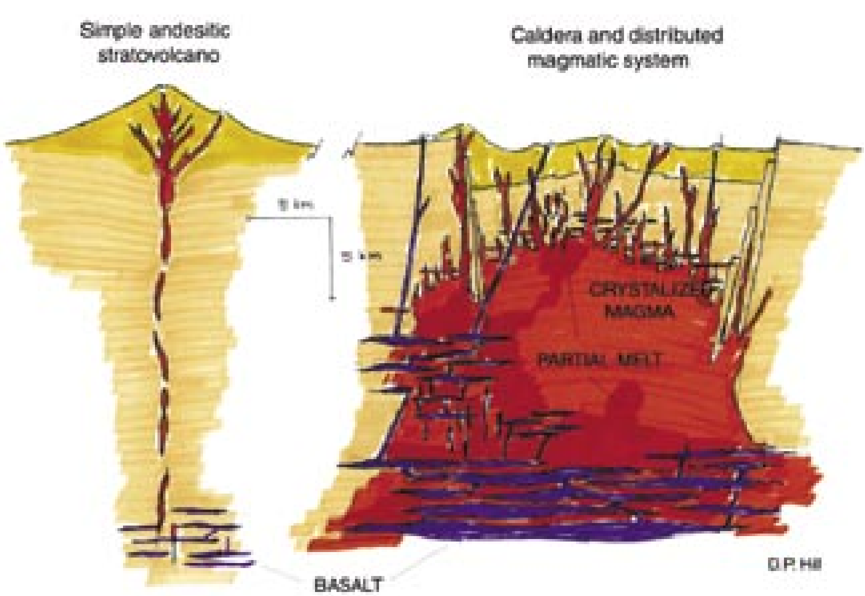


Figure 6. Cartoon showing end members of magmatic plumbing systems. The left-hand figure shows a single-conduit system feeding a small-volume stratovolcano such as is found in Cascadia and the Aleutians. The right-hand figure shows a larger volume system, such as occurs in large caldera-forming eruptions in the Basin and Range and the Snake River Plain where extensive melting of the lower crust occurs due to the intrusion of large volumes of basalt rising from the mantle below. Figure courtesy of Dave Hill, USGS.

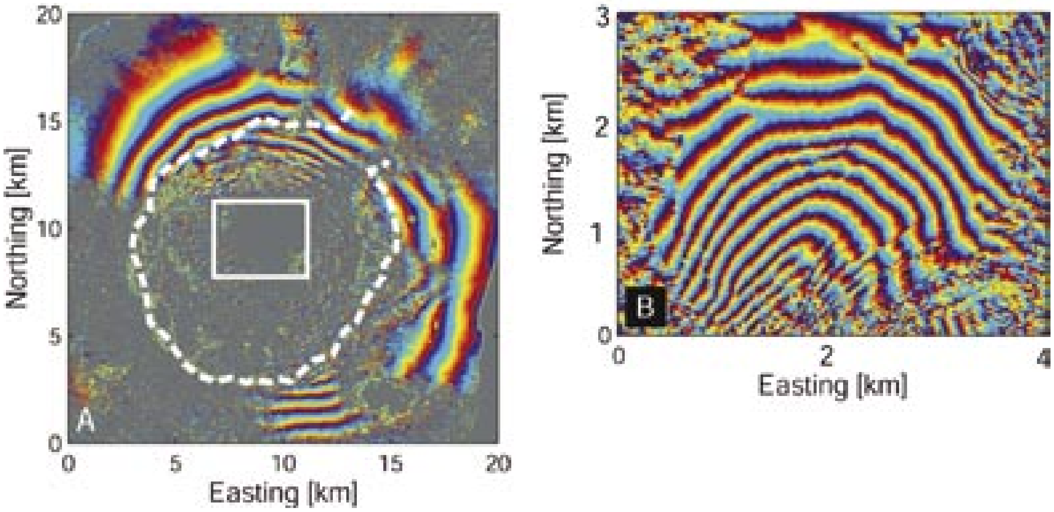


Figure 7. InSAR interferogram spanning the time of the 1997 eruption of Okmok caldera, Aleutians. Each cycle of colors, or fringe, represents 2.83 cm of deformation in the radar's line of sight direction, which is predominantly vertical. Okmok deflated during the eruption, with the maximum subsidence being approximately 1.4 meters. The data can be explained by the removal of magma from a magma body centered at a depth of 3.5-4 km. (A) View of the deformation seen over the entire volcano. The outline of the caldera is shown as a dashed white line, and the solid box shows the location of B. (B) Detail of deformation observed within the caldera. Figure after Mann, D., J.T. Freymueller, and Z. Lu, 2002, Deformation associated with the 1997 eruption of Okmok volcano, Alaska, *J. Geophys. Res.*, in press.

2. Magma Transport. Magmas move via diapirism, porous flow, or magma fracture, creating a plumbing structure on their way toward the surface. Although we have been able to identify a variety of magma conduits, reservoirs, and networks in the mid- to shallow crust, we still have a poor understanding of the causes of these different magmatic architectures and their implications for volcanic hazards. Simplistic end-member examples of the magma plumbing systems in the shallow crust are shown in Figure 6. Extending our understanding of magmatic plumbing beyond the simplified cartoon of Figure 6 will require answers to questions such as:

- What controls the depth of magma accumulation in the upper crust, and why do some volcanoes accumulate magma quasi-statically and others episodically?
- What controls the shape and size of magma reservoirs and conduits?
- How is magma transport related to tectonic setting, magma composition, magma supply rate, lithospheric structures, and/or local stress regime?
- How do different plumbing structures constrain the dynamics of magma flow, deformation, eruption dynamics, and hazard potential?
- What is the residence time of magma in the crust?
- Can rising magma be detected before it reaches the brittle-ductile transition as a means to probe conditions in the deeper crust?

3. Volcanic Eruption, Prediction, Hazard Mitigation. EarthScope will provide a wealth of data on the active deformation of volcanic and plutonic structures. Some deformation events are part of the natural breathing of the volcano, while others lead to catastrophic eruption. Our ability to predict the timing, volume, and explosivity of eruptions will improve dramatically if we are able to accurately read the deformation record. Recent deformation data have provided exciting new information about eruptive processes, ranging from constraints on the location of magma prior to eruption (Figure 7) to constraints on the dynamics of magma flow in dikes. Important science questions on this topic include:

- What is the relationship among deep magma movement, surface deformation, and volcanic eruption?
- Over what temporal and spatial scales do earthquake deformation and volcanic eruptions couple?
- Are there telltale signs in deformation data that can be used to infer whether magma moving toward the surface will

reach the surface, and if it does, how explosive the eruption will be?

- What is the effect of tectonic setting, magma composition, lithospheric structure, and stress on eruption style?

To turn this understanding of volcanic processes into accurate predictions of volcanic eruptions and the hazards they pose will require assembly of a number of tools and background data. The need to respond rapidly will require development of rapid interpretive tools for volcanology such as automated event-detection algorithms, high-precision relative location algorithms for volcanic earthquakes, and a rapid-response capability for monitoring a restless volcano (could be termed Hotfoot). To understand the significance of the data taken during the "restless" stage of the volcano will require the availability of such baseline information as GPS, InSAR, and gravity measurements for all potentially active volcanoes along with longer-term information on past eruptive history (including ancient analogs) and the ability to compare these data with other, similar volcanic centers using global volcanological data (e.g., WOVOCAT initiative). Given the pivotal role of the USGS in volcano monitoring in the United States, EarthScope should further define with USGS the ways in which collaborations between EarthScope and the USGS can most effectively advance capabilities for eruption prediction.

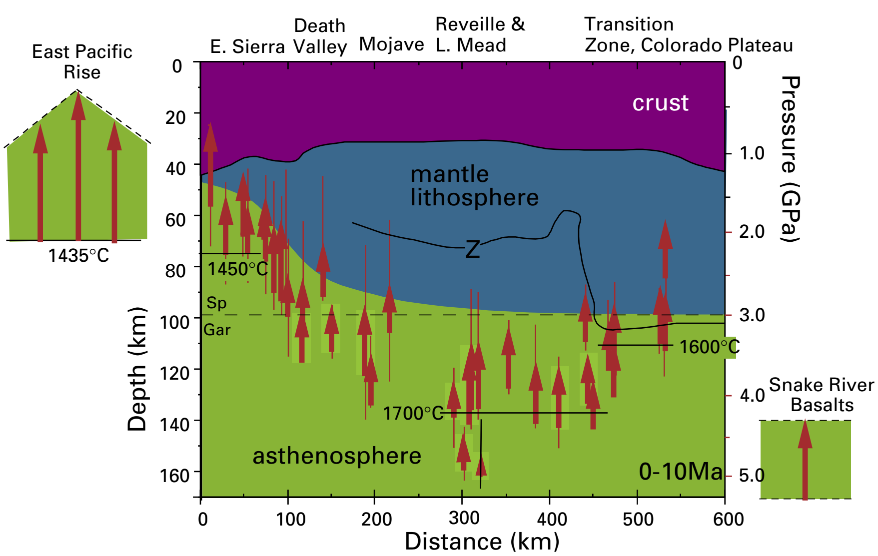


Figure 8. Melting profile across the Basin and Range. Arrows represent the melting column calculated for each volcanic field based on the most primitive magma compositions. The bottom of the arrow marks the onset of melting at the solidus, and is a function of mantle temperature, while the top of the arrow marks the end of decompression melting, presumably due to the change in rheology near the lithosphere/asthenosphere boundary. East Pacific Rise shows analogous melting calculation for primitive MORB near the Tamayo Fracture Zone assuming melt pooling from a triangular shaped melting regime. Figure after Wang, K., T. Plank, J.D. Walker, E. I. Smith, 2002, A mantle melting profile across the Basin and Range, SW USA, *J. Geophys. Res.,* 107, B1.

The EarthScope Contribution

North America contains a diverse range of magmatic systems including the "classic" convergent margin volcanoes of Cascadia and the Aleutians, and the large-volume and wide-spread basalt and caldera-forming silicic eruptions associated with extension in the Basin and Range and the Snake River Plain/Yellowstone magmatic field. How this magma is generated in the mantle and crust will be the target of EarthScope's seismic imaging.

Systematic variations in basalt composition across the Basin and Range most likely relate to variations in depth and temperature of melting (Figure 8). Tomographic images of the mantle beneath the western United States, to be provided by USArray, can be compared with geochemical data and volcanic volumes to identify mantle source regions for the magma and address the question of whether varying eruptive volumes are due to geographically varying mantle melting rates or to tectonic controls on magma ascent through the crust. Similarly, detailed tomographic images of the mantle across the Snake River Plain-Yellowstone magmatic province will provide further clues as to whether this volcanism follows a propagating crustal rift or instead is driven by ascent of hot material from the deep mantle. Tomographic images of the mantle wedge in Cascadia and

Alaska such as those shown in Figure 9 will help define the extent of mantle melting in these subduction systems. These images also show how mantle melting along Cascadia relates to the surface localization of volcanic centers and to the encroaching volcanic systems of the Basin and Range, such as at Newberry caldera, Oregon and Medicine Lake, California.

Seismic instrumentation from USArray, particularly the flexible array, will be useful for tracking the ascent path of magmas through the crust and examining how magma ascent is either influenced by, or influences, crustal structure, rheology, and tectonic state. Seismic imaging will be complemented by the magnetotelluric information to be obtained by USArray, potentially detecting local concentrations of magma as well as the fluid transport paths used by the hydrothermal systems instigated by the presence of shallow magma reservoirs.

Data on volcanic eruptions will come primarily from geodetic and strain instruments deployed by PBO, images of deformation around active volcanic centers from InSAR, and from permanent (short period) seismic networks deployed by the USGS. The temporary seismic deployments planned by USArray are not likely to catch eruptions, although we may get lucky. Detailed seismicity along with both GPS and InSAR measurements of surface deformation will track magma ascent paths into the shallow crust. These deformation measurements will be aided by improved digital elevation models, measured as part of PBO, which will allow detection both of magmatic inflation and the potential for landslides associated with often unstable volcanic slopes. Such information, when coupled with gas-monitoring and strain measurements (from PBO) around a potentially active volcanic center, will allow investigation of the critical last step of magma migration in the shallow crust, including the climactic effects that lead to violent degassing and explosive eruptions. Understanding this step is of fundamental importance in predicting an eruption and providing information on the magnitude of hazard to be expected.

EarthScope for Hydrogeologists

As EarthScope begins and progresses with investigation of large-space-scale processes, it will form the basis for a closer examination and critical coupling of geophysics, geochemistry, hydrology, and biota. For example, EarthScope will likely provide a fundamental opportunity and basis for:

- experimental designs to test hydrologic processes that are hypothesized to occur over long time scales;
- experimental opportunities to sample fluids, rocks, gases, and biota at depth;
- resampling of rocks and fluids exposed at the surface, with new insights;
- three-dimensional (3D) coupling of geochemical/structural/fluid flow processes identified by the geophysical signatures.

Some of the process investigations to which EarthScope will contribute include:

- deep crustal fluid flow;
- pressure-temperature-driven metamorphism and metasomatism;
- deep crustal degassing;
- fluid coupling to stress/strain;
- deep basin hydrogeologic processes;
- how crustal rheology contributes to chemical and mass transport in the crust;
- how crustal strength and its deformation mechanisms contribute to secondary reaction and transport;
- how to scale laboratory deformation experiments to the crustal scale to define the frequency of episodic fluid transport.

Seismic and geophysical properties of rock at depth can be used to infer the potential for fluid velocity and the accompanying fluid dispersion. EarthScope also will define the domain in which to apply geochemical reaction theory and infer concentration as a function of position and time. InSAR will provide 3D storage constraints on water-bearing hydrologic basins as well as erosion and geomorphological changes for surface hydrology. SAFOD and its successors will enable sampling at specific places, while USArray and PBO data will allow extrapolation of data from drilling sites to a broader area. Seismic/geophysical anisotropy could be used to infer shear/flow directions whereas SAFOD will allow and define specific observations of flow in space. The coupling of the fundamental geochemical and hydrogeological processes, as defined by geochemistry and tested *in situ* with SAFOD, coupled to the spatial variations of processes inferred from geophysics and geophysical structure, represents a significant and important step in moving Earth science from a component decoupled description to a coupled integrated process model.

USArray's production of very high-quality 3D images of the continental crust will better define the extent and boundaries of groundwater resources. Appropriate inversions of seismic and electromagnetic data will help to quantify the spatial scale of hydraulic properties that govern the use of these resources. Furthermore, evaluation of the InSAR images will elaborate mechanisms of basin inflation and deflation to allow better management of shallow-water resources. Water level head measurements should be acquired at all PBO and ANSS sites to identify possible strain couplings reflected in porosity. The installation of groundwater wells is not a simple task and requires a level of understanding of the hydraulic properties of the media being monitored. Liaison with the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI; http://www.cuashi.org: John Wilson, New Mexico Tech is the current CUAHSI Chair, jwilson@nmt.edu) will be instrumental in designing PBO and ANSS boreholes that will be useful for hydrological measurements. This group also can assist with the local level design of USArray deployments to best define the boundaries and capacity of groundwater reservoirs.

Convergent Margin Processes

From nanostrain to mega-thrust: understanding and forecasting the geohazards of North America's Ring of Fire

Convergent margins are the most dynamic tectonic environments on Earth. Subduction of oceanic lithosphere leads to arc volcanism, an essential component in the creation and development of continental crust. On geological timescales, subduction, and the deformation of the overriding plate that accompanies it, create elevated topography such as mountains and plateaus. On shorter timescales, convergent margin dynamics are responsible for the vast majority of all energy released in earthquakes. More than 99% of the historical seismic moment release comes from earthquakes at convergent boundaries.

Convergent margins provide an excellent setting for resolving transient deformation on a variety of time scales. Typically deformation rates are high, and the free surface on which we observe deformation lies above a large and gently dipping fault, providing a geometry that is favorable to detecting and characterizing time-dependent deformation. Subduction zones are the source of the world's largest earthquakes, tsunamis, and volcanic eruptions, all of which impose severe hazards to populations nearby (e.g., Seattle, Portland, and Anchorage in the United States).

Key Questions

1. What is the nature of the plate boundary megathrust and how does it affect the subduction zone seismic cycle? The largest earthquakes in the world all have occurred on megathrusts at subduction zones. Great earthquakes at subduction margins pose hazards not only to nearby regions, but also across the ocean basins via destructive tsunamis. Recurrence studies of great earthquakes shows complex behavior, just as is found on strike-slip margins. It is important to compare and contrast aspects of subduction earthquakes with those at strike-slip margins and extensional regimes to understand whether any features of earthquake occurrence are universal to faults and whether any are specific to particular types of faulting. Although subduction-related faults are generally less accessible at the surface than continental transforms such as the San Andreas system, the magnitude of the earthquakes and deformation signals found at subduction zones are substantially greater, providing ample signals for in-depth studies. In addition, paleo-earthquakes at subduction zones are recorded in sediments over a broad area instead of only at the fault trace.

Several differences between subduction-zone and strike-slip fault behavior are obvious. The seismogenic width of the fault is generally much wider for dip-slip faulting for geometrical reasons, and at subduction margins the average slip per major event may be up to several times larger than for strike-slip faults. There also are obvious similarities. At both subduction and strike-slip boundaries there can be significant along-strike variations in earthquake behavior. Regions that are essentially aseismic due to steady creep are found in both types of margins. One open question is whether the earthquake nucleation phase differs in strike-slip and subduction environments; although considerable study and modeling have been applied to the San Andreas fault system and other strike-slip faults, much less has been applied to the subduction setting (at least in the English-speaking world). Subduction events often are preceded by large or complex foreshock sequences, such as the M~8 foreshock to the 1960 Chile earthquake or the abundant foreshocks preceding the 1997 Kronotsky earthquake in Kamchatka. These features lead to the following questions:

- What is the geometry of the plate boundary megathrust and how does it relate to spatial and temporal variations in convergence, strain rates, seismicity, and paleoseismicity along the convergent margin?
- Can we identify asperities (areas of maximum seismic moment release) or barriers along the megathrust and characterize their physical properties?
- What are the roles of transients, slow earthquakes, and postseismic slip in subduction zone deformation budgets?
- Are there observable differences in physical properties or fault behavior between subduction zone faults and those in continental thrusts or strike-slip faults? In particular, are there systematic differences in the role of transient slip, preparation for earthquake rupture, or the earthquake nucleation process?
- Can we identify the landward limit of locking and characterize the geometry and physical properties of the deep megathrust beneath the forearc where transient slip has been observed? What is the physics of these transients?
- What is the role of sediment input and dewatering to seismogenesis?
- What is the real convergence direction in Cascadia? Can we measure it directly?

2. What is the deeper slab and upper mantle structure and how does it relate to intermediate-depth Wadati-Benioff zone seismicity? There is abundant deep seismicity at subduction zones. Below the shallow thrust zone, most or all of this deep seismicity occurs within the downgoing slab, though seismicity in the slab is observed at all depths. In some subduction zones, earthquakes are observed within the slab to a depth of ~600 km, although the deep limit of seismicity within North America's downgoing slabs is much shallower. The subducting slab also induces flow within

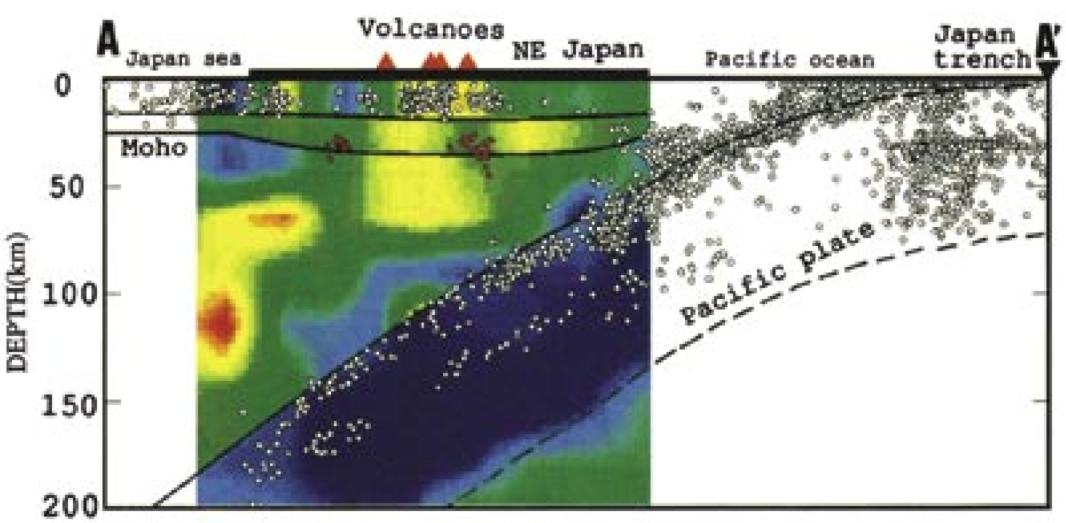


Figure 9. Tomographic image of the asthenospheric wedge, northern Honshu, Japan. Figure from Zhao, D., A. Hasegawa and S. Horiuchi, 1992, Tomographic imaging of P and S wave velocity structure beneath Northeastern Japan, *J. Geophys. Res.*, 97, 19,909-19,928.

the overlying asthenospheric wedge that may be critical to magma genesis and also to the long-term deformation of the overriding plate.

- What causes intermediate-depth Wadati-Benioff zone seismicity in the down-going slab? Is it the result of phase changes and dehydration embrittlement reactions in the slab or is it the result of body forces like slab pull (or both)?
- Do the large earthquakes in the slab occur in slab crust or mantle? Do the small earthquakes occur in the slab crust or mantle? If these populations occur in different spatial volumes, why? Can we characterize the physical properties of slab mantle and crust well enough to elucidate the role of dehydration reactions in warm slabs?
- What is the flow in the mantle wedge in 3D? How does it control or impact forearc processes? How does fluid flux occur? Does it go into the forearc? What is its relationship to forearc seismicity?
- Is there a connection between megathrust postseismic processes and earthquakes within the slab?
- Is there a causal relationship in the apparent correlation between the geometry and location of basins in Cook Inlet (Alaska) or the Georgia-Puget-Willamette Lowland (Cascadia) and the locus and rate of in-slab seismicity?
- How do recent large, in-slab events relate to the rupture areas and timing of megathrust earthquakes in Alaska?
- Is the present seismic quiescence beneath Oregon, and the concentration and location of damaging earthquakes beneath Puget Sound, a result of variations in the presence or absence of a deep slab, differences in interplate coupling on the megathrust, mantle dynamics of the Basin-Range/Yellowstone system, or the petrologically controlled velocity structure of slab crust?

EarthScope will permit a quantum leap in our understanding of faulting and deformation of convergent plate boundaries.

3. How is strain partitioning accomplished in the forearc? Permanent deformation of the overriding plate is extremely common at subduction margins. One common deformation style involves translation or slivering of the arc or forearc region. A common cause for this deformation is slip partitioning of oblique subduction into roughly normal convergence on the trench and strike-slip deformation of the overriding plate. Translation and rotation of the forearc might also result from other mechanisms.

- How is the margin-parallel component of convergence accommodated along the convergent margin? What percentage is resolved by oblique slip on the megathrust versus migration of a forearc sliver, and how does this behavior relate to the rheology of the forearc and the distribution and rate of upper plate strain and seismicity?
- What are the hazard implications of partitioning?
- What is the role of the magmatic arc in accommodating crustal strain and migration of the forearc?
- What are the relative importances of Pacific-North America dextral shear, Basin and Range extension, and subduction in driving upper plate deformation in the Pacific Northwest?
- How is arc translation and fragmentation accommodated in the western Aleutians, where plate convergence becomes so oblique that it is dominantly strike-slip?

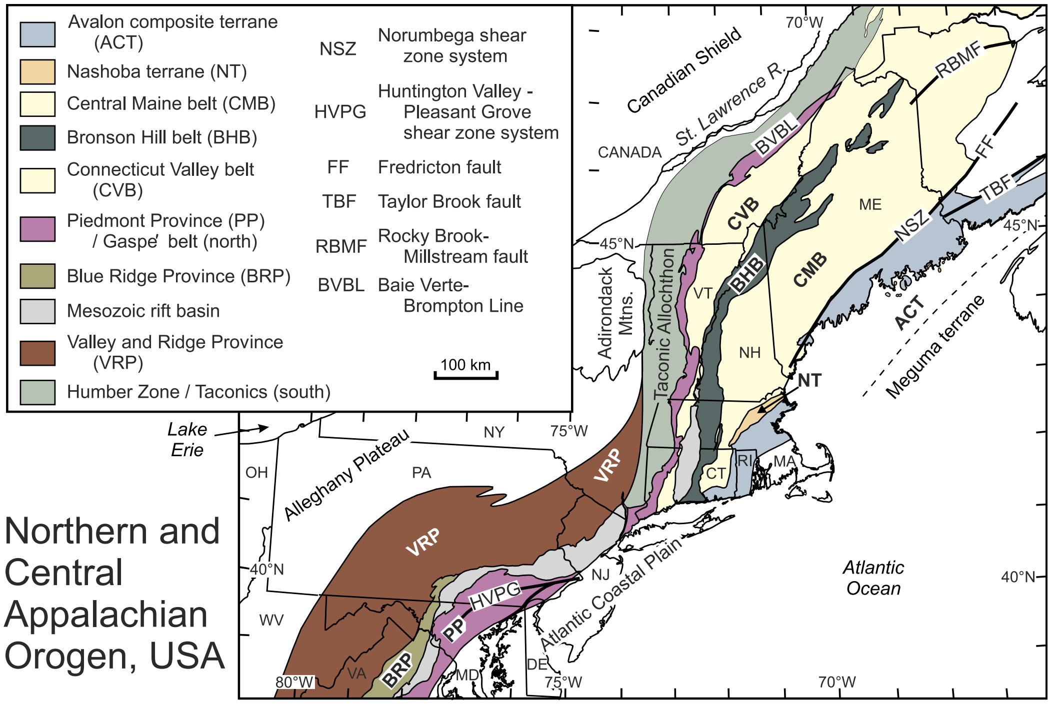


Figure 10. Terrane map of the northeastern seaboard of North America showing the large number of accreted terranes that form the continental border in this region. Figure courtesy of Michael Brown.

4. What causes coast ranges and basins in forearcs? Forearc regions display a great variety of topographic and structural features along the subduction margins of North America. Offshore, forearc basins show a variety of sizes and depths, while in a few cases there are extremely large forearc basins, for example, Cook Inlet and Puget Sound. In some places, there are large coastal mountain ranges in the forearc (e.g., the coastal mountains from Prince William Sound to Kodiak Island in Alaska, or the Olympic Peninsula and Vancouver Island in Cascadia), while in others there are only coastal lowlands or low-lying mountains.

- How does the architecture of the forearc evolve over many seismic cycles, that is, what is the relationship of interseismic elastic deformation and coseismic slip to the permanent deformation and structural evolution of the forearc? In some great earthquakes, seismic slip is concentrated beneath the forearc basins, suggesting a causal link.
- How do forearc basins form? Are they trapped oceanic crust? Are they mafic underplates? Why do they subside? How do they subside above a subduction zone? What is the role of sediment input in the cycle of basin evolution?
- What is the role of slab buoyancy in the deformation of the overriding plate?

5. What controls the locus of volcanism in the upper plate? Subduction usually leads to a line of volcanism on the upper plate that overlies a specific isobath in the subducting slab, however, the underlying control on the position of volcanism is still not understood. Locations of volcanic centers are often correlated with broad-scale crustal faults, but it is not clear whether the faults control the location of the volcanoes or the volcanoes control the location of the faults. Possible tectonic and structure controls include: (a) lower plate (thermal structure, convergence rate, age, dip, dehydrations reactions), (b) mantle wedge (pressure gradients in the wedge flow field (Figure 9), magma fracture, melt-mineral surface energetics, the position of the wedge corner), and (c) upper plate structures and stress field (possible density, temperature, and stress-field variations in the crust).

6. How does the continent grow? Continental growth at convergent margins occurs by both magmatic and tectonic additions (Figure 10). Magmatic additions involve the transfer of mantle melts into the crust, but magma production rates are poorly known. Tectonic additions are made by accretion of pre-existing crustal material, terrane docking, and orogeny. Continental growth may also be modulated by foundering of lower crust material into the mantle during orogenic events. There is no convergent margin where all such mechanisms of crustal growth rates have been determined. One of EarthScope's goals is to capture events of continental growth, from volcanic eruption to active deformation associated with incipient terrane accretion, to final crust and mantle structure of a mature orogen, to provide the data necessary to calculate continental accretion rates.

- What is the juvenile (magmatic) growth rate of the continents? Can this rate be deduced from the volume island arcs and duration of their volcanism?
- Is continental growth incremental or episodic?
- Does variability in accreted terrane structure and composition affect the distribution of subsequent deformation, seismicity, and magmatism in the upper plate?
- What causes high mountain ranges along some subduction zones? Is collision of accreted terranes required?
- How are terranes transferred from oceanic to continental crust? How does this transfer process affect magmagenesis, subduction zone seismicity, and mantle flow patterns? Also, how does this process deform the continental margins and interiors?
- How do new subduction zones form?

The EarthScope Contribution

Most of the questions listed above can be addressed by the measurements to be taken by EarthScope. How EarthScope measurements relate to the questions raised above is summarized in Table 2. EarthScope contributions to the questions outlined above will be enhanced if the Bigfoot array could go all the way out the Aleutian Island chain and the density of stations in continental Alaska is as close to the national average as possible. In the western Aleutians, magnitude 4 earthquakes probably go unrecorded, and the third and sixth largest earthquakes recorded on Earth occurred in this region.

Table 2: Data Sets Needed for a Better Understanding of the Convergent Margin Processes

Data Set	Relevant to Questions	Available?	Will EarthScope Provide?	What Else?/Comments
GPS geodetic data—both campaign and permanent stations	1,3-5	Substantial GPS campaign data, minimal continuous	Yes	Geodetic data from the seafloor at a few targeted locations
Seismic images—including tomographic images of velocity, attenuation, and anisotropy	1-3,5	Some	Yes	Catalogues of seismic reflection and refraction images
Detailed seismicity	1-5	Some	While USArray is present	ANSS for longer-term monitoring
Magnetotelluric data	1,5	No	Yes	
InSAR	1,3,4,6	From volcanoes only	Yes	
Stress field maps—needed in 4D	1,3,4,6	No	Some	
Digital elevation models	3,4,6	Some	Some	Needed for a variety of GPS, InSAR, and geology investigations
Baseline geology—bedrock mapping, Quaternary deposits, structure, volcanic rocks (esp. xenoliths, geochemistry, isotopes), intrusive rocks, sediments, metamorphic rocks, geochronology	1,3-6	Some	Some	In EarthScope Science Plan
Paleoseismology	1,3-6	Minimal	Some	
Potential field data	5	Some	No	
LIDAR and other high-resolution topography, with sophisticated "Virtual Deforestation" algorithms for heavily vegetated areas.	1,3,4	No	No	Needed for understanding long-term deformation and strain transients
Marine geology and geophysics—seafloor geology, borehole geologic data, seismic reflection data, gravity and magnetic data, OBS and seafloor geodesy	1-4	Some	No	
Water well data including chemistry and pore pressure	1-4	Very little	No	Monitor changes in waters on margins of volcanoes, sampled at rates of 1 hertz

Large-Scale Continental Deformation

Continental Tectonics of the United States

EarthScope: The New Continental Tectonics

The North American active margin provides one of the most diverse plate-boundary regions on Earth. It includes a continental transform system, with extensional, strike-slip and contractional regimes, and continental arc and oceanic arc settings. It records the long-lived interaction of a continent with the great Pacific and Farallon plates, and their influence on continental accretion and deformation. The diversity of tectonic regimes within the continent violates rigid-plate precepts and requires development of a new paradigm to explain global continental tectonics. Any robust paradigm must be rooted in detailed and comprehensive views of deformation and crustal evolution. North America will be viewed through the unprecedented EarthScope, which can be focused on a spectrum of spatial and temporal scales across a large, complex, and globally important plate boundary. Complex patterns of deformation and mountain building belie the heterogeneity and varied rheology of continental lithosphere, and its complex interactions with the underlying mantle.

In spite of the success of plate tectonics to explain myriad previously disparate geologic observations, many first-order questions regarding continental-scale deformation, as exemplified in the geology of North America, remain. Some of these questions are sufficiently fundamental that they limit our most basic understanding of plate tectonic processes. Since the mid-1960s, a reasonably good kinematic perspective of plate tectonics has emerged, but understanding of the forces driving plate motion is in its infancy. Only through knowledge of these forces can we move beyond a kinematic description and offer predictive capabilities beyond the present theory.

Links between specific geologic areas and newly generated EarthScope data sets will offer unique natural laboratories to examine Earth's short- and long-term evolution, for example, in examining the connections among lithospheric deformation and mantle processes, exhumation rates, intraplate deformation, and fault strength.

A broadly based EarthScope project has the opportunity to resolve fundamental questions in plate tectonics, "expose" new areas and offer greater detail in other places, and pose and answer new questions. This effort would better constrain our attempts at numerical modeling of Earth's plate activity, leading to much greater predictive value than current models. Ultimately, the EarthScope project has the potential to offer a full formulation of plate tectonic theory, that includes both kinematics and dynamics, when a spatially and temporally integrated approach is adopted.

The numerous fundamental questions on these issues can be grouped under three general themes:

1. Lithospheric Strength and Crust-Mantle Coupling. What is the lithospheric strength profile? What defines tectonic regimes in the United States? Examples include: what is the structure beneath the Snake River Plain–Yellowstone volcanic system; what causes Basin and Range extension;

and, what defines a craton? What processes act at the Mendocino Triple Junction? Do faults cut the Moho? What is the nature and degree of coupling between crust and mantle? What is the origin of seismic anisotropy and how does it relate to deformation? What is the origin of intraplate faulting/earthquakes? What is the degree of elastic vs. permanent strain?

2. Composition, Fluids, and Rheology of the Lithosphere. What is the role of fluids in crustal deformation? What are vertical and lateral compositional variations? What is the rheology of mixed mineralogies? What is the nature of Cascadia convergent zone?

3. Spatial and Temporal Scales of Deformation. Is continental deformation localized or distributed? What is continental elevation over time? How do geologic and geodetic rates of deformation compare? How did eastern passive margins evolve? What is the Moho topography under North America?

The EarthScope Contribution

EarthScope data sets will contribute to a comprehensive image of the deformation field and material properties of North America and its temporal variation and evolution. This image will be sharply focused at a variety of temporal and spatial scales and will form the basis for a new, physics-based description of the dynamics of the whole Earth (Figure 11). We strive to articulate a time-dependent geodynamical model of continental evolution that assimilates and integrates geologic, geodetic, and seismological data sets. We strive to create a geodynamic model that parallels plate tectonics in its power to integrate our understanding

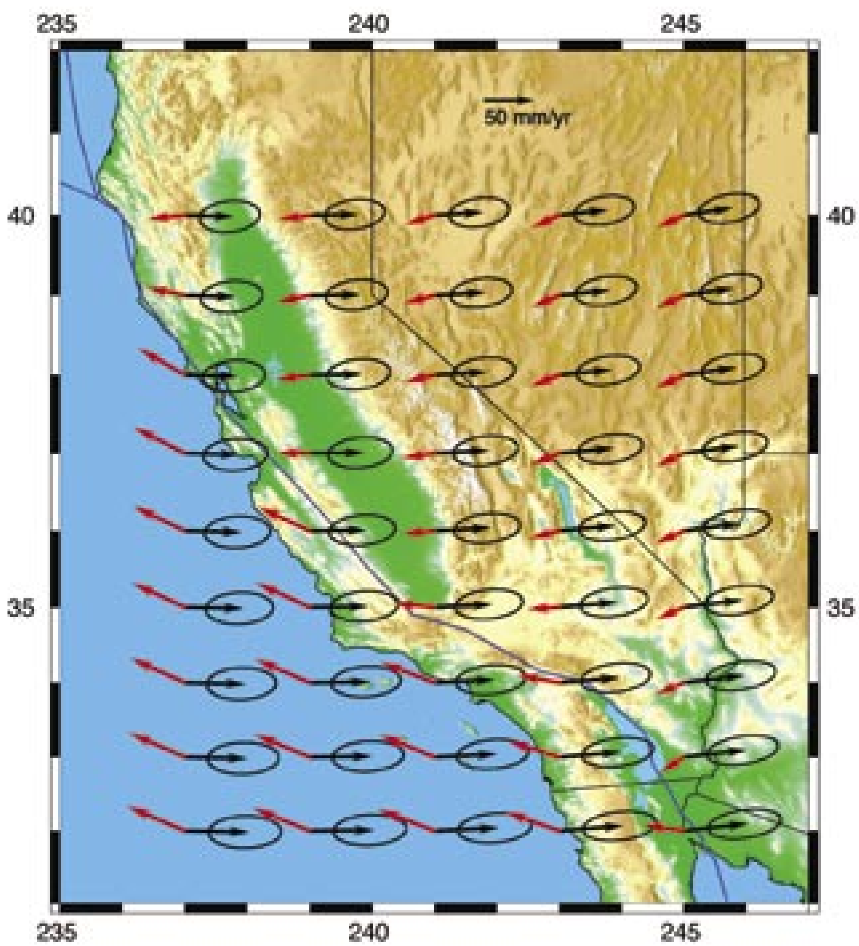


Figure 11: Estimated sub-lithospheric mantle flow velocity in a hotspot frame (black arrows) along with lithospheric motion (including lithospheric deformation; red arrows), also in a hotspot frame. Ninety-five percent confidence ellipses in sub-lithospheric velocity incorporate formal uncertainty from inversion plus uncertainty in the hotspot frame. Mantle flow is approximately eastward at 5.5 cm/yr. From Silver, P. G. and W. E. Holt, 2002, The mantle flow field beneath western North America, *Science*, 295, 1054-1057.

Table 3: Data Sets Relevant to Issues of Large-Scale Continental Deformation

Data Set	Relevant to Questions	Available?	Will EarthScope Provide?	What Else is Needed?
Velocity field (detailed and averaged)	1,3	Partial	Yes	Regional networks with local densifications
Constitutive equations, texture and fabric development, crustal (=mixed mineralogy) rheology	1,2	Some	No	Laboratory experiments—rock deformation, material properties
Portable and continuous GPS: nationwide	1-3	Some	Some	
Fault-zone drilling and sampling	2	No	SAFOD	
Shallow (km-depth) drilling nationwide	2	Some	No	Program for stratigraphic drilling across North America
Reflection seismology (3D geometry)	2	Some	Yes	
Field-based geology and geochemistry	1-3	Some	No	Support for EarthScope-related projects using these disciplines
Modern seismicity	1,3	Localized	Yes	
Pre-Holocene (paleo) seismicity	1,3	Limited	Some	
Geochronology (short- and long-term)	1,3	A little	No	Support for EarthScope-related projects using these disciplines
MT and (new) potential field data	2	Some	Some	
High-res (paleo) topography and elevation	1,3	Very little	No	

of Earth evolution, and that goes beyond tectonics in creating a rigorous understanding of the physics of Earth.

The image of the deformation field and material properties of North America will contain many elements: the surface strain field over a variety of time scales from seconds to geologic; a three-dimensional image of the seismic velocity structure of North America; resolution of the depth of the Moho and its topography; 3D constraints on anisotropy and rheology variation with depth; geologic observations of strain fields over a variety of time scales; mapping of the nature and distribution of seismicity; geochemical and hydrological models for the crust; and geochronological information on the rates of lithospheric processes.

A list of data sets required to answer many of the fundamental questions above is given in Table 3. However, additional data sets are needed to provide a context of site characterization for EarthScope results, as well as offer supporting information that will be crucial for interpreting the results.

Continental Structure and Evolution

The continents record at least four billion years of Earth history. Continental crust is compositionally distinct from that of the crust of all other planets and satellites, implying that the processes that lead to the formation of Earth's continents are unique in our solar system. The continents and their margins also hold most of Earth's recoverable natural resources. And, we live on the surface of the continents. Despite these special attributes, the continents and the forces that have shaped them remain poorly understood.

> Continents are unique in the solar system and are the repositories of most of Earth's history.

Key Questions

While there are many questions that can be posed regarding the composition and evolution of Earth's continents, most of those questions are subsets of the following three:

- What is a continent?
- How is lithosphere formed?
- How are continental structure and deformation related?

1. What is a continent? We lack a robust structural characterization of the continental crust and associated upper mantle or tectosphere. Structural characterization includes the three-dimensional seismic velocity structure, seismic anisotropy distribution, the thermal and compositional structure, and the distribution and nature of fluids. Important corollary investigations include describing the nature of the crust-mantle boundary, or Moho, measuring the depth of continental keels, and determining how continents and convecting mantle interact. In some continental regions (Figure 12) there is a good correspondence between the seismic structure of the crust and upper mantle and the history of continent assembly. In others, this connection may have been disturbed by post-formation tectonic or volcanic events.

In North America, the old central craton (Superior Province) has one of the deepest seismically defined lithospheric mantle keels. Archean continental terranes commonly have deep keels, but the whole upper mantle of western North America shows very slow seismic velocities independent of the age of the overlying crustal sections (Figure 13). These slow velocities are associated with the extensive recent magmatism and tectonism in western North America, but their lack of correlation with crustal age poses the question of whether the seismic velocities are tracking primarily the temperature or composition of the continental lithosphere. If western North America is underlain by mantle of similar age to the overlying crust, where is its expression in the seismic tomography? Does this imply that the lithospheric base of continental North America is as shallow as 100-150 km west of the Rockies?

EarthScope will provide important components of the answers to these questions. By inversion of a variety of data sets to be collected by USArray and associated denser subnetworks of seismometers, we shall learn the mean seismic structure of the continental crust, associated mantle, and crust-mantle transition as well as the variability in that structure about the mean properties. We shall derive a three-dimen-

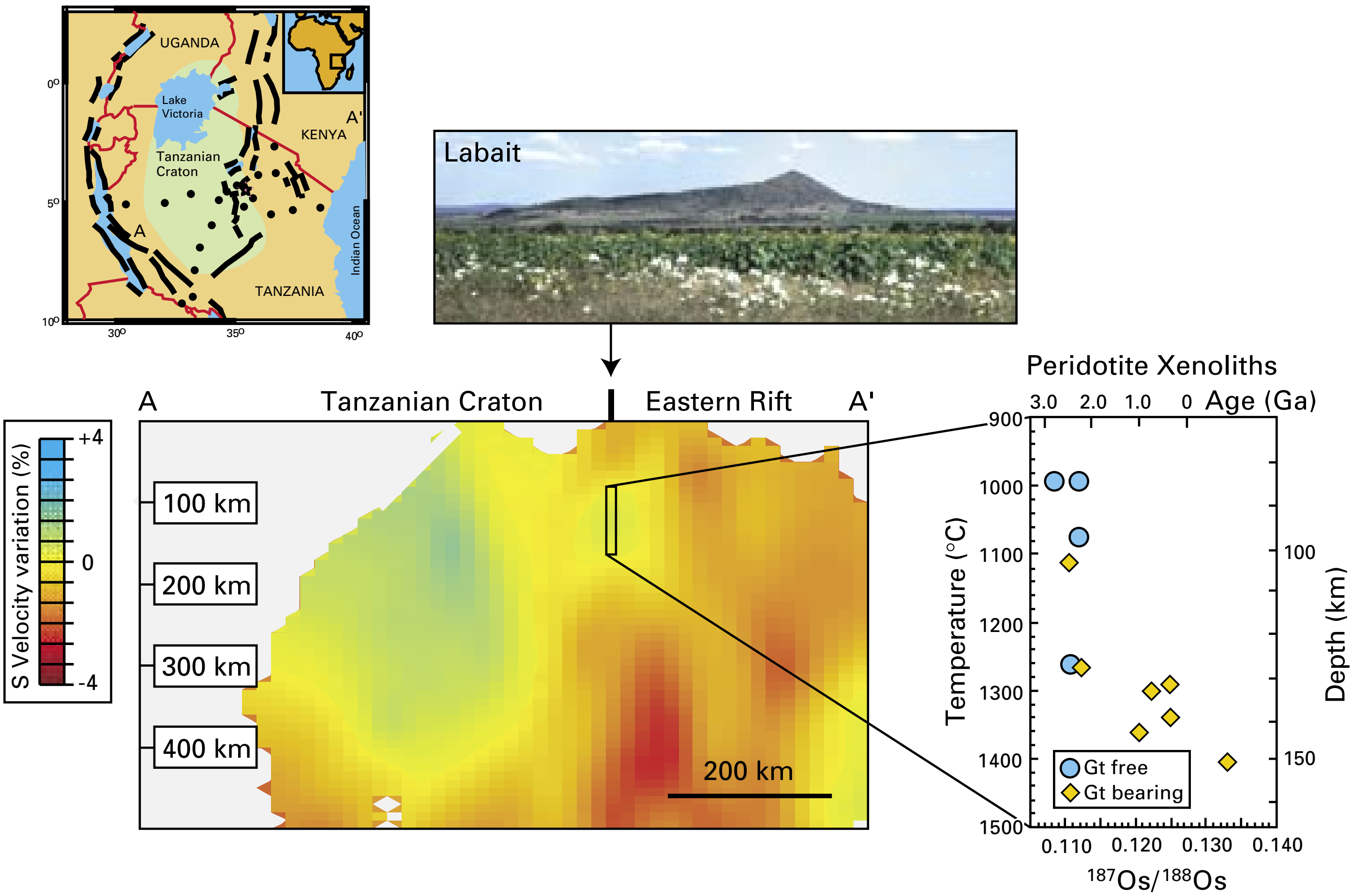


Figure 12. Combined seismological and petrological studies of the Tanzanian craton show that ancient cratonic lithosphere persists beneath the East African rift to depths of ~130 km. S-wave velocities are fast beneath the craton and to ~150 km on the craton margin (Ritsema, J., A.A. Nyblade, T.J. Owens, C.A. Langston, J.C. VanDecar, 1998, Upper mantle seismic velocity structure beneath Tanzania, east Africa: Implications for the stability of cratonic lithosphere, *J. Geophys. Res.*, 103, 21,201-21,213). Peridotite xenoliths from Labait volcano, located on the craton margin, have old Os model ages (~2.8 Ga) to depths of 130 km. Between 130 and 150 km, $^{187}Os/^{188}Os$ increases. The lowermost lithosphere may represent ancient craton infiltrated by rift-related components, or may represent Proterozoic lithospheric additions to a previously thinned Archean lithosphere (Chesley, J.T., R.L. Rudnick and C-T. Lee, 1999, Re-Os systematics of mantle xenoliths from the East African Rift: Age, structure, and history of the Tanzanian craton, *Geochim. Cosmochim. Acta*, 63, 1203-1217; Lee, C.-T. and R. L. Rudnick, 1999, Compositionally stratified cratonic lithosphere: Petrology and geochemistry of peridotite xenoliths from the Labait volcano, Tanzania, in Gurney, J.J., J.L. Gurney, M.D. Pascoe and S.H. Richardson eds, *Proceedings of the 7th International Kimberlite Conference*, Red Roof Design, Cape Town, 503-521). Cross section A-A′ passes through the section sampled by the Labait magmas. Grey bar represent the depth extent of the mantle xenolith samples.

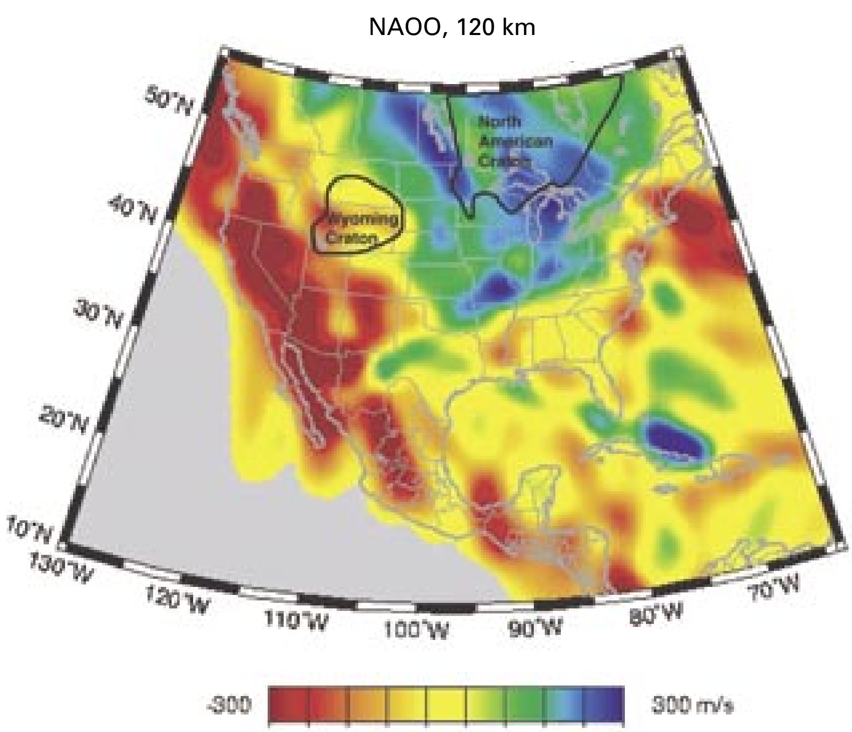


Figure 13. Outline of the surface exposure of two areas of Archean crust in North America relative to the S-wave tomography at 120 km depth in the underlying mantle. Tomography base map from S. Van der Lee et al., 2002, Variations in lithospheric thickness from Missouri to Massachusetts, *Earth Planet. Sci. Lett*, submitted.

> High-resolution images of the continental lithosphere, and the development of integrated kinematic and dynamic models for its formation and evolution, will make a fundamental contribution to all Earth science.

sional image of seismic structure, which will permit us to relate the deeper aspects of that structure with the shallower aspects amenable to mapping by geological methods. Together with a program of analysis of samples from surface outcrops, boreholes, volcanic rocks, and xenoliths, as well as a program to continue laboratory measurement of the dependence of seismic velocity on rock composition, we can convert knowledge of seismic structure to constraints on compositional, thermal, and mechanical structure in three dimensions.

The natural laboratory for this component of EarthScope is the entire continent of North America. The USArray observations will provide structural information for the continental United States, and we recommend that collaboration with Canada and Mexico be accelerated to extend the U.S. observations to the rest of the continent. At the end of EarthScope operations, particularly if our neighbors mount complementary programs, we will have a three-dimensional view of a continent of unprecedented resolution and coverage.

Figure 14. Photograph of the large, broadly granitic, bodies that define Yosemite scenery. Rocks of similar composition make up most of continental crust, but are nearly non-existent in the oceanic crust. Photo courtesy of R. Carlson, Carnegie Institution of Washington.

2. How is continental lithosphere formed?

Our knowledge of the structural and compositional development of continents is incomplete. The average composition of continental crust is approximately known (Figure 14), but rocks of that composition cannot be derived simply by partial melting of the mantle. Island arcs, produced by magmatism closely tied to the release of volatiles from subducted oceanic lithosphere, are thought to be the locus for at least some of the modern production of continental crust, but arc compositions are not a perfect match to that of the continents. There are hints in the geological record that portions of the more mafic lower continental crust may, under some conditions, be recycled into the mantle, but the extent of such recycling is unknown. The ancient cratonic cores of the continents have, in a large part, been remarkably stable for billions of years, but the origin of the cratons and the conditions favoring stability versus vulnerability to disruption are not understood. Whether the dominant processes leading to the formation of continental crust have changed through Earth history is an open question.

The general age progression from old continental core to young continental margin indicates that continents grow primarily around their margins. In some areas this growth occurs through magmatic additions along convergent plate boundaries, as in the numerous Mesozoic and younger intrusive and extrusive rocks of the western United States including the Sierra Nevada and Cascades. In other areas, the growth is through collisional accretion of continental fragments (Figure 10). How these accreted terranes eventually become welded to the continent is an outstanding question. Do they have expression well into the mantle or do they primarily reflect shallow overthrusting of crustal blocks? Do boundaries between terranes have unusually low strength that localizes deformation along terrane boundaries?

USArray will yield images of seismic velocity structure, and provide associated constraints on compositional structure, that will directly address these issues. There are also a number of potential regional targets for natural laboratories to study aspects of continental formation and evolution with higher resolution, particularly in mapping out terrane boundaries and their depth extent. These areas are candidates for portable seismic array studies carried out in concert with USArray.

Detailed studies of cratons and their margins could be carried out on the Wyoming Craton and the southern reaches of the Superior Province, both within continental United States. Type examples of continental arcs and arc-continent collisions can be found in the Pacific Northwest and in Alaska, respectively. Intercontinental regions of active magmatism are to be found throughout the Basin and Range and extending along the Snake River Plain to the Yellowstone Plateau. There are diverse examples of both active and now preserved examples of continental extensional provinces, important loci for the modification of continental crust and lithosphere by stretching, faulting, and magmatism. Active examples include the Rio Grande Rift, the Imperial Valley-Salton Sea, and the Basin and Range Province. Older examples of extensional provinces include the Mid-Continent Rift, the Mississippi Embayment, the Atlantic continental margin, and the California Borderland. Accreted terranes are found in abundance along both the Atlantic and Pacific seaboards of North America.

3. How are continental structure and deformation related? The continents are continually responding to the forces imparted by mantle convection and to the gravitational stresses arising from lateral variations in topography and density. The nature of that response, and its relationship to extant structure, is imperfectly understood. In many settings there is evidence that the deformational response is strongly influenced by structures surviving from older tectonic and magmatic episodes. While many fault systems localize deformation in the shallow crust, the depth extent of faulting and the compositional and thermal conditions marking the depth limit to fault behavior are not well known. Seismic anisotropy, particularly in the continental mantle, is thought to be largely the product of accumulated finite strain and therefore also strongly tied to past deformational history, but the extent to which strain in the mantle parallels strain in the upper crust is not well characterized. Studies of seismic anisotropy, at the resolution that will be

Deep knowledge of the continent and its 4 Ga history is central for strategic long-term planning about hazard reduction, preservation of the environment, and conservation of mineral and fossil resources.

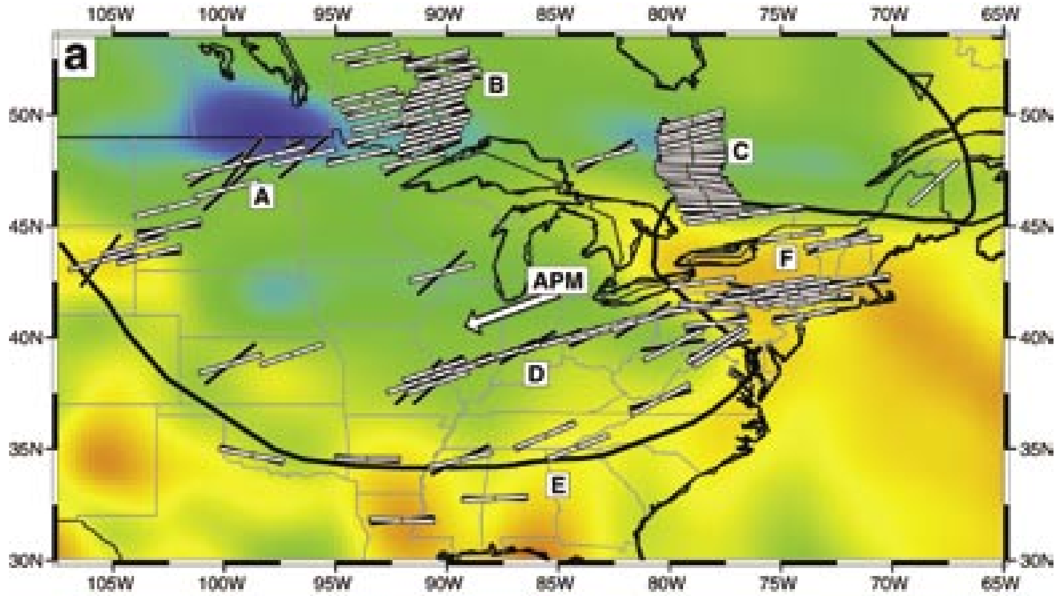


Figure 15. Comparison of predicted and observed fast shear wave polarization directions for the sublithospheric mantle beneath eastern North America based on a mantle flow model for the keel divot caused by a rigid, deep mantle root to cratonic North America, denoted by thick solid line. Background velocity model and map projection are from van der Lee and Nolet (1997). With the exception of region A and portions of regions C and F, fast directions mimic regional fast direction patterns. Figure from Fouch, M.J., K.M. Fischer, M.E. Wysession, and T.J. Clark, 2000, Shear wave splitting, continental keels, and patterns of mantle flow, *J. Geophys. Res.*, 105, 6255-6276.

possible with USArray, will help define the degree to which deformation of the continent is tied to, or decoupled from, flow in the underlying mantle (Figure 15).

The natural laboratories for addressing these questions are both the actively deforming portions of the continent and older, well-preserved examples of these deformation processes. Much of western North American has been dominated by large-scale regional extension for at least the last 15 million years, but the driving mechanism for this deformation is not fully understood. North America also contains natural laboratories for active strike-slip terrains (e.g., the San Andreas and related fault systems) and orogenic belts (e.g., Rocky Mountains, Sierra Nevada, Alaska). Sites for detailed study of structure and fabric in now inactive regions are plentiful as well.

The actively deforming natural laboratories are prime candidates for combining all of the components of the EarthScope program in a coordinated attack on the deformation field, seismic structure, and their interconnections. For such target areas, important advances can be expected through the integration of different physical properties (e.g., seismic velocity and effective viscosity) because of the distinct dependence of different properties on temperature, strain, and other controlling variables. Models linking the mechanical and deformational fields will be needed, both to interpret the diverse observations and to guide in the design of high-resolution, regional-scale observation programs.

Deep-Earth Structure

Significance of Deep-Earth Science

The study of Earth's interior provides the foundation for crustal and lithospheric studies in many different ways. It is not possible to completely understand North America's surface structure and composition without understanding the deep-Earth processes that have formed them. Surprisingly, deep-Earth geology addresses questions that are of societal importance, such as when the next magnetic field polarity flip will occur, with consequent effects on navigation and the amount of solar and cosmic radiation that reaches Earth's surface, and global sea level change caused by large changes in the mean temperature of the upper mantle. Most people assume that the ground beneath their feet is stable, and are fascinated by concepts such as rising hot mantle plumes, sinking slabs of seafloor, and vigorously convecting molten iron in the outer core.

Key Questions

EarthScope will provide a unique opportunity to learn about the deep-Earth structure, composition, and dynamics. The scientific questions that can be addressed in the framework of EarthScope fall into two broad classes. The first concerns the connection between the deep mantle and relatively shallow structures that will be sampled seismologically immediately beneath the North American continent. The second concerns the lower mantle and core, for which optimally sampled regions will be elsewhere (e.g., beneath the Pacific Ocean and Central America), with seismic waves traveling from earthquake sources in the western Pacific and South America through the deep mantle to rise again and be detected by USArray seismometers. We have thus chosen to group the questions roughly in order of increasing depth.

> Beyond plate tectonics: a high-resolution window into Earth's dynamics from the crust to the core.

1. How and where are forces generated in the upper mantle, and how and where are they transferred to the crust? At what depth do subducting plates become assimilated in the mantle? How do subducting plates interact with mantle discontinuities? Is the origin of the Yellowstone hotspot deep or shallow? What are the interactions among rifts/hotspots, continental lithosphere and subducting plates (e.g., Yellowstone hotspot, Farallon plate)? What is the relationship between mantle flow and surface deformation? How do mantle processes stabilize or disrupt continents?

2. How is the evolution of continents related to upper mantle processes? Can we link mantle characteristics inferred from seismic tomographic images to mantle characteristics derived from geological, geochemical, and other surface data? How steep are lateral velocity gradients in the upper mantle and how are they associated with geological boundaries? For example, where is the margin between tectonically active west and stable eastern North America, how sharp is it, and how deep does it extend? What are the lateral variations in composition and temperature

beneath continents? What are the lateral variations of the Lehmann discontinuity (220 km) at the continental scale? How do lateral variations in continents affect upper mantle discontinuities? What are the variations in depth, velocity contrast, and gradient across upper mantle discontinuities at continental scales? Can we establish the existence of elusive discontinuities such as that at 550 km?

3. Is the mid-mantle as "boring" as it seems? How strong is layering in the mid-mantle region? Why is the spectrum of heterogeneity in the mid-mantle so different from that in the upper and lowermost mantle? What is the origin of fast anomalies in the mid-mantle, especially those that cannot be correlated with past subduction?

4. What is the nature of the lowermost mantle and D″? What is the role of plumes in mantle dynamics? How can we reconcile the structure of plumes as seen by seismic tomography with that produced in geodynamic models? Is there a seismic discontinuity at the top of D″, and how does it change laterally? What is the relative importance of chemical and thermal processes in D″, or more generally, in the boundary layer at the base of the mantle? What are the processes at the edges of major lower mantle plumes? What are their scales of heterogeneity and anisotropy? What are their thermal/ chemical natures (e.g., the central Pacific is well illuminated)? What are the fate of subducted plates (e.g., Central America is well positioned to be studied by USArray)? Are there ultra-low velocity zones and what is their nature? What is the nature and importance of coupling between the mantle and the core, in particular with respect to the geodynamo? Can we resolve lateral variations of electrical conductivity in the deep mantle?

5. What is the detailed structure and dynamics of Earth's core? Is there heterogeneity (e.g., "sediments") at the top of the outer core? How much complexity is there in the inner core? What is the origin of the South Sandwich to Alaska anomalies in PKP data? What are the trade-offs between D″ and inner core structure? What are the limits on the rate of inner core differential rotation? How does the magnetic coupling between inner core and geodynamo work?

The EarthScope Contribution

North America is in an excellent geographical position with respect to the global distribution of seismicity to address various aspects of the questions listed above (Figure 16). The USArray component of EarthScope is essential in that it will provide unprecedented seismic resolution at the continental scale needed to understand:

- lateral and vertical relationships between shallow and deep processes at continental scales;
- spatial scales of lateral transitions in the upper mantle beneath North America, and in the lowermost mantle, in several different settings such as the central Pacific (major low-velocity regions, e.g., "megaplumes"), Central America, Alaska, and the Aleutians (e.g., major high-velocity regions, possibly slab graveyards);
- scales of lateral variations in inner core anisotropy and heterogeneity. The Alaska component of USArray is particularly important for addressing the origin of strongly anomalous PKP(DF) paths from the South Atlantic to Alaska, elucidating the causative structure (inner core or elsewhere) and consequences on inner core anisotropy and heterogeneity.

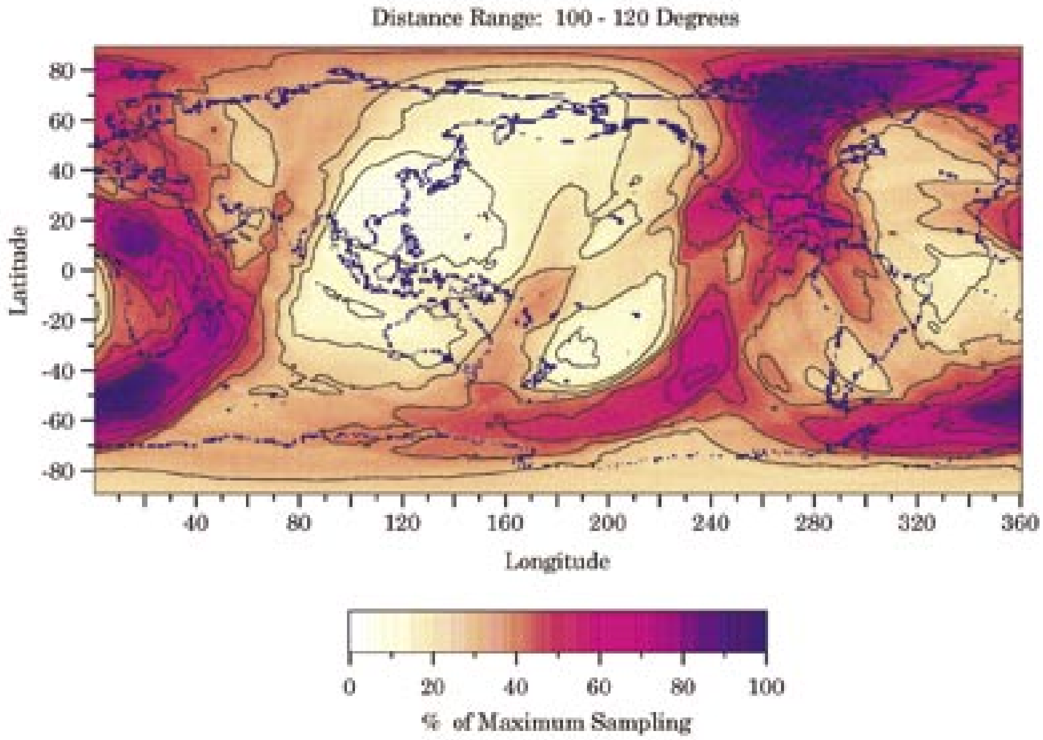


Figure 16. A prediction of the sampling of global seismicity in the distance range of 100-120 degrees, which is good for sampling the core and core-mantle boundary region with phases such as Sdiff, Pdiff, SKS, SKKS, and SPdiffKS. Sampling is based upon 30 years of global seismicity (1963-1993). Because North America is the best place on the globe for recording teleseismic waves in this range, it is one of the best places in the world to establish seismic arrays for investigating the deep structure of the Earth. Figure from: M. E. Wysession, 1996, How well do we utilize global seismicity?, *BSSA*, 86, 1207-1219.

For deep-Earth structure, the most relevant EarthScope component is USArray. However, some of the additional questions asked under questions 1 and 2 of this section, particularly those related to the rheology of the continent, will benefit from combining seismological data from USArray with geodetic data from permanent GPS deployments across the continent, as well as with gravity data available independent of EarthScope.

Data Needed

Most, if not all, of the questions posed in the previous section relating the deep Earth to the phenomena observed at the surface require more reliable and more detailed images of: (1) seismic P and S velocity variations, (2) the principal direction(s) of seismic anisotropy, and (3) seismic attenuation (Qmu). To make these parameters useful for geodynamic modeling, the temperature and density need to be derived from comparison with laboratory-measured rock properties. Tomographic images of P and S velocity variations, as well as the depth and sharpness of upper mantle discontinuities near 410 and 660 km depth, give independent estimates of temperature, and this can be used as a control on the assumed composition. However, with the resolving power available today, disagreement may just as well indicate that P and S velocity are not equally well resolved. In addition, the composition needs to be adjusted, especially in the case of anomalously low S velocities, where volatiles or melts are present. Figure 17 gives a recent example of such a temperature interpretation. With the station density of USArray, there will be fewer problems due to limited resolution.

USArray's flexible and permanent seismic networks will provide the data necessary to construct more reliable and detailed images. The workshop participants agree with the conclusions of the *ad hoc* meeting in April 2001 in La Jolla that USArray's current design (70 km station spacing with N-S oriented deployments moving W to E in a 10-year time span) is adequate for achieving EarthScope's high-resolution

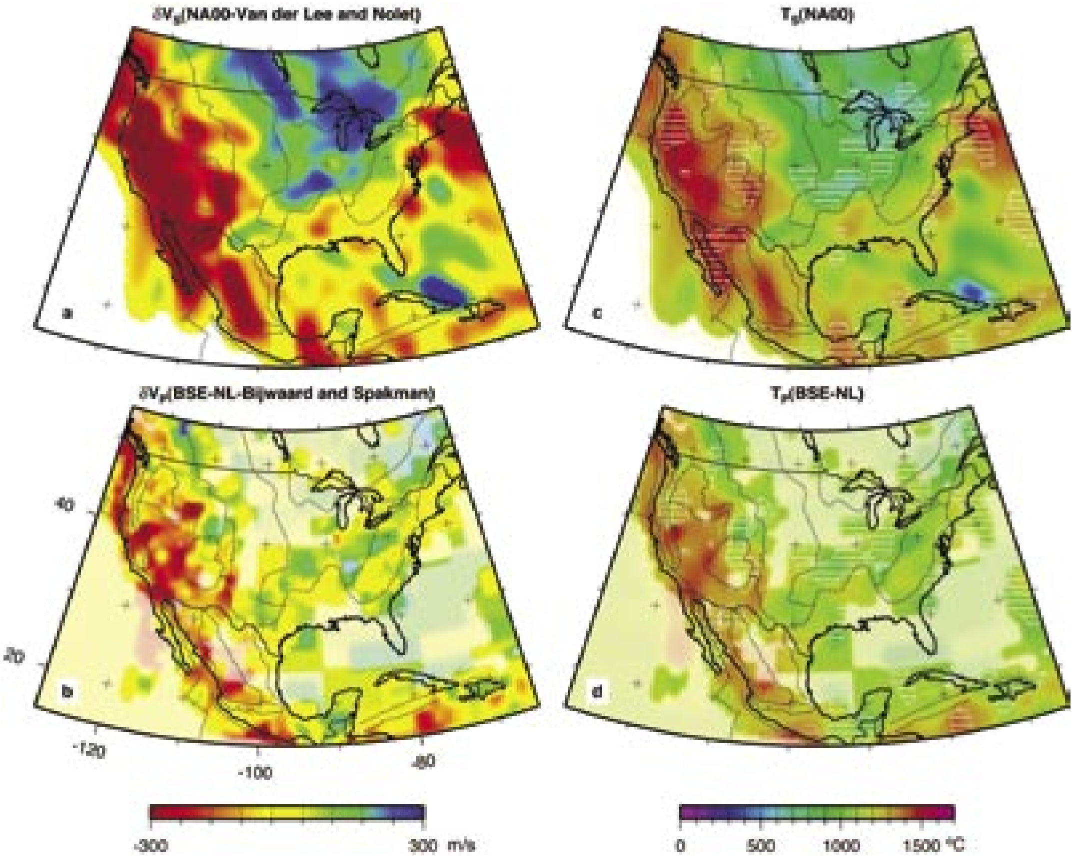


Figure 17. Maps of temperature (c, d) as estimated from tomographic models for S and P velocity (a, b, respectively) at a depth of 110 km. Faded colors indicate low resolution in the tomographic model. Regions where the two temperature derivatives differ by more than 150 degrees are indicated by hatching. These may be regions of partial melt, high volatile content, or with composition significantly different from the garnet lherzolite composition (67% ol) used in the computations. Figure from: S. Goes and S. van der Lee, 2001, Thermal structure of the North American uppermost mantle inferred from seismic tomography, *J. Geophys. Res.*, in press.

goals. This station spacing should not be reduced, and we strongly support the recommendation to assure an adequate calibration of instrument response as well as orientation. The reason for this is that wave polarities are taking on an increasingly important role as we abandon the assumptions of an isotropic, layered Earth in which seismic waves travel in the sagittal (great circle) plane.

Complementing the La Jolla meeting's recommendation to make sure that OBS deployments provide resolution at the western and eastern edges of the land-based array, we recommend a close collaboration with seismologists in Mexico and Canada. The planned US/Dutch/Mexican NARS-Baja project is already committed to share data with USArray, but infrastructure problems in Mexico (manpower, Internet connections) have so far complicated efforts to make full use of existing high quality instrumentation in other regions in Mexico.

EarthScope Products

Data. EarthScope's primary product concerning deep-Earth science will be the seismic waveforms recorded by USArray's permanent, transportable, and flexible arrays. In addition, there will be many intermediate seismic data sets that will include earthquake locations, arrival times, source time functions, cross-correlated phases, shear-wave splitting measurements, normal modes, and so on. EarthScope will provide data from Earth's inner core to its upper mantle. It is also likely that a Reference Data Set will be established as a standard that successive modeling can use in benchmark tests.

Models. EarthScope's secondary product concerning deep-Earth science will involve the generation of 3D and 4D models of Earth's interior. A primary focus will be the development of 3D models of the seismic properties of the crust, mantle, and core, including P and S velocities, Poisson ratio, attenuation, and anisotropy. In collaboration with scientists in mineral physics, geochemistry, geodesy and geodynamics, these seismic models can be presented in terms of other parameters. A major goal will be to cast the seismic data into 3D models of temperature, composition, density, buoyancy forces, and material flow. The long-term aim of this will be to develop a 4D time history of mantle motions that includes the history of plate kinematics but ties these plate motions to the flow history of the entire mantle. This would be the equivalent of a 4D Earth atlas.

Tools and Technology

Development. To carry out the desired deep-Earth scientific goals, there must be technological development in several areas. The IRIS DMS has continued to develop tools that have improved the manner in which seismic data is mined. It is important that this development continue, as the task of extracting data from increasingly larger data sets and incorporating them into new software technologies will become more complex. There also will need to be advances in information technology software development that will allow investigators to examine, process, and analyze large amounts of data in fast and easy ways. One example of this kind of development has been the development of 3D seismics within the petroleum industry. We will need to do the equivalent of 3D seismic profiling at the scale of 1000s of kilometers.

It is very important that the geoscience community foster advances in seismic wave theory. Most teleseismic work currently uses very limited parts of the seismograms that are available. The goal with USArray data will be to use as much of the seismic waveforms as possible in the analysis of 3D Earth structure. A vital step in this process is the development of fast and accurate 3D synthetic seismograms that can be used in the modeling of waveform data.

There also needs to be a better framework for collaborations between seismologists and geoscientists from other disciplines. A greater level of interdisciplinary communication is needed to convert the seismic data directly into the kinds of 3D models of material properties that are need to solve the research's major geophysical questions. One step in this process is establishing standardized formats for both data and models.

Analysis Tools

Using tools adapted to processing large volumes of data, USArray will provide an opportunity to extend the theoretical analysis into domains hitherto out of reach for global seismology, and to interpret a larger part of the seismogram.

Theoretical and computational tools. Much of global seismology is still rooted in ray theory or uses perturbations to one-dimensional solutions of the wave equation to handle the effects of lateral heterogeneity. Exact computational techniques are advancing rapidly with the growth of computer power. Spectral element techniques now permit the forward calculation of the wavefield for frequencies up to about 50 mHz. However, extension of this technique to short period body waves is far in the future, and there is a clear need for faster methods to handle, for example, short period wave propagation through anomalies in D″. Receiver function migration is an example of the import of industry techniques into the teleseismic arena. Involvement of experts from the exploration seismological community and from the mathematical community in the development of theoretical tools is strongly desired and a pro-active role of NSF is very welcome; the recent NSF initiative to foster collaboration between mathematics and the sciences is a good starting point.

Data management and processing tools. Because seismic data provide the bulk of the information needed to study Earth's deep interior, this section is by necessity devoted to the data to be expected from the USArray component of EarthScope. We expect no problems in managing USArray data if they are incorporated into the present IRIS Data Management Center (DMC) system. Data processing tools could be improved, though. The most popular and powerful program available so far, the Seismic Analysis Code (SAC) developed at Lawrence Livermore Labs, urgently needs to be adapted to handle multichannel data. Tools for vetting large data volumes so as to avoid being swamped by useless noisy data without actually downloading and inspecting them are virtually absent. However, they should be easy to develop on the basis of intermediate data products that are a natural by-product of the quality assessment process (delay times, amplitudes).

IRIS is a diverse community of often-small institutions. Some attention should be paid to the planning of research projects with USArray data beyond the regular, but informal, 'workshop' model that has proven to be very effective for guiding top research, but which is less well suited to handling undergraduate and other more educational research opportunities. We greatly favor a system in which it is easy to check what is already being done with the data and by whom, so as to avoid needless duplications. Finally, we shall need to develop software that makes it easy to visualize and analyze the typical seismological data products, such as tomographic maps.

Needs Beyond the EarthScope Facility

EarthScope instrumentation will provide an unprecedented stream of geophysical data on North America's surface motion and its structure extending from the shallow crust into the deep mantle and core. Extracting the most information from these data will require three major efforts beyond those previously identified in the development of the four EarthScope observational components.

1. EarthScope must effectively communicate its progress, data availability, and research opportunities to the broad scientific community to permit them to use and benefit from EarthScope data.

2. EarthScope must create, maintain, and continually update various derived data sets to make the data useful to a broader research community. EarthScope raw data should not be considered an end product.

3. Data and research efforts from fields critical to the interpretation of data from EarthScope instrumentation must be considered an intrinsic part of the overall EarthScope project and be allowed to compete on an even basis for EarthScope science funding.

Communication Within the Scientific Community

The scale and scope of EarthScope will allow it to have an impact on a much broader range of questions than those outlined in the Scientific Targets section of this report. Indeed, some of EarthScope's greatest discoveries are likely to come from unexpected areas, on unanticipated topics of research. To promote these unanticipated opportunities, EarthScope must proactively develop a communication mechanism with the broad research community capable of using EarthScope data and results. Other large Earth science initiatives, for example ODP, MARGINS, and RIDGE, have faced this problem with some success. Their example would be useful to EarthScope in planning its scientific outreach mechanisms. One option discussed within many of the groups at the workshop entails creating an "EarthScope Office" with permanent staff and infrastructure. In addition to serving as the central clearing house for the EarthScope product, the office could maintain an EarthScope help desk to help users easily and efficiently find what they need. The office could be responsible for instigating peer-reviewed, integrated compilations of EarthScope results (similar to AGU monographs), proactively organizing multidisciplinary/interdisciplinary workshops and sessions at national meetings, and publishing monthly newsletters as well as a comprehensive annual EarthScope report of scientific results.

To increase the use of data sets by nonspecialists in other fields, advertising the availability of data, tools, and services would be a helpful step. It is also critical to educate EarthScope scientists on the project's progress, data availability, and research opportunities to facilitate coordination of activities with complementary research efforts such as IODP, MARGINS, and DEOS. EarthScope must construct a framework for on-line interaction, including promoting and developing digital libraries for EarthScope products and setting standards to facilitate interaction with the information technology community. The purpose here is to create a flexible environment for collaboration and data dissemination. One model for this is to define a hierarchy of EarthScope products that would include:

a. Data Products (raw geophysical data collected by EarthScope instruments). Raw GPS data, seismic waveforms, strainmeter records, etc.
b. Derived Products (first level of reduction of EarthScope data). GPS coordinates, GPS velocities, earthquake locations, moment tensor inversions, etc.
c. Interpretive Products (technical analysis of EarthScope data). Strain-rate map, tomograms, mantle anisotropy map, seismic discontinuities, etc.
d. Knowledge Products (ultimate scientific interpretation of EarthScope data). Earthquake probability map, volcano source model, mantle flow model, etc.

Items a and b would probably be developed and archived as part of EarthScope infrastructure support; items c and d would probably result from P.I.-driven scientific investigations and perhaps be archived as part of the responsibility of the "EarthScope Office."

Extending the Usefulness of EarthScope Data

Production of "derived" data sets

Extensive planning for collecting and archiving raw data is an intrinsic part of the EarthScope MRE request. For these data to be useful to scientists other than the specialists capable of reducing them will require the production of "derived" data sets. In the case of GPS, this could be as simple as a time series of positions for each GPS site. For seismology, a number of different derivative products would be desired. For example, high-resolution maps of seismic velocity, anisotropy, discontinuities, Moho depth and sharpness, and seismic attenuation are key elements in applying geologic interpretations to the seismic results. Other components of the "derived data" could include real-time availability of GPS and strainmeter time series, consensus GPS velocity models, consensus interferograms from InSAR, and a catalog of geodetically determined transients from strainmeters, InSAR, and continuous GPS.

Data and Analysis Centers

Data and analysis centers are needed to organize tools and assist in the development of additional products. These centers could contain a description of modeling frameworks intelligible to multidisciplinary users, and a modeling code archive containing both technical descriptions for specialists and tutorials for non-specialists. In the process of developing Data and Analysis Centers, effort should be made to reach out to targeted users, particularly those in industry and in emergency preparedness. EarthScope's potential usefulness to society will be much greater by anticipating the needs of these groups, and they should play an active role in developing the centers.

Software utilities to manipulate data

Software utilities should be made available to help both specialists and non-specialists process raw data and produce data products for themselves. These two elements (data archiving and software utilities) should be part of any data center. Data accessibility and visualization across the spectrum of Earth science disciplines will require a new set of data management and analysis tools. The need for greatly enhanced visualization tools was a topic of discussion in most working groups. Some commercial products are available (e.g., ENVI), but it was suggested that a 3D version of GMT also be developed. Mature data sets need to be accessible on the web in comprehensible formats, and in versions that invite feedback on their scientific significance and interpretation. The SCEC velocity field, the Harvard CMT solutions, and the USGS seismic hazard maps are good examples of widely available data sets that improve from version to version because of their visibility and resulting feedback. Integration of data sets, such as velocity fields with geological structure, will also enhance their utility to a broad cross section of the Earth science community.

Community research products

The purpose of community research products is to permit the scientific community to make progress in multi-disciplinary research by providing useful results obtained by researchers from many disciplines. Community models are one method for generating integrated data sets and evaluating their implications. Where consensus does not exist, visibility and common formats for disparate models, such as common sampling and grid points, will aid in their comparison by non-specialists who have a stake in the data. EarthScope's real success in developing such accessibility will be measured in the collaborations created among subdisciplines that have had little interaction such as petrology, structural geology, hydrology, and geophysics.

Associated Research Activities

From its inception, EarthScope should include a sampling and experimental capability for disciplines not directly driven by the geophysical infrastructure intrinsic to the project. A Steering Committee for the project that includes representatives from Earth science disciplines with sufficient breadth to identify ancillary scientific goals and opportunities is paramount. The significance of the EarthScope product will be greatly enhanced by the input of a broad scale Earth science committee in the initial design and implementation stages. EarthScope represents an unprecedented opportunity that should be as inclusive as possible.

Compilation of existing information

Interpretation of much of the data to be produced by EarthScope instrumentation will be aided by baseline geologic, geophysical, and geochemical information. In advance of installing EarthScope instrumentation, efforts should be made to implement a nationwide GIS database of existing complementary geophysical, geological, and geochemical data (topography, gravity, regional geology, space-based images, heat flow, electrical conductivity, digital short-period seismic data, rock composition and ages, etc.). Where these data are already available and compiled into digital databases, simple links, perhaps through the EarthScope Office, could be advertised and made available to the EarthScope research community. Where the data are available, but not yet compiled into useful formats that can be readily accessed and compared with EarthScope data, encouragement for, and collaboration with, outside compilation efforts such as Geoinformatics, will be necessary. Of particular merit, the GIS database might also include development of 3D reference models for baseline data sets such as crustal structure, upper mantle structure and anisotropy, deformation, geochemistry, geochronology, and other geologic data. This material could serve as a base on which to begin construction of EarthScope models of continental structure and evolution.

Geology, geochemistry, geochronology

Though a large and diverse set of geological information exists for North America, this information base has been assembled in a somewhat piecemeal fashion over the past few decades. Consequently, this information, which will be of use in addressing a wide variety of EarthScope-related science questions, may not be sufficiently comprehensive for EarthScope purposes. Where such data do not exist, but are critical to the interpretation of a given EarthScope data set, research funding should be available to support complementary field- and laboratory-based studies. As a baseline, it may be worth considering collection of geological information on the same continent-wide scale as the USArray data. For example, at each grid point in the Bigfoot array, it may be useful to collect comprehensive geological data such as rock types/petrology/structure, pressure and temperature of equilibration, whole-rock geochemistry, and rates of uplift and/or exhumation.

Systematic geochronology is required to understand the key concept of time, captured by the slogan "no dates, no rates." The basement geology of the United States was the subject of extensive geochronologic study in the 1960s, but geochronologic techniques have improved in precision sufficiently since then to render many of these earlier age determinations inadequate to address modern questions. This is particularly true for age determinations in the 100 to 1,000,000 year range where a variety of techniques now are available to address a time scale that is critical in investigations of subjects such as earthquake and volcanic eruption repetition cycles. To ensure that geochronology can play its essential role in EarthScope investigations, the current provision and capacity of geochronology laboratories should be evaluated and needs for renewal of facilities identified (e.g., with respect to provision of high-resolution ion-probes, laser ablation –ICP-MS, Ar-Ar dating facilities, and accelerator mass spectrometer capacity).

In critical areas, field verification of remotely determined features and inferred processes may be necessary. One way to assist in this endeavor would be to create an equipment loan facility to support the field geology element of EarthScope (e.g., for tripod-mounted LIDAR, differential GPS, and total stations). Additional "field" examinations may require selective drilling in poorly exposed areas.

A focused workshop is planned for 2002 to evaluate what facilities are needed and are available, what new investment is required, and how the geological community can most effectively and efficiently provide digital forms of geological data.

Mineral physics and petrology

Mineral physics and petrology experiments are needed to measure parameters relevant to the interpretation of seismic models. These include: (1) temperature and pressure dependence of velocities for different assemblages of minerals, (2) melting temperature of a variety of mantle and crustal rock compositions under fluid absent and fluid present conditions, (3) anisotropy of minerals as a function of temperature, pressure and phase, (4) stability fields of minerals and modal mineralogy as a function of composition, temperature, and pressure, (5) mechanisms for anelastic attenuation, and (6) velocity/density relations as a function of temperature and pressure. Experimental data are needed on pressure and temperature derivatives of seismic velocities for a range of probable mantle compositions. Many data are available at room temperature and pressure, and the database for ambient conditions is growing. It should be a relatively simple matter to start and maintain a database that permits easy access to the most recent laboratory data. Laboratory data on the dependency of Q on temperature are scarce even at ultrasonic frequencies and, with one or two exceptions, are absent at seismic frequencies. Similarly, a better understanding of seismic anisotropy and its relationship to strain, strain rate, and strain history is wanting.

For these reasons, the capacity of experimental petrology, rock deformation, and mineral physics laboratory facilities within the geologic community should be evaluated. This may require additional provision of high-sensitivity gas media apparatus, solid-media apparatus, EBSD, increased access to synchrotron X-ray sources, and a range of microscopy facilities.

Additional geophysical measurements

Higher-precision potential field geophysical data (i.e., gravity and magnetic) is needed in areas where USArray's flexible component will be deployed. Heat flow data are spotty, and it would be ideal to have more uniform coverage. For EarthScope to be successful and result in significant advances in the domains outlined above, a high-quality, healthy global seismic network must be maintained to be able to link the observations collected at the continental scale to global processes. Also, some global seismic data collected outside of the United States will provide important complementary constraints on structure beneath the North American continent (e.g., SS waves bouncing under North America).

Theoretical efforts

We currently are limited in the theoretical tools at our disposal to effectively extract the full wealth of information contained in seismic waveforms from deployments at the scale of USArray. Most of the methodologies currently used in seismic modeling rely on travel time and phase information in the framework of ray theory. Efficient approximations for 2D and 3D wavefield computations need to be further developed for broadband waveform modeling. We also need to develop effective broadband array data processing techniques.

Given that a major goal of EarthScope is to understand the connection between structure and dynamics of the solid Earth, expanded efforts in geodynamic modeling will be an essential component. Geodynamic theoretical approaches will be key in translating observational data into an understanding of the mechanical processes that drive continental deformation; magma production, migration, and eruption; and the interaction of continents with the rest of the solid Earth.

Ocean bottom observations

The processes we wish to study in the lithosphere and upper mantle do not stop at the shore. It is therefore important to link EarthScope to initiatives in ocean bottom observatory deployments, particularly on the margins of North America, in order to collect a more complete view of the transitions from continent to ocean structure. An extension of observations offshore, through coordination with planned programs (e.g., Ocean Observatories Initiative) and targeted campaigns with ocean-bottom seismometers and seafloor geodetic systems would expand EarthScope capabilities.

"Historic" seismic data

Because USArray is limited in time, it is important to maintain access to older databases such as WWSSN and LASA. However, it is not considered cost-effective to undertake a massive and indiscriminate digitization effort of WWSSN data. There is wide agreement that the DMC has made remarkable headway in making these data available to the seismological community. We encourage efforts to broaden the station population for which data are available through the DMC with known and well-developed tools. We encourage collaboration among IRIS, USGS, and regional networks in defining protocols at the detailed technical level, with the aim of keeping data accessibility and quality high, and seamless merging with USArray data effortless.

The EarthScope Audience

The Scientific Community

As outlined in the preceding sections of this report, EarthScope has the potential to serve as a unifying effort for a diverse set of solid Earth science research disciplines. Driven in part by the need for expensive research facilities and instrumentation, fields such as physics and oceanography have developed mechanisms that foster collaboration across disciplinary boundaries. Earth science is now well poised to develop such mature collaborations. Over the course of the last decade and more, research consortia such as IRIS, CHiPR, SCEC, and UNAVCO have laid a framework for large-scale, multidisciplinary projects that makes an effort like EarthScope possible. The scale of the problems to be addressed by EarthScope span many Earth science disciplines, and the continent-wide data collection can be expected to attract many unexpected uses of the data, for example, measurement of atmospheric humidity across North America with GPS apparatus. EarthScope's success will be tremendously enhanced by continued appreciation of its wide-ranging impact across many areas of study and a sustained effort to make the research opportunities and data availability open to the broader scientific community.

> EarthScope's results will permit a new understanding of Earth processes, helping society to mitigate hazards and use resources more responsibly.

Hazards, Resources, and Technology

EarthScope offers tangible steps forward in areas directly relevant to society such as providing constraints on natural hazards monitoring and predictability, and improvements to GPS infrastructure that support the geotechnical and engineering communities, cities, counties, states, and meteorology. In addition, EarthScope work concerning characterization of continental structure and evolution will support ore deposit genesis studies and estimates of seismic shaking potential. Recent advances in characterizing the role of fault interaction in earthquake hazards will escalate. The framework for understanding intraplate earthquakes will be greatly enhanced by USArray by imaging structures on which such earthquakes have occurred, determining intraplate microseismicity, characterizing areas of vulnerability, and inferring stresses in areas away from known deforming regions. Characterization of subsidence supports groundwater management and strategies for reinjection that maintain porosity in reservoirs and aquifers. Hillslope stability studies and zoning will benefit from LIDAR and the GPS infrastructure used by the geotechnical community. By combining high-resolution topography with sea level rise observations, our understanding of climate change and its impact on coastal hazards will advance. Soil dehydration trends can be detected by InSAR. Continental slope stability and tsunami hazard studies may advance through better OBS monitoring and by developing real-time detection of transient deformation events. Seismically imaging the structure and nature of sedimentary basins will result in a better understanding of seismic hazard in lowland areas.

Earthquakes and the faults that cause them are of exceptionally broad interest to society. Scientists and educators are keen to understand the tectonic processes that shape our globe. The engineering community needs the seismic ground motion predictions, generally couched in probabilistic terms that guide their designs of major structures. The public needs to have a much better understanding of seismic hazard so as to make informed decisions about mitigating these hazards to the greatest extent feasible. In conveying hazard-related information to policy makers and the public it is critical that this information be transmitted accurately and carefully to avoid policy outcomes that are unintended or inconsistent with their scientific basis. Accordingly, a staff member with some training in government affairs should serve as an EarthScope liaison in this sort of information transfer.

EarthScope will richly contribute to science literacy, building on the successes of NASA and SCEC, and development of a professional and technical workforce. In this vein, concern was expressed over whether there will be enough graduate students to do the work and whether there would be too many Ph.D.s produced. This issue is tied to raising the image of Earth science in the general public. States will make important contributions to EarthScope outreach through their state geological surveys, consistent with their public education mission. In addition, state universities play a critical role in the education of future teachers. Finally, the role of industry could be one of fruitful exchange of information, both with the geotechnical firms who will richly benefit from EarthScope data sets, and the petroleum and mineral resource industries. EarthScope's success will be greatly enhanced by a partnership structure with industry, where many suitable data sets are available. However, access to industry data is often limited because of time and effort constraints in industry, so EarthScope should offer personnel and financial support to industry for this partnership in exchange for access to their data.

Students

What opportunities exist for contributions to education at all levels? How can EarthScope raise the general public's perception of Earth science? EarthScope, particularly the USArray, will pass through virtually every single community in the United States. Many seismic stations will be sited near schools. Every deployment will involve the participation of state geologists, K-12 teachers, university faculty and students, local landowners, and local, state, and federal government officials. The incoming data and models that have already been produced will be available to the entire nation on line and in real time. Informational materials aimed at every educational and interest level must be an integral part of the EarthScope program and distributed as EarthScope rolls across the continent.

Because of the capability of visualizing the 3D and 4D models of EarthScope products, as well as their intellectual appeal, it is important that major efforts be made to make these products available at K-16 levels and to the general public. Materials need to be prepared that can be easily implemented by K-16 teachers, and EarthScope should play a proactive role in incorporating EarthScope products into K-16 curricula. In an ideal world, students would take Earth sciences in 12th grade, as this subject is the most interdisciplinary of high school sciences, combining aspects of physics, chemistry, and biology. Serious efforts will have to be made to change K-12 Earth science from a qualitative to a quantitative subject, but EarthScope products could provide a foundation for this. Laboratory experiments involving intuition-based and analysis-based approaches could be developed from the EarthScope results. These changes have the goal of educating young citizens about the dynamic Earth, and changing the common view of Earth as static and unchanging.

The General Public

The power of geology, geophysics, and geodesy in captivating the public imagination has been robustly characterized in the K-12 curriculum through the common use of the "learning moments" posed by volcanoes, earthquakes, dinosaurs, and the global theory of plate tectonics. The literature of writers such as John McPhee, Simon Winchester, and Dava Sobel and the success of Discovery, Nova, and Explorer programs illustrate that geology captivates the public imagination. Public perception of U.S. history and the westward expansion is shaped by the landscapes produced by mountain building and the mysteries of the geodynamic processes that underlie them. Fascination with the application of modern technologies, such as GPS and computing technology, to these mysteries is great. We are well poised to exploit this public support for the basic discovery and natural hazards aspects of our disciplines, and for the prospect of a great new-millennium advance in understanding continental tectonics. The regional aspect of USArray could be accompanied by an aggressive outreach program, even incorporating "EarthScope Vans," similar to those employed by NASA. For the general public, it is important that magazine features, Nova shows, and other media venues be used to convey EarthScope results. This is an excellent opportunity to convey to the general public that geology is more than "skin deep," and that the subject is interdisciplinary, subtle, complex, and fascinating.

EarthScope presents many opportunities that can be used to raise the general public's image of Earth science. Examples of such outreach activities include:

- developing links with museums;
- making community models accessible to educational institutions;
- developing 4D visualization tools;
- Using HAZUS to link EarthScope results to public policy;
- building EarthScope exhibits near the SAFOD site and those PBO and USArray installations where feasible;
- sponsoring an Earthquake Report on television (e.g., the Weather Channel)
- disseminating public information newsletters ("Under the EarthScope");
- developing portable museum displays (connected with USArray/PBO deployments);
- providing real-time interactive data visualization tools;
- developing a program of educational affiliates ("Join EarthScope");
- building a network of media contacts (Nova, Discovery, National Geographic, etc.);
- developing high-quality visualization/animation displays;
- focusing on high-technology aspects of EarthScope;
- having scientists in schools programs
- encouraging student participation in field experiments;
- developing a NSF Research Experience for Undergraduates (REU) program;
- developing a program for summer field experience (high school/college students);
- linking EarthScope to professional E&O organizations (DLESE, AGI, NSTA, etc.).

Conclusions

The clear conclusion from the workshop is that EarthScope's measurements can uniquely address a rich mix of scientific problems and natural hazards issues. Though suggestions were offered for detailed changes in instrument distribution and installation procedures that could help extend instrument capabilities, in general, the various components of EarthScope are well designed individually and offer tremendous synergy in their goals and capabilities. At least judging from the enthusiasm present at the workshop, the Earth science community is anxiously awaiting the initiation of EarthScope science activities. If anything, the main topics of discussion at the workshop focussed on what needs to be done once the EarthScope "instrument" is installed and running. To maximize the reach of EarthScope results across the many disciplines that potentially can become involved in this project, discussion at the workshop highlighted the following three needs:

1. EarthScope needs to develop a management and/or community advisory structure that will foster communication among all the disciplines likely to benefit from, and contribute to, EarthScope-related science. Because most EarthScope research will be funded outside the MRE, it will be necessary to have community input and oversight to assure fair and even-handed consideration of the many research topics likely to be considered for funding under the EarthScope science umbrella.

2. EarthScope needs to establish an office that would be responsible for proactively communicating EarthScope progress, data, and research opportunities to a broad community. An important EarthScope office activity will be to archive "derived" data sets and community models produced from EarthScope data in a "products warehouse."

3. EarthScope must take advantage of the abundant education and outreach opportunities. Efforts should be underway now to promote outreach to involve the larger Earth science community in EarthScope planning and development. Once the EarthScope project begins, these activities can be extended to the broader communities including state geological surveys, policy makers, students at all education levels, and the general public.

Appendix I: Abstract Titles and Authors

Full abstracts can be found at www.earthscope.org.

Author	Affiliation	Title	Coauthors
Abercrombie, Rachel	Boston Univ.	Physics of Earthquakes: Nucleation and source properties.	
Abers, Geoffrey	Boston Univ.	Subduction to accretion to continental mantle: Cascadia and Alaska to Craton	
Agnew, Duncan	Scripps (UCSD)	The Salton trough and Eastern California shear zone: an EarthScope target area for fault-system studies.	Tom Rockwell
Ahern, Judson	Univ of Oklahoma	Understanding displacements and crustal strain in the midcontinent.	M. Charles Gilbert
Allen, Richard	Caltech	Extending the lessons of regional tomography to a continent.	
Ammon, Charles	Penn State	High-resolution shear-velocity mapping & the evolution of continental lithosphere.	Jordi Julia, Robert Herrmann, Thorne Lay
Anderson, Greg	SCEC	Roles for EarthScope in understanding Earthquake stress transfer.	
Arrowsmith, Ramon	ASU	The South-Central San Andreas Fault system: a natural laboratory for EarthScope.	
Artemieva, Irina	USGS-Menlo Park	Thermal thickness of cratonic lithosphere: a global study	Walter Mooney
Bawden, Gerald	USGS-Menlo Park	Recognizing and exploiting the effects of human-induced surface motion on continuous GPS networks.	
Ben-Zion, Yehuda	USC	Multi-disciplinary imaging of structural and material properties of Earthquake fault zones.	David Okaya
Bokelmann, Gotz	Stanford	Interaction of Continents with the underlying mantle.	
Brocher, Tom	USGS-Menlo Park	Interactions of the slab, seismicity, and forearc basins in the Pacific Northwest	Ray Wells, Sam Johnson, Craig Weaver, Steve Kirby, Tom Pratt, Rick Blakely, Pat McCrory
Brodsky, Emily	UCB	Distant dynamic triggering and EarthScope	
Brown, Michael	Univ. of Maryland	The Northern Appalachians: what we know and what we would like to know, and how studies of ancient orogens can contribute to interpretation of regions of active tectonics.	
Bruhn, Ronald	Univ. of Utah	EarthScope opportunities in the Saint Elias Orogen, Southern Alaska - Western Canada.	Terry Pavlis, Lora Serpa
Carlson, Richard	Carnegie	Mechanisms of continent growth: an example from the Pacific Northwest.	
Christensen, Douglas	Univ. of Alaska	EarthScope in Alaska	Roger Hansen
Christensen, Nikolas	Univ. of Wisconsin	Deep crustal processes: constraints from EarthScope seismology and laboratory velocity studies.	
d'Alessio, Matthew	UCB	Heat, friction, and the mechanics of faults	Roland Burgmann
Dennis, Allen	Univ. of South Carolina	Reference stations for continuous GPS measurements in the intraplate region of the eastern US are necessary for the Plate Boundary Observatory and can help solve geodynamic problems in the eastern US.	
Dorsey, Rebecca	Univ. of Oregon	Use of Plio-Pleistocene stratigraphy and geomorphology in the study of Active Plate-Boundary deformation: an example from the San Jacinto Fault Zone.	
Dragert, Herb	Geo Survey of Canada	Episodic silent slip: a new aspect of Cascadia megathrust behavior.	
Ducea, Mihai	Univ. of Arizona	USArray and xenolith studies	
Dziewonski, A.M.	Harvard	Crust-mantle interactions: Mapping the deep structure of North America.	M. Nettles, L. Boschi, Y.J. Gu, G.Ekstrom

Earle, Paul	USGS-Denver	Investigating fine-scale deep earth structure using the USArray.	John Vidale
Fialko, Yuri	UCSD	Study of the dynamics of large-scale crustal magmatism and the associated deformation using InSAR measurements in neovolcanic areas.	
Fitzenz, Delphine	Switzerland	The SAFOD project: an opportunity to combine field and laboratory data to constrain forward modeling parameters.	Stephen Miller
Flesch, Lucy	SUNY	Using GPS, seismic, gravity, and topographic data to understand the dynamics of the western North American Plate boundary zone.	Bingming Shen-Tu, William Holt, A. John Haines
Foulger, G.R.	USGS-Menlo Park	Testing topside tectonics.	
Freed, Andrew	UCB	Listening in on conversations between faults.	Roland Burgmann
Freund, Friedemann	SJSU/NASA	Electronic charge carriers in Igneous rocks and their activation through tectonic processes.	
Fuis, Gary	USGS-Menlo Park	USArray targets in Southern California: Los Angeles Region, Ventura Basin	
Fuis, Gary	USGS-Menlo Park	USArray high-resolution seismic-imaging targets in Southern California	Rufus Catchings, Michael Rymer, David Okaya, Thomas Henyey
Furlong, Kevin	Penn State	Imaging the partitioning and localization of the Pacific-North America plate boundary: completing the circuit in Northern California and Southern Oregon.	Tim Dixon, Rocco Malservisi, Jane Lock
Grant, Lisa	UCI	Paleo-PBO: a fault database for 4D Plate Boundary Observation.	
Gwyther, Ross	CSIRO, Australia	Focussed study of aseismic fault processes.	Michael Gladwin, Rhodes Hart, Marie Mee
Hacker, Bradley	UCSB	Deformation and diagenesis within the San Andreas fault zone & intermediate-depth earthquakes and dehydration in the Cascadia Slab.	
Hadizadeh, Jafar	Univ. of Louisville	Textural analysis and strain estimation in Cataclastic deformation supported by digital image technique.	
Haeussler, Peter	USGS-Anchorage	Tectonics, mountain building, subduction, and volcanism in South-central Alaska.	Jeff Freymueller, Seth Moran, John Power, Rick Saltus
Hall-Wallace, Michelle	Univ. of Arizona	Developing National and local efforts for EarthScope education and outreach.	Terry Wallace
Hamburger, Michael	Indiana Univ.	An Integrated education and outreach program for the EarthScope initiative.	Chuck Meertens, Michelle Hall-Wallace, John Taber
Hammond, William	USGS-Menlo Park	The dynamics of western United States Tectonism.	Wayne Thatcher
Hansen, Roger	Univ. of Alaska	Seismicity and Seismo-tectonics of Alaska: Alaska as a natural laboratory for EarthScope	Natasha Ratchovski, Trilby Cox, Douglas Christensen
Harris, Robert	Univ. of Utah	Thermal measurements for EarthScope: Implications for rheology and deformation.	David Chapman, Colin Williams
Herring, Tom	MIT	Development of an integrated GPS network management and data distribution system for PBO.	R. King, C.Meertens, M.Johnson, W. Shiver, Y. Bock, M. Scharber, B.Gilmore, P.Jamason, G.Blewitt, B.Holt, D. Stowers, F.Webb, Y.Bar-sever, C.Noll
Hildenbrand, Tom	USGS-Menlo Park	USArray initiative and the U.S. Geological Survey	Walter Mooney
Hildenbrand, Tom	USGS-Menlo Park	USArray science and crustal structures related to mineral deposit patterns in the Great Basin	Keith Howard

Hill, David	USGS-Menlo Park	The Long Valley Caldera - White Mountains region: a study of coupled tectonism and magmatism	William Ellsworth, Susan Owen
Holt, William	SUNY	Using surface observations to constrain the direction and magnitude of mantle flow beneath western North America	Paul Silver
House, Leigh	LANL	Studies of microseismicity and fluid systems, imaging of the crust and upper mantle, and wave propagation and verification studies with EarthScope data	L.Steck, J. Rutledge, C. Aprea, W.S. Baldridge, M. Fehler, H. Hartse, D. Krier, W.S. Phillips, S. Taylor, A. Velasco
Howard, K.A.	USGS-Menlo Park	Strain partitioning at a transpressional plate boundary: Crustal and lithospheric underpinnings of the Southern California knot.	V.E.Langenheim, G.S.Fuis
Hudnut, Kenneth	USGS-Pasadena	Decimeter-order spatial resolution: Imaging and swath mapping systems for tectonic, volcanic, geodetic and paleoseismic research	
Igel, Heiner	Germany	Regional to global 3D seismic wave effects relevant to EarthScope: Site effects, fault zones, volcanoes, subduction zones, plumes.	Yehuda Ben-Zion
Iturrino, Gerardo	Lamont-Doherty	Integration of core and downhole images in the San Andreas fault zone.	David Goldberg, Richard Ketcham
James, David	Carnegie	The EarthScope facility and its application to understanding the formation, evolution and stability of continental crust and lithospheric mantle.	
Janecke, Susanne	Utah State	Applications of the USArray and BO facilities to tectonic problems in the northern Basin-and-Range province and the eastern Snake River Plain.	
Johnston, M.J.S.	USGS-Menlo Park	EarthScope and PBO real-time borehole seismic/strain/pressure/GPS sites	M. Lisowski, R. Mueller, J. Power, D. Myren
Julian, Bruce	USGS-Menlo Park	Detecting and Resolving seismic and volcanic sources by radar interferometry.	G.R. Foulger
Karner, Garry	Lamont-Doherty	Symbiotic relationship between the MARGINS program and EarthScope	Olaf Svenningsen
Kenner, S.J.	Univ. of Kentucky	Estimating stress accumulation rates along major faults: inferences from studies of postseismic deformation following the 1906 San Francisco earthquake.	P. Segall
King, N.E.	USGS-Pasadena	Lessons for EarthScope from the Southern California integrated GPS network.	D.C. Agnew, J.Galetzka, K.Hurst, J.Langbein, M.van Domselaar, F.H. Webb
Klemperer, Simon	Stanford	Ultra-low frequency electromagnetic monitoring within PBO.	Tony Fraser-Smith, Greg Beroza, Darcy Karakelian
Langbein, John	USGS	Earthquake Research at Parkfield	
Levin, Vadim		Some things for EarthScope to do: Delamination of the mantle lithosphere-a widespread process?	William Menke, Jeffrey Park
Li, Yong-Gang	USC	Characterization of the San Andreas fault by fault-zone trapped waves.	John Vidale, Steven Day
Liu, Mian	Univ. Of Missouri	Geodynamics of diffuse plate boundary deformation: opportunities and challenges.	
Lowry, Anthony	Univ. of Colorado, Boulder	Keeping tabs on the slip transition at major faults.	Kristine Larson
Masterlark, T.	USGS-Sioux Falls	Homogeneous vs. realistic heterogeneous material-properties in subduction zone models: Coseismic and postseismic deformation.	C. DeMets, H.F. Wang, O. Sanchez, J. Stock
McBride, John	Illinois State Geo Survey	Refining the target for EarthScope in the central Midcontinent	Dennis Kolata, Thomas Hildenbrand
McGarr, Art	USGS-Menlo Park	Probing the rheology of the San Andreas fault using seismic data.	

McGuire, Jeff		Imaging of aseismic slip transients to study fault mechanics.	Paul Segall
Mellors, Robert	SDSU	Combining InSAR and seismology with EarthScope.	
Miller, Stephen	Switzerland	Inferring fault strength from earthquake rupture properties.	
Molnar, Peter	CIRES/Colorado	Large-scale continental dynamics.	
Moran, Seth	USGS-Anchorage	Seismic studies in the Mount Peulik/Becharof Lake area, Alaska	Peter Haeussler, John Power
Nadeau, Robert	UCB	Integrating EarthScope components and geology using repeating earthquakes.	
Nettles, M.	Harvard	Seismotectonics and the state of stress in the North American lithosphere: Analysis of small, unusual earthquakes.	G.Ekstrom, A.M. Dziewonski
Nicholson, Craig	ICS-UCSB	Past is key: tectonic evolution of the Pacific-North American plate boundary and its implications for crust/mantle structure and current plate boundary strain.	
Nolet, Guust	Princeton	A wealth of waves, a load to lift	
Olsen, Kim	ICS-UCSB	Rupture dynamics natural laboratory	Sophie Peyrat, Raul Madariaga
Ouzonunov, Dimitar	NASA Goddard Space Flight Center	Ground-atmosphere-ionosphere interactions related to earthquakes: how can EarthScope help?	Friedemann Freund
Park, Stephen	UCR	Shocking results: electromagnetic studies with USArray.	Robert Bielinski
Plank, Terry	Boston Univ.	Using igneous rocks to probe the evolution of the lithosphere.	
Pollitz, Fred	USGS-Menlo Park	Deep structure and driving forces in the New Madrid Seismic Zone.	
Power, J.	USGS-Anchorage	Magmatic, eruptive and tectonic processes in the Aleutian Arc, Alaska	M. Johnston, J.Freymueller, M.Lisowski, T.Murray, Zhong Lu, J. Eichelberger, D.Dzurisin, S.McNutt, S.Moran, M.Wyss, D.Mann, S.Wicks, S.Nye, W.Thatcher, J.F.Larson, P.Haeussler
Prescott, William	USGS-Menlo Park	Access to Strain and other low frequency geophysical observations.	Kathleen Hodgkinson, Douglas Neuhauser, Stanley Silverman, Page Stites, Stephane Zuzlewski
Price, Evelyn	Univ. of Alaska	Seismicity and active tectonics of interior Alaska	
Ritsema, Jeroen	Caltech	NARS-Baja: a 5-year deployment of broadband seismic instrumentation around the Gulf of California.	
Ritzwoller, M.H.	Univ. of Colorado, Boulder	Lithospheric inversions and the assimilation of complementary information: Some examples relevant for EarthScope.	N.M. Shapiro
Rolandone, Frede-rique	UCB	Heat flow paradox and thermo-mechanics of faulting and ductile deformation in a stike-slip shear zone.	Claude Jaupart, Roland Burg-mann
Romanowicz, Bar-bara	UCB	A Pitch for the Alaska component of USArray.	
Romanowicz, Bar-bara	UCB	The “mini-PBO” project: goals and current status.	M.Murray, R.Burgmann, T.McEvilly, P.Silver, A.Linde, S.Sacks, .Bock, D.Sandwell, M.Johnston, W.Thatcher, J.Langbein

Rudnick, Roberta	Univ. of Maryland	Making continents	
Rushmer, Tracy	Univ. of Vermont	The role of magmatism in the evolution of continental lithosphere: Possible tests using high resolution seismic imaging.	
Sandwell, David	Scripps-UCSD	InSAR and EarthScope: The good, the bad, and the ugly.	
Savage, Brian	Caltech	Seismic velocity variations beneath the Southern Sierra Nevada and the Western Basin and Range.	Ji Chen, Don Helmberger
Schmidt, David	UCB	Scientific discovery through the study of transient deformation	Roland Burgmann
Seber, Dogan	Cornell	A Prototype information system for EarthScope.	Muawia, Barazangi, Christine Sandvol, Carrie Brindisi
Segall, Paul	Stanford	EarthScope's Role in the earthquake and volcano mechanics	
Sheng, J.	Univ. of Utah	Imaging of Crustal layers by teleseismic Ghosts and its application to studies of structure and extensional tectonics in the Wasatch Front Region, Utah	G.RT.Schuster, R.L.Nowack, J.C.Pechmann
Shervais, John	Utah State	Intermediate depth drilling of the Snake River Plain in support of EarthScope: Tracking the Yellowstone plume (?) through space and time.	
Spiess, F.N.	Scripps-UCSD	Oceanic connections	S.D.Shadwell, H.Dragert, J.A.Hildebrand
Spotila, J.A.	Virginia Tech	Enhancing EarthScope by constraining vertical motions of the continental crust and surface.	
Talwani, Manik	Rice Univ.	Airborne gravity gradiometry an important new technology.	
Tandon, Kush	Univ. of Louisiana	Mechanics of continental rupture: Red Sea as a test laboratory (integrating 3D numerical modeling and an InSAR mission).	
Thatcher, Wayne	USGS-Menlo Park	EarthScope and natural hazards research	
Tikoff, Basil	Univ. of Wisconsin	The need to combine geological and geophysical data.	
Torgersen, Thomas	Univ. of Connecticut	Fluid Transport Analysis and Rare Gas "Ages" of Matrix Porosity Fluids in Drill Core	Martin Stute and Peter Schlosser
Torgersen, Thomas	Univ. of Connecticut	EarthScope for geochemists, hydrogeologists and petrologists.	
van der Pluijm, Ben	Univ. of Michigan	Mineral transformations and faulting (SAFOD)	
Velsaco, Aaron	LANL	The EarthScope knowledge base	
Wannamaker, Philip	Univ. of Utah	Physico-chemical state and cryptic structures of the crust and upper mantle: Role of the electromagnetic array measurements in EarthScope.	Steven Park, John Booker
Wdowinski, Shimon	Tel Aviv Univ.	Geodetic detection of active faults along the Pacific-North America diffuse plate boundary	Yehuda Bock
Williams, Colin	USGS-Menlo Park	Heat flow and the EarthScope Initiative with an emphasis on heat flow studies in support of the San Andreas Fault Observatory at Depth (SAFOD)	Arthur Lachenbruch, John Sass
Wyession, Michael	Washington Univ.	Using USArray as a window to the core-mantle boundary.	
Zhdanov, Michael	Univ. of Utah	Electromagnetic methods in the EarthScope project.	Nikolay Golubev

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Appendix 3:

Acronyms

AGI .... American Geological Institute

ANSS .... Advanced National Seismic System

CHiPR .... Center for High Pressure Research

DEOS............... Dynamics of Earth and Ocean Systems

DLESE .... Digital Library for Earth System Education

DMC .... IRIS Data Management Center

EBSD .... Electron Backscattered Diffraction

GIS .... Geographical Information System

GPS .... Global Positioning System

InSAR .... Interferometric Synthetic Aperture Radar

IODP .... Integrated Ocean Drilling Program

IRIS.................. Incorporated Research Institutions for Seismology

LASA .... Large Aperture Seismic Array

LIDAR .... Light Detection and Ranging

MARGINS .... An NSF program to study continental margins

MRE................. Major Research Equipment

NASA .... National Aeronautics and Space Administration

NSF .... National Science Foundation

NSTA............... National Science Teachers Association

OBS .... Ocean Bottom Seismometers

ODP .... Ocean Drilling Program

PBO .... Plate Boundary Observatory

P.I. .... Principal Investigator

RIDGE.............. Ridge InterDisciplinary Global Experiments

SAFOD .... San Andreas Fault Observatory at Depth

SCEC .... Southern California Earthquake Center

UNAVCO .... University NAVSTAR Consortium

USArray .... United States Seismic Array

USGS .... United States Geological Survey

WOVOCAT ...... World Organization of Volcano Observatories Catalog

WWSSN.......... World Wide Standard Seismographic Network

earthscope

WWW.EARTHSCOPE.ORG

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